A Comparative Review of Hydrologic Issues Involved in Geologic Storage of CO_2 and Injection Disposal of Liquid Waste

Chin-Fu Tsang, Jens Birkholzer, and Jonny Rutqvist
Earth Sciences Division
Lawrence Berkeley National Laboratory
Berkeley, California 94720, USA

Abstract

The paper presents a comparison of hydrologic issues and technical approaches used in deep-well injection and disposal of liquid wastes, and those issues and approaches associated with injection and storage of CO_2 in deep brine formations. These comparisons have been discussed in nine areas:

- Injection well integrity
- Abandoned well problems
- Buoyancy effects
- Multiphase flow effects
- Heterogeneity and flow channeling
- Multilayer isolation effects
- Caprock effectiveness and hydrogeomechanics
- Site characterization and monitoring
- Effects of CO_2 storage on groundwater resources

There are considerable similarities, as well as significant differences. Scientifically and technically, these two fields can learn much from each other. The discussions presented in this paper should help to focus on the key scientific issues facing deep injection of fluids. A substantial but by no means exhaustive reference list has been provided for further studies into the subject.

1. INTRODUCTION

Reduction of net atmospheric emissions of greenhouse gases (DOE, 1999a) through injection of anthropogenicCO_2 into deep brine formations is being actively studied, both in the USA and internationally. If this technology is to be deployed broadly enough to make a significant impact on global emissions of CO_2, thousands of wells, each injecting large quantities of CO_2, will be needed. For example, in the U.S. alone, the coal-fired electric generating capacity in 1999 was 278,000 MWe (DOE 1999b). A single coal-fired plant with 1,000-MWe capacity generates about 30,000 tonnes of CO_2 per day (Hitchon 1996) or more than ten million tonnes of CO_2 per year. The large scale of effective CO_2 geological storage suggests the need for a careful evaluation of technical issues associated with this endeavor. Such an evaluation should specifically include the identification and incorporation of the best CO_2 injection practices, the best scientific understanding of migration in subsurface formations, and the development of monitoring technology to ensure that geologic sequestration is safe and effective.

In this effort, it is useful to review the extensive history (over the last 50 years or so) of liquid waste injection into geologic formations in the U.S. (Apps and Tsang, 1996; Tsang and Apps, 2005). Many of the hydrologic issues involved in injection disposal of liquid waste and injection storage of CO_2 are similar, although there are some significant differences. The purpose of the present paper is to review these common hydrologic issues, and to evaluate whether studies of CO_2 geologic storage can draw on some experiences from liquid-waste injection. The emphasis is on the issues and methodologies, rather than quantitative comparisons of characteristics between the two cases. In the next sections, we first give a brief history of liquid-waste injection in the U.S. Then, the special physical and chemical characteristics of CO_2 (in contrast to liquid waste) are discussed, and the relevant hydrologic issues and technical approaches involved in the two cases are compared.

2. BRIEF HISTORY OF LIQUID-WASTE DISPOSAL BY DEEP INJECTION WELLS IN THE UNITED STATES

The practice of using injection wells for waste disposal started in the oil fields in the 1930s, when depleted reservoirs were used for the disposal of brines and other waste fluids from oil and gas production (Clark et al., 2005; Brasier and Kobelski, 1996). The first report of injection of industrial waste was published in 1939 (Harlow, 1939). The literature indicates only four such wells in 1950. A 1963 inventory by the U.S. Bureau of Mines listed 30 wells (Donaldson, 1964). Most of these early wells were converted oil production wells. By the early 1970s, the number of injection wells had grown to approximately 250 (Warner, 1972), and they were being used to dispose of municipal sewage effluent as well as industrial wastes. A number of well-integrity failures in the 1960s and 1970s have been documented (Lehr, 1986). These included contamination of a drinking water aquifer in Beaumont, Texas, caused by an injection well that did not have a separate injection tube within the well. The injected waste caused corrosion of both the inner and outer casings and the surrounding layers of cement, resulting in leakage from the injection well. In Odessa, Texas, an injection well was clogged owing to precipitation from interaction between two incompatible waste streams, and surface injection pressures quickly exceeded the allowable limits. In Denver, Colorado, injection activated seismic events in a fault zone, which allowed injected liquids to escape through rock fractures and facilitated earthquake activities (Hsieh and Bredehoeft, 1981; Wesson and Nicholson, 1987).

Concerns about the safety of deep injection disposal led the U.S. Environmental Protection Agency to develop regulations in the 1980s and 1990s, and to set requirements and standards for underground injection of liquid waste (Brasier and Kobelski, 1996). These requirements included a well-designed and carefully monitored construction of injection wells and periodic testing of their integrity. They also included a demonstration, through the use of computer models, that the contained hazardous wastes would not migrate out of the injection zone for at least 10,000 years. This demonstration could be based on models of flow and waste transformation within the injection zone. Since the setting of these standards, no significant well failures have occurred. By 2000, there were 485 deep injection wells in the U.S. for disposal of industrial liquid waste (Clark et al., 2005), and the depth of injection zone ranges typically from 1500 to 2500 m (see e.g., Mercer et al., 2005).

3. HYDROLOGIC ISSUES RELATED TO CO_2 INJECTION STORAGE AND LIQUID-WASTE INJECTION DISPOSAL

CO_2 sequestered by injection in a deep brine formation (e.g., about 1,000 m) would be stored in three forms: a dense supercritical gas phase, a dissolved state in pore water, and an immobilized state through geochemical reaction with *in situ* minerals (Hendricks and Blok, 1993; Bachu et al., 1994). The fraction of pore space available for sequestration varies widely, from the 2 to 6% estimated by van der Meer (1995) to the range of 20−30% calculated by Pruess et al., (2001a). The dissolved-state CO_2 at equilibrium is estimated to range from 2% in saturated NaCl brines to 7% in dilute water. CO_2 immobilization in formation matrix minerals is a very slow process and varies considerably with rock types. The amount of CO_2 sequestered through such mineral reactions can be comparable to CO_2 dissolution in pure waters. Thus, among all three forms of CO_2 sequestration in the injection brine formation, the supercritical gas phase is the main storage form, with properties quite different from those of pore water in the injection formation. Thus, for storage of CO_2 at 1,000 m depth, its density is about 60−75% that of water in the formation, and its viscosity is about 15−20 times less than that of water (Vargaftik 1975).

Figure 1 illustrates a basic scenario of injection and storage of CO_2 in a brine formation, with a storage injection zone greater than 800 m in depth, overlain by a caprock. Three main physico-chemical processes are indicated. First, there is the hydrological process of density-driven or buoyancy flow for the supercritical CO_2 with a lower density and an order-of-magnitude (or more) lower viscosity. Thus, the plume of injected CO_2 migrates outward from the injection well and up toward the caprock via buoyancy, with a large spread in terms of surface area. Such density-driven flow also operates in the formation fluid with dissolved CO_2 since its density will also be different from the initial formation brine. In this case, the density of CO_2-saturated brine will be higher and it will flow downwards. In contrast, for liquid-waste injection, the density tends to be within 10% of that of the formation brine, and the viscosity is about the same—thus, the buoyancy effect is significantly less. At the caprock, both waste liquid and injected CO_2 are hindered from flowing upwards. However, for CO_2, there is an additional effect of gas entry

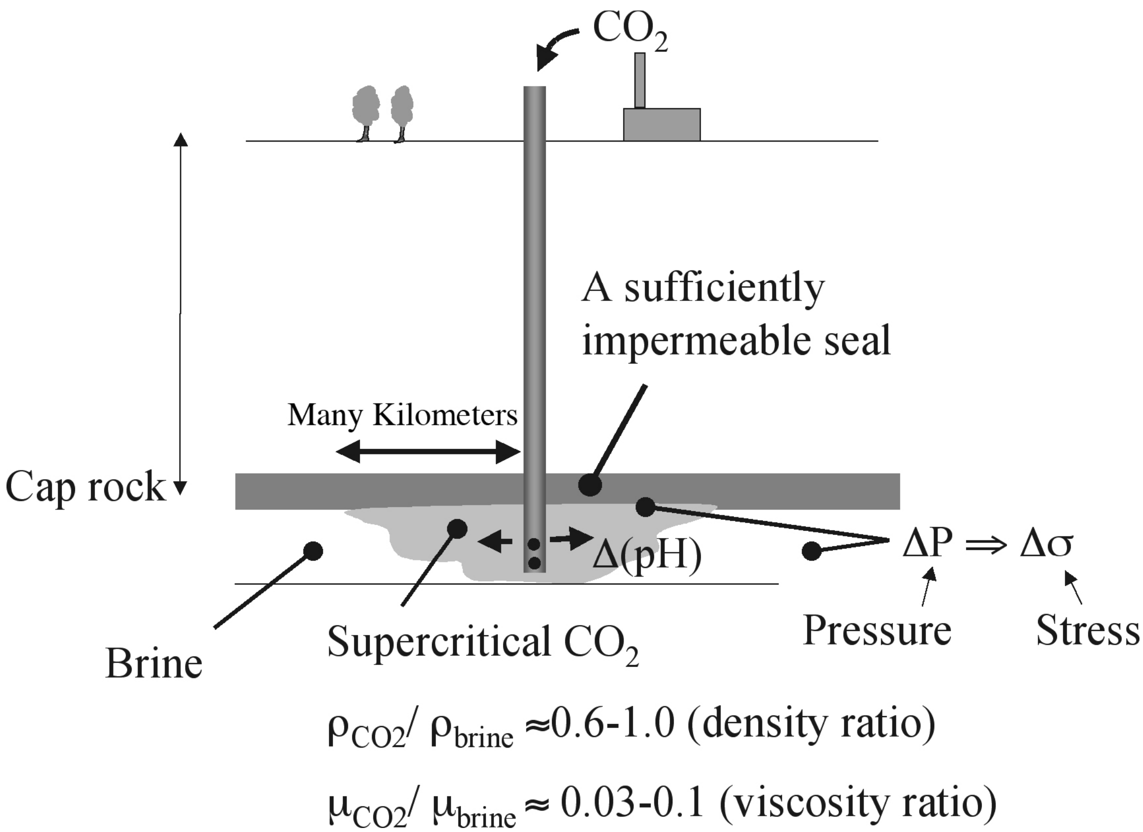


Figure 1. A general sketch of hydrophysical processes associated with CO_2 injection in a deep brine formation.

pressure that acts as a threshold to prevent the CO_2 to enter into the pores of the water-saturated caprock.

Second, for liquid injection, with respect to the mechanical responses of the system, only the injection pressure needs to be considered for hydromechanical effects such as hydrofracturing. The mechanical impact is mainly in the immediate vicinity of the injection well, because injection pressure decreases rapidly with radial distance. For the CO_2 case, however, both injection and buoyancy provide additional stress on the rock. For injection pressure, the impact is similar to that in the liquid injection case. But buoyancy pressure operates where the CO_2 is, which can be over a very large area, both because of the large volume of CO_2 that needs to be stored and because of its spread as a result of buoyancy flow. In response to these pressures, the rock matrix may be deformed, with changes in the values of matrix porosity, and, if fractures are present in the injection formation or the caprock, possible changes in fracture apertures may occur as well. These changes, in turn, may cause variations in flow permeability and, consequently, the flow field. Finally, in general, the injected CO_2 plume interacts chemically with the formation minerals. For example, exsolution of CO_2 from water along a pressure-temperature gradient might cause precipitation of carbonate minerals. Such interactions could give rise to local porosity and permeability changes and modify medium heterogeneity (see, e.g., Ross et al., 1981; Mathis and Sears, 1984), but positively, such chemical changes can also react with the injected CO_2 to form new minerals in the rock matrix, thus trapping the CO_2 chemically.

3.1 Injection Well Integrity

As can be seen in Section 2, problems associated with well integrity were historically the main mode of failure in deep-well injection of liquid waste (Lehr 1986). Thus, construction of properly designed injection wells is one of the main concerns (Bundy and Fizer, 1996). Figure 2 shows a typical injection-well design required for deep injection of hazardous liquid waste (Brasier and Kobelski, 1996; Rish, 2005). The well as shown in this figure must have at least two strings of casing. The so-called surface casing is cemented to the land surface and is designed to isolate the well from the shallower aquifers of drinking water. The second casing, labeled "protection casing" in Figure 2, extends all the way to the injection zone and is cemented to ensure no cross flow between adjacent brine formations. Furthermore, an injection tubing is set into a packer, which is a mechanical device set in the well to isolate the injection zone to ensure that injection via the tubing is emplaced in the target injection zone. Materials and (in particular) the cements used in the construction of the injection well must be resistant to corrosion caused by injected liquids or formation brines (Whiteside et al., 1996; Kelly and Fleniken, 1996)

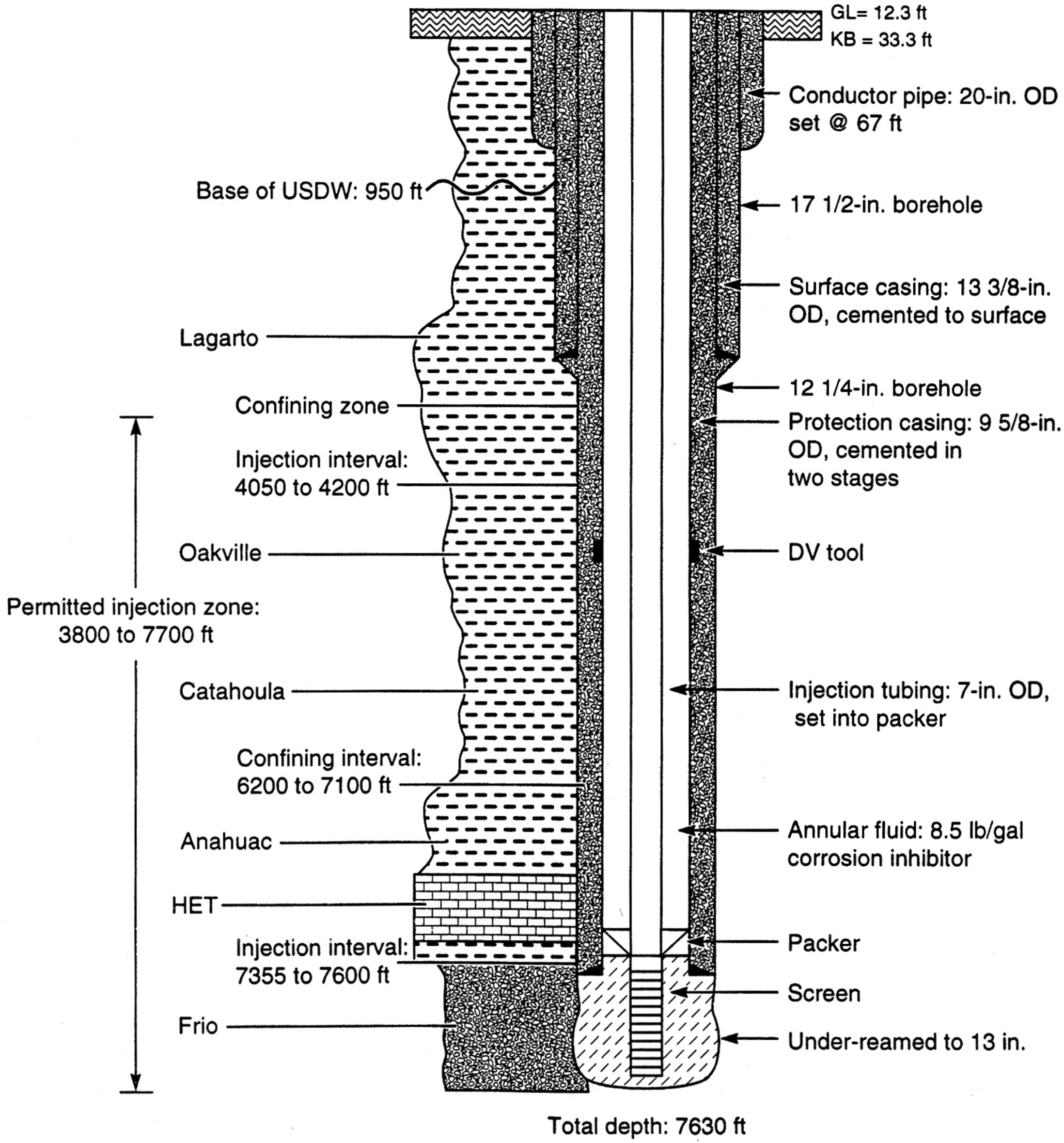


Figure 2. A typical injection well design required for deep injection of hazardous liquid waste (prepared by DuPont Company and shown in Brasier and Kobelski, 1996 and Rish, 2005)

The design of injection wells for CO_2 storage will have to be carried out with similar considerations (Gerard, et al., 2006). In fact, because of the corrosive properties of CO_2 and the expected long life of CO_2 injection wells—with an operation period of 25−100 years and a safety period of 1,000 years or more—evaluation of materials for well integrity will be even more stringent (IEA, 2005). Fortunately, we have extensive experience in enhanced oil recovery (EOR), which has been reviewed in a general discussion on CO_2 injection well integrity under the auspices of International Energy Agency (IEA, 2005), and also in acid gas injection (for example in Canada) over the last ten years or so (Bachu et al., 2005). From these areas, the transfer of technology and knowledge to CO_2 injection and storage is possible.

3.2 Abandoned Wells

Abandoned wells are a concern for deep-injection disposal of liquid wastes. Part of site selection for liquid-waste injection is to ensure that there are no abandoned wells within the so-called area of review around the injection well (see, e.g., Platt and Rectenwald, 2005; Rish, 2005). If there are, then special effort must be taken to investigate and improve their condition, if necessary, so that they will not act as leakage paths for the injected liquid. One problem is that records of old abandoned wells are sometimes nonexistent or lost, and research has been conducted to develop the capability to detect these wells by geophysical or other means. It turns out that the amount of liquid waste injected deep underground is limited, so that the area of review is not too large, on the order of 100's to 1,000's of meters in radius. Furthermore since the driving force for leakage of liquid waste is the injection pressure, which is largest close to the injection well and decays quickly as a function of radial distance, the region of most concern is liable to be close to the injection well.

For CO_2 injection and storage, on the other hand, the region of concern will be larger. First, the area covered by the injected CO_2 will be very large, with a radius perhaps of tens of kilometers—not only because a large volume of CO_2 must be stored, but also because the buoyancy effect causes the CO_2 plume to move upwards and spread out farther. Second, the driving force for CO_2 leakage is not just the injection pressure, but also the buoyancy force, so that the leakage potential exists wherever CO_2 migrates. Celia and coworkers, in a series of papers (Celia et al., 2005, 2006a, 2006b), studied the problem in some detail. They pointed out that one type of region for CO_2 storage is mature sedimentary basins, some of which have undergone oil and gas exploration over the last century. In these basins, there are a large number of wells. For example, in Texas, USA, more than one million wells have been drilled; and in Alberta, Canada, more than 350,000. Celia et al. (2006b) estimated that, in high well-density areas, a CO_2 plume with a radius of about 5 km would come into contact with several hundred wells, and with tens of wells even in low well-density areas. The former (high well-density areas) correspond to areas where productive oil and gas wells have been found; the latter (low well-density areas) where hydrocarbon resources have not been found.

When CO_2 encounters a well without proper plugging, it will tend to migrate upwards under buoyancy force. When a well is abandoned prior to development for oil or gas production, it would typically be filled by a series of cement plugs. If it were abandoned after development and oil or gas production, it would have a casing, with cement emplaced not only in the hole within the casing, but also in the annular space between the case and the borehole. Figure 3 shows the possible leakage paths in such an abandoned

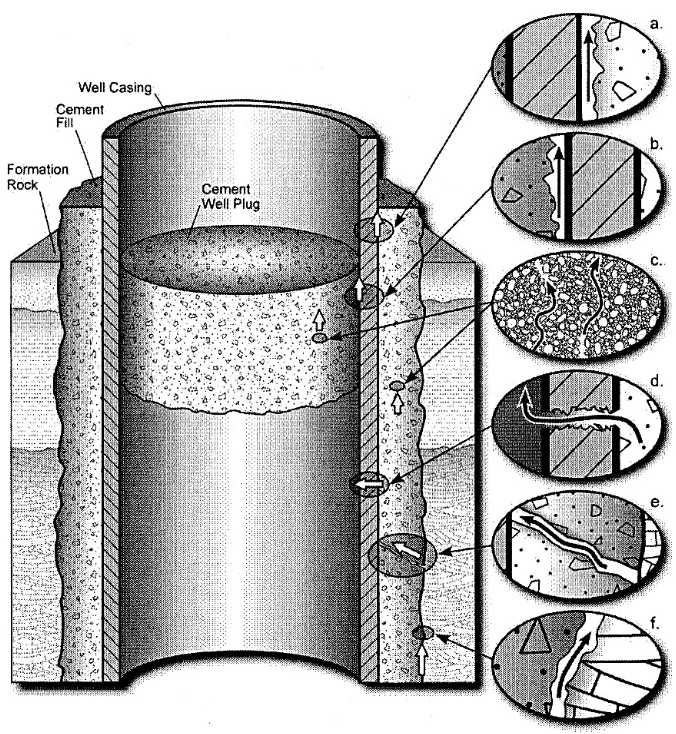


Figure 3. Possible leakage paths in an abandoned well (from Celia et al., 2005). Leakage paths include those at well plug-well casing interface (a), well casing-cement fill interface (b), and cement fill-formation rock interface (f), as well as flow lines through cement itself (c), and through cracks in the well casing and cement fill (d and e).

well, which include preferential flow pathways along rock-cement and casing-cement interfaces, as well as through degraded materials or materials improperly formed during the plugging processes (Celia et al., 2005). Long-lasting cement that can withstand the corrosive effects of CO_2 is currently an active area of research in CO_2 storage (see, e.g., Strazisar and Kutchko, 2006). It is needed not only for plugging abandoned wells but also for plugging injection well at the end of its service. This kind of problem has also been considered for liquid-waste injection (Whiteside et al., 1996). One advantage for liquid waste is that because of the relatively much smaller volume involved, it is possible to pre-treat the liquid waste to moderate its corrosive characteristics.

3.3 Buoyancy Effect

As pointed out above, buoyancy effects are much more important for CO_2 than for the liquid-waste injection case. Nevertheless, questions on their impact on potential migration of injected waste have been raised concerning injection of liquid that is denser or lighter than the *in situ* brine. These questions that have stimulated many studies (see, e.g., Samsonova and Drozhko, 1996; Tsang, 1996). Hellstrom et al. (1988) presented a formula for a dimensionless measure γ of forced convection flow compared with buoyancy flow as

$$\gamma = \frac{Q < \mu >}{Bg\Delta\rho\sqrt{k_x}k_z}$$

where Q is the injection flow rate, $<\mu>$ is the mean viscosity between the injected liquid and the formation brine, B is the injection zone thickness, g is the gravitation constant, $\Delta\rho$ is the density difference between the injected fluid and the formation brine, and k_x and k_z are the permeabilities in the x and z directions, respectively.

This formula is essentially the same as the ratio of viscous to gravity effects $R_{v/g}$ divided by the parameter accounting for anisotropy R_L, given by Ennis-King and Paterson (2000) in their discussion of CO_2 injection and storage. It also corresponds to the dimensionless parameter group Γ proposed by Celia et al. (2005) for CO_2 injection, except that the $<\mu>$

factor is replaced by brine mobility, defined as the ratio of relative permeability to viscosity. In addition, Celia et al. (2005) did not consider formation anisotropy, so that k_x and k_z were equal.

Because of the buoyancy flow of CO_2 to the top of the injection zone, the areal extent of the injected CO_2 will be larger than a buoyancy-neutral fluid. For example, storage of 2.7 x 10^{11} kg CO_2 at the rate of 350 kg/s for 30 years in a 100 m thick formation, with isotropic permeability $k = 10^{-13}\ m^2$, will have an increase in areal extent (due to buoyancy flow) of about 1.4 (Pruess et al., 2001b). In this example, because of the large volume of CO_2 injected, the areal extent of the injected supercritical CO_2 in the injection zone is as much as 120 km^2. A typical injection of liquid waste (Mercer et al., 2005) will have an areal extent that is one or two orders of magnitude smaller.

3.4 Multiphase Flow Effects

Injection of liquid waste generally involves single-phase fluid flow, because the injected liquids are typically miscible with water. Injection of supercritical CO_2 involves multiple phases. Along any potential leakage paths, three phases are present in varying proportions–namely, liquid water (with or without dissolved CO_2), liquid or supercritical CO_2, and gaseous CO_2. These phases will interfere with each other, which is often described by three-phase relative permeability functions. These relative permeability functions may be different for a fluid that is receding (draining) or advancing (imbibing), and may further depend on the initial saturation level of the fluid. Much research is being done to better understand the three-phase flow behavior of CO_2-brine systems (e.g., Bachu and Bennion, this issue; Chalbaud et al., 2006; Gallo et al., 2006; Pruess et al., 2004; Pruess and Garcia, 2002; Chang et al., 1994).

Hydrothermal effects combined with those of phase transition between supercritical and gaseous CO_2 can lead to very complex flow processes. Figure 4 shows an example of the complex phase-interference effects during fast CO_2 discharge through a fault. The figure shows the results of a numerical simulation conducted by Pruess (2006) on a schematic model of a fault zone initially containing water at a geothermal equilibrium of 30°C/Km

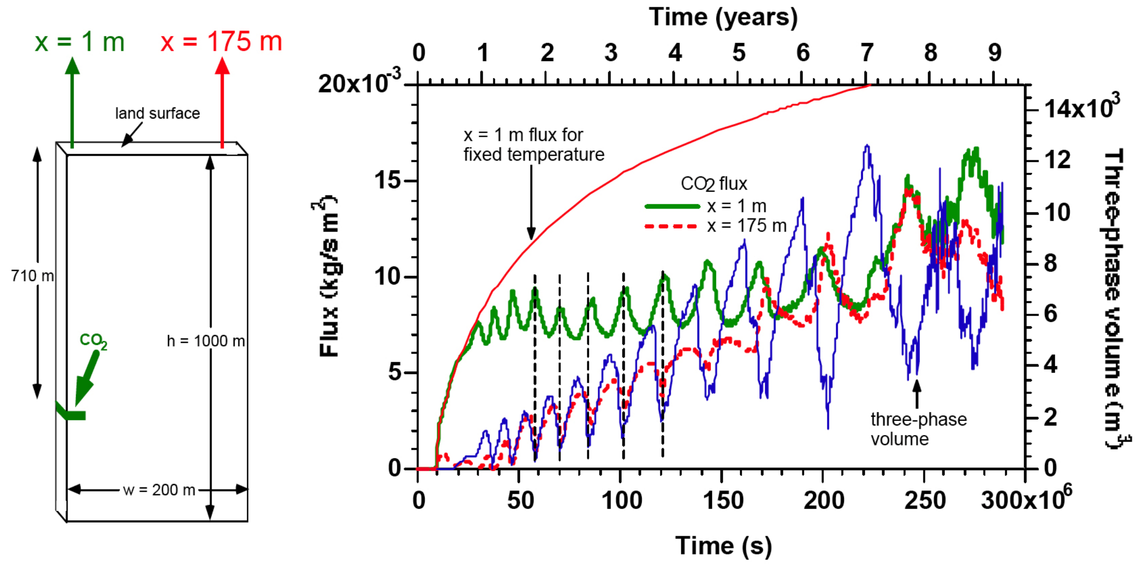


Figure 4. Simulation results on complex phase interference effects during fast CO_2 discharge through a fault. The model design is shown on left and upward fluid fluxes as a function of time at two locations, x = 1 m and x = 175 m are shown on the right, together with occurrence of three-phase volume. The figure shows that a large three phase volume would reduce upward flux at x = 1 m, by pushing fluid to the side so that upward flux at x = 175 m is increased (from Pruess, 2006).

in hydrostatic equilibrium, with the land surface maintained at 15°C (Figure 4a). CO_2 is discharged at 710 m depth in the fracture with an overpressure of 10 bars. As the CO_2 flows up (through buoyancy) and expands, it experiences strong cooling resulting from the Joule-Thomson effect, which in turn results in CO_2 existing in two phases, as gas and as liquid.. The two CO_2 phases interfere with each other and with the liquid water, creating phase interference and a slowdown of the leakage. At slower leakage rates, the three-phase fluid is heated more effectively by the neighboring rock wall (which was at normal geothermal gradient), then part of the liquid CO_2 boils off, and the three-phase interference effect decreases. As a result, the simulations show a persistent flow cycling effect, with an increasing and decreasing leakage rate, after a period of initial growth, as shown in Figure 4b. The importance of such a behavior on the performance or safety of CO_2 storage is yet to be determined, but the example demonstrates the significant difference in flow processes between liquid-waste disposal and CO_2 storage in the subsurface. It also indicates that the predictive modeling necessary for performance assessment of future sites is much more complex for CO_2 versus liquid-waste storage.

3.5 Heterogeneity and Channeling Flow

Heterogeneity is one of the factors that gives rise to fingering or channelized flow (Tsang et al., 2001; Pozdniakov et al., 2005), which increases the spread of liquid waste injected into a deep brine formation. Thus, the area of review for liquid-waste injection has to be larger than otherwise. Tsang (1996) presented a rough analytic estimate of such a spatial increase for liquid injection. Similar considerations on the spatial extent of stored CO_2 with the effect of heterogeneity are presented in Ambrose et al. (2006) and Doughty et al. (2001). However, for CO_2 injection storage, other factors come into play, so that heterogeneity may not be altogether negative. Flett et al. (2005, 2006) described heterogeneities of several types important for CO_2 storage; namely, stratigraphic layering within the storage formation, faults, depositonal mixing, compartmentalization, and channel systems. For example, stratigraphic layering counteracts buoyancy flow by limiting the flow to the injection zone and acting as a structural barrier. If CO_2 is injected into the lower part of the storage formation, heterogeneity (layering) may actually prevent it from migrating upwards and coming near potential leakage paths in the caprock. This effect is evident in the seismic profiles taken at the CO_2 injection site at Sleipner (Torp and Gale, 2004). Furthermore, heterogeneity with flow channeling increases the contact between the brine formation and the injected CO_2, thus increasing the potential for CO_2 solution and mineral trapping (Doughty et al., 2001).

To demonstrate the effects of heterogeneity on CO_2 storage, Doughty et al. (2001) conducted simulations on a geological model based on data from the Frio formation in Texas, USA, where a small-scale pilot test for CO_2 injection was conducted (Hovorka et al., 2004). A three-dimensional stochastical model was constructed, with model layers derived from three idealized representations of fluvial depositional settings found in this part of the Frio–namely, barrier bars (continuous high-permeability sands), distributary channels (intermingled sands and shales, with a large high-permeability sand component), and interdistributary bayfill (predominantly low-permeability discontinuous shale lenses, interspersed with moderate-permeability sand). Figure 5 shows a model of 1 km × 1 km × 100 m, designed to represent part of the subsurface storage volume for a 1,000 MW power plant located near the site (called the Umbrella Point oil field). The top and bottom boundaries are closed to represent sealing shale layers. Lateral boundaries are held at a constant pressure. Carbon dioxide is injected at a rate of 21.6 kg/s (680,000 metric tons per year) for a period of 20 years; then the system is monitored for an additional 80 years to watch the evolution of the CO_2 plume. This injection rate represents about half of the CO_2 output from the 1,000 MW gas-fired power plant.

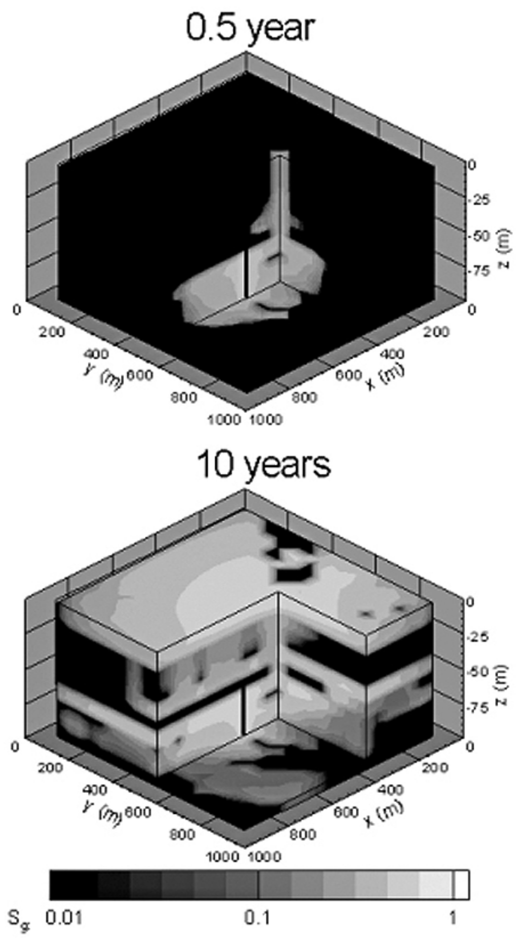


Figure 5. Example of the role of heterogeneity on CO_2 distribution in the storage brine formation after injection of0.5, 1, 10, and 20 years (from Doughty et al., 2001)

The figure shows that the interplay between geological heterogeneity and buoyancy flow is crucial in determining where and how effective structural and stratigraphic traps are. However, the heterogeneity-buoyancy interaction also strongly impacts the character of the subsurface CO_2 plume—that is, how CO_2 is distributed in space. Low-permeability lenses provide flow barriers that may retard vertical buoyancy flow; but if the barriers are discontinuous, the buoyant CO_2 will move upward between them, creating a sinuous extensive plume. In contrast, for a homogeneous sand, buoyancy flow simply drives the plume to the top of the formation, where it may collect in a compact shape or spread extensively along the lower boundary of the caprock.

Other hydrologic effects, such as dipping storage formations (Akervoll et al., 2006; Flett et al., 2006), have also been considered with respect to their impact on storage capacity and CO_2 migration.

3.6 Multilayer Isolation Effect

For liquid waste injection, the multilayer stratigraphy above a storage formation is usually not considered, because the site chosen is supposed to have an effective barrier that would prevent escape from the injection zone. Nevertheless, Miller et al. (1986), in their discussion of liquid-waste injection, did consider this case (Figure 6) and suggested the benefit of having multiple low-permeability layers to ensure that the injected liquid would not reach the shallow subsurface.

For CO_2 injection, on the other hand, the benefit of isolating injected CO_2 through multiple layers of low-permeability layers has been recognized through the Sleipner field studies (Torp and Gale, 2004; Chadwick et al., 2004). Further, in contrast to liquid waste injection, CO_2 leakage will probably be allowed, provided that there are acceptable health, safety, and environmental concerns, and that the objective of reducing net greenhouse gas emission is achieved. With this in mind, a detailed analysis of the multilayered system needs to be made to evaluate the efficiency of injection-storage of CO_2. For systems with leakage paths, the expected leakage rate is an important input to

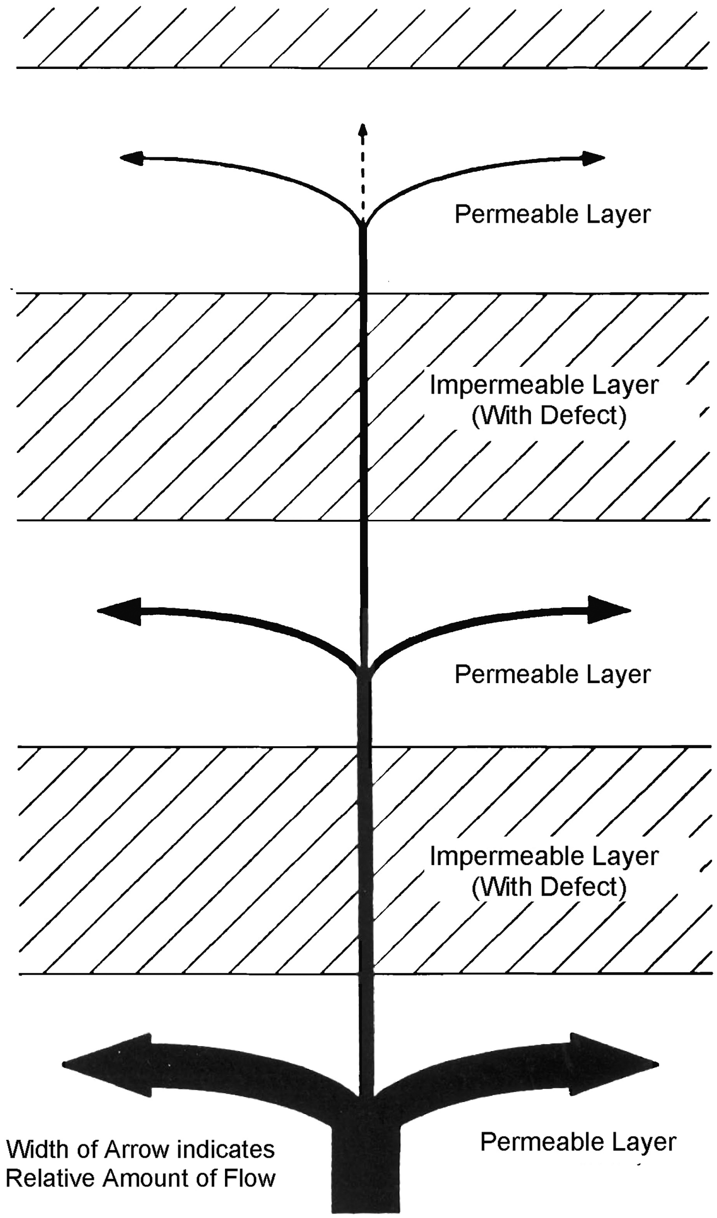


Figure 6. A schematic picture of the multiple barrier effect of a liquid disposal site with multiple layers of impermeable layers (caprocks) (from Miller et al., 1986)

CO_2 storage performance and risk assessment. The results will also be needed to design a monitoring system for CO_2 storage (see Section 3.8 below).

As an example of such an effort, Figure 7 presents the results of numerical simulations considering CO_2 injection into a deep multilayer system with pre-existing faults. In the simulations, CO_2 is injected at a rate of 0.04 kg/m/s over 30 years into a deep saline

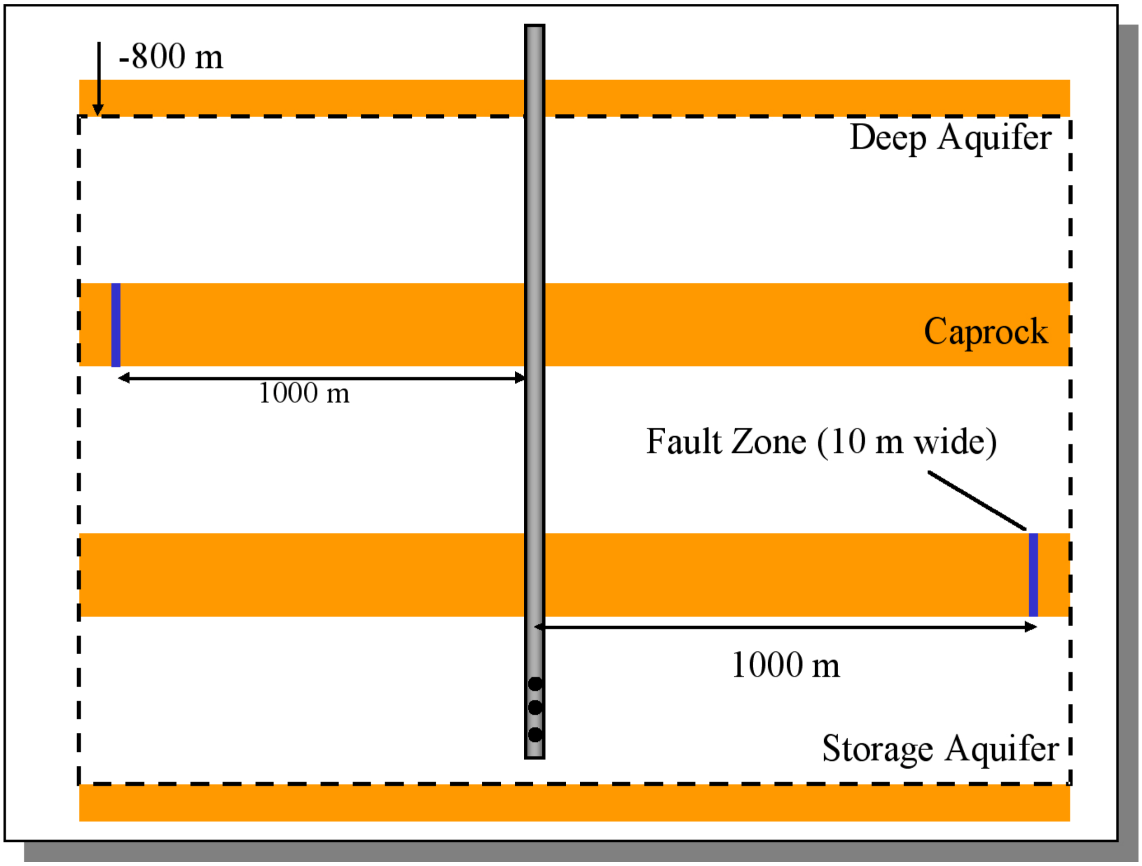
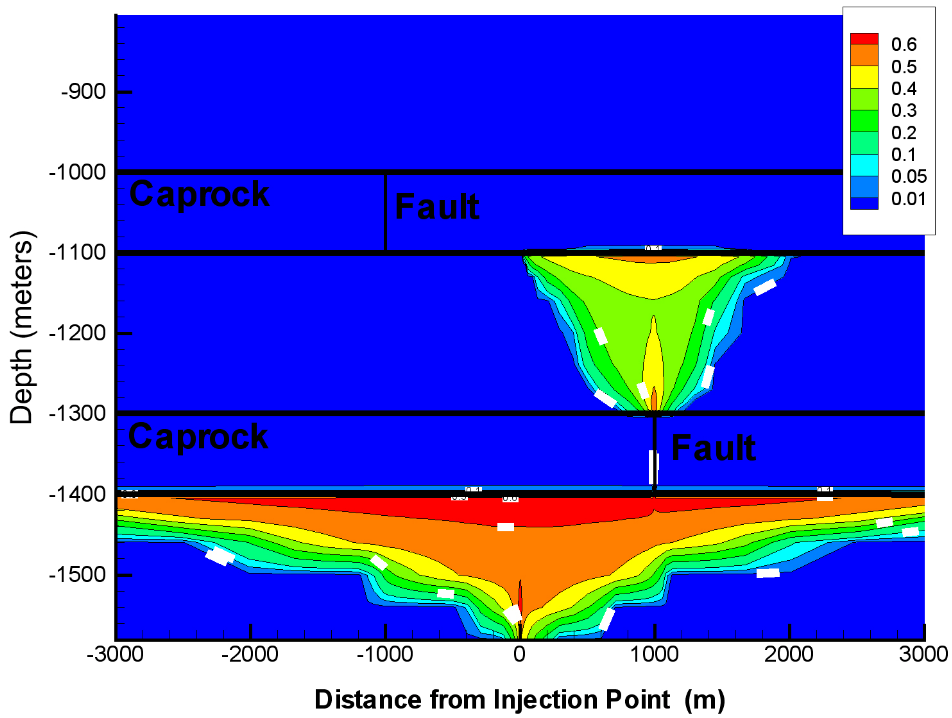


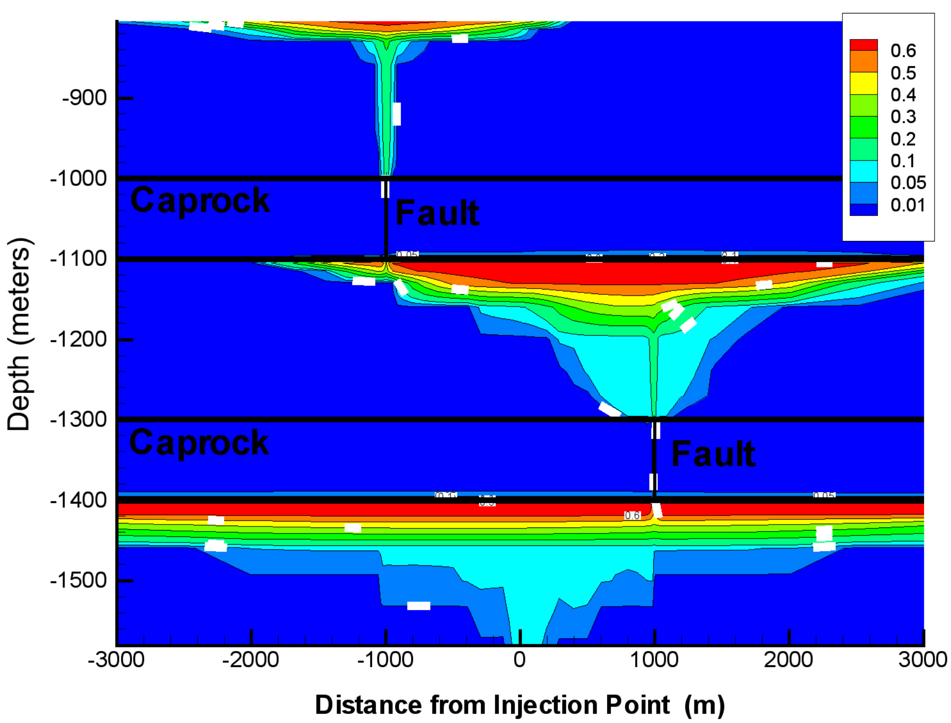
Figure 7. Model setup for studying effect of multiple caprocks in retarding leakage of CO_2 from storage formation

reservoir overlain by a sequence of two additional caprock units and two additional aquifer layers. One fault is assumed to intersect the lower caprock unit, about 1,000 m away from the injection well, while a second fault intersects the upper caprock unit at a 2,000 m distance from the first fault, on the other side of the injection well. The simulation study aimed at (1) determining the CO_2 migration patterns in such a system, (2) evaluating the benefit of injecting into a multilayer system with possible attenuation of the migrating CO_2, and (3) evaluating leakage rates as a function of fault and formation properties.

Figures 8a and 8b show the distribution, in the form of saturation values, of the CO_2-rich phase (supercritical CO_2 with small amounts of dissolved water) at the end of the 30-year injection phase and at 500 years, respectively. CO_2 first spreads within the storage



(a)



(b)

Figure 8. The distribution of saturation values of the CO_2-rich phase at the end of the 30-year injection phase (a) and at 500 years (b)

formation, both upward and laterally. As indicated by the CO_2 saturation in upper aquifers, the fault zones allow for significant leakage of CO_2 from the storage formation. The upflow of CO_2 in the fault zones is partially diverted sideways into the middle and upper aquifers, which mitigates further upward migration. At the end of the injection phase, the lateral diversion in the middle aquifer is not wide enough to reach the off-setting upper fault zone, and the CO_2 plume is limited to the middle aquifer. After 500 years, CO_2 has eventually leaked into the upper aquifer, indicating that the lateral extension of CO_2-phases can lead to leakage through fault zones at a large distance from the spill point. Depending on the geologic and hydrologic conditions, such leakage may occur when the injection period has ended.

3.7 Caprock Effectiveness and Hydrogeomechanics

Rutqvist and Stephansson (2003) provide an overview of the role of hydromechanical effects for a number of underground industrial activities, including deep injection of liquid waste and CO_2. The potential for hydrofracturing caused by injection pressure is a concern for liquid-waste injection, and it is useful to monitor and maintain injection pressure below the lithostatic pressure all through injection operation, to ensure that the pressure is well controlled and hydrofracturing is avoided. For CO_2 injection and storage, it will be comparatively more important to evaluate the associated mechanical effects due to the presence of both the injection and buoyancy pressures.

Below we shall discuss hydromechanical processes in the context of CO_2 injection and storage, but similar processes occur for liquid injection without the extra driving buoyancy force. First, injection of CO_2 will result in an increase in formation fluid pressure, especially around the injection source. Such a fluid pressure increase will cause local changes in the effective stress field, which, in turn, will induce mechanical deformations, possibly increasing the porosity and permeability and thus reducing the fluid pressure. However at the same time, increasing pressure may also cause irreversible mechanical failure in the caprock. This mechanical failure may possibly involve shear-slip along existing fractures and creation of new fractures (hydraulic fracturing), which reduce the sealing properties of the caprock system. Rutqvist and Tsang (2005) and

Yamamoto (2006) provided a good overview of the general problem. In addition to these mechanical processes, replacing the native formation fluid with CO_2 may also cause changes in rock mechanical properties through chemo-mechanical interactions between the CO_2 and the host rock, or through desiccation of fractures.

Rutqvist and Tsang (2002, 2005) and Rutqvist et al. (2006a and 2006b) used a code TOUGH-FLAC that they developed to conduct analyses of hydromechanical effects during CO_2 injection in both single-caprock and multilayer systems. For example, in a hypothetical multilayer system, Rutqvist et al. (2006a) studied CO_2 injection for 30 years in a 200 m thick permeable saline water formation located at 1,600 m depth (Figure 9). In their model, several layers of caprocks as well as water-bearing formations were located above the intended storage formation, all of which were intersected by a permeable fault zone. The analysis showed that during injection, CO_2 migrates laterally and upwards in

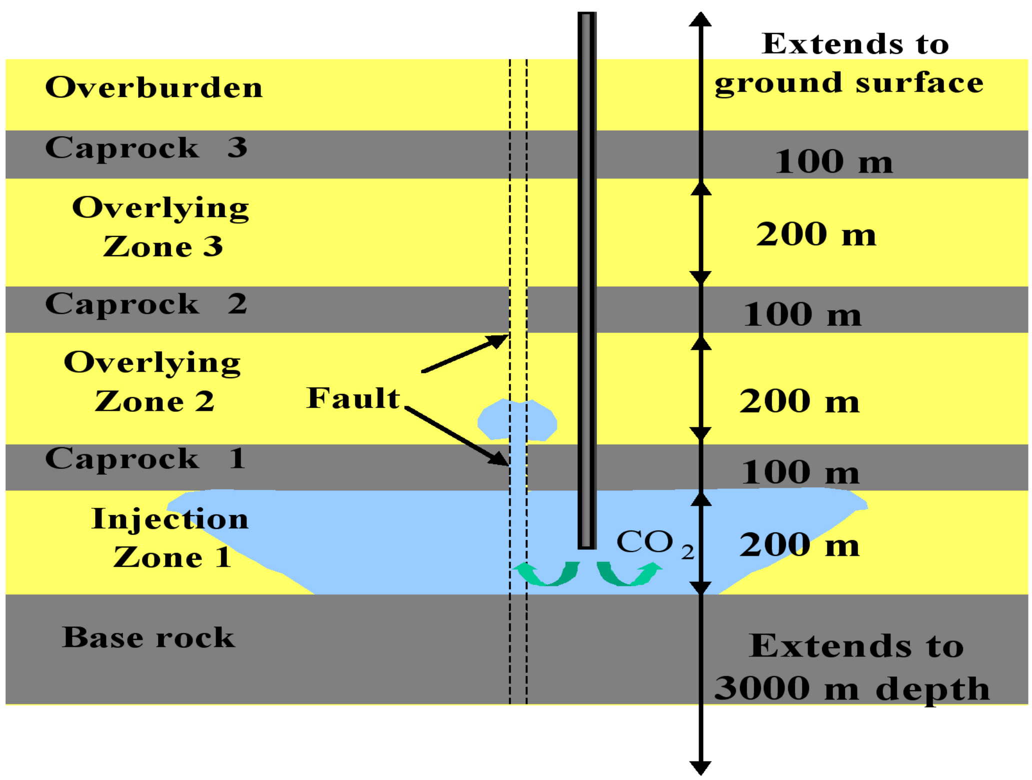


Figure 9. Model geometry for simulation of hydromechanical effects during CO_2 injection into a multilayered reservoir-caprock system

the storage formation, driven by injection pressure and buoyancy forces. When the plume encounters the fault zone intersecting the caprock, a considerable amount of CO_2 migrates upwards, spreads laterally into the upper overlying zones, and may cause considerable fluid pressure increase there. Based on the changes in effective stresses, the potential for fault slip and fracturing is calculated.

Figures 10 and 11 present, respectively, the results of potential for fault slip and hydraulic fracturing for two different initial stress regimes—a compressional stress regime (horizontal stress larger than vertical) and an extensional stress regime (horizontal stress smaller than vertical). These results are given in terms of pressure margins to the onset of shear slip or fracturing. A positive pressure margin in these figures implies that the local fluid pressure may be above the critical pressure for onset of geomechanical damage. Dark contours indicate areas of the highest potential for onset of shear slip. Results

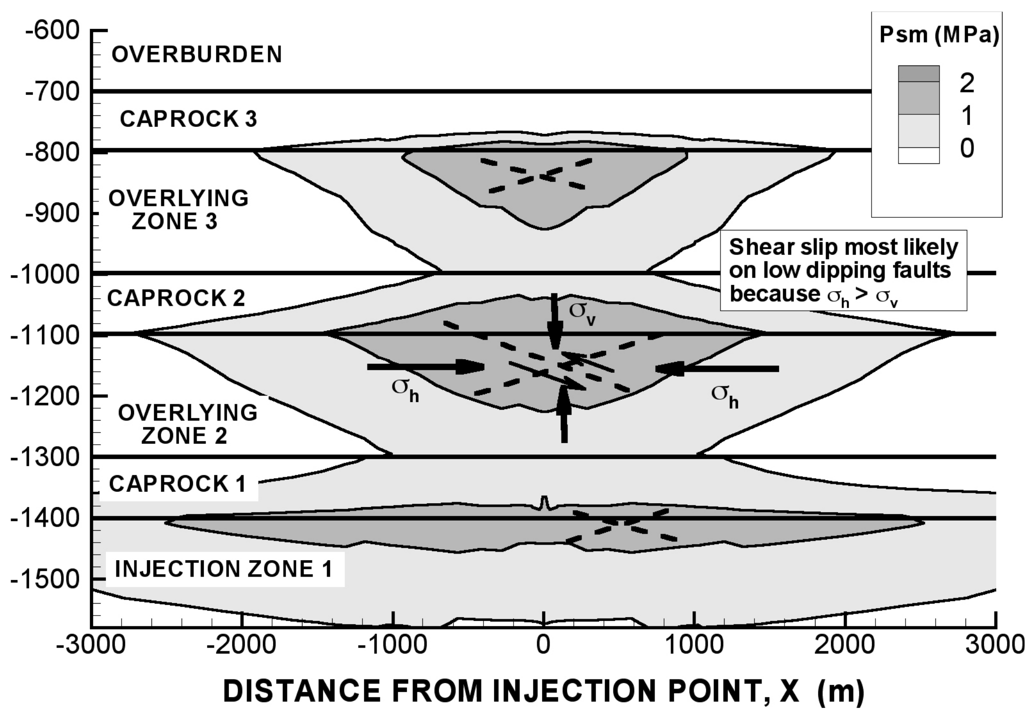


Figure 10. Calculated pressure margin for shear slip along pre-existing fractures after 30 years of CO_2 injection for compressional stress regime (with magnitude of horizontal stress being 1.5 times the vertical).

suggest that, once leakage of CO_2 occurs, the potential for fault reactivation and fracturing could be larger in the overlying units than in the storage formation, a result of the smaller *in situ* stress fields in shallower units. Knowledge of the initial stress regime is very relevant. In the case of a compressional stress regime (Figure 10), the shear slip is most likely to be initiated in subhorizontal fractures, at the interfaces between the permeable formation layers and the overlying caprocks. In the case of an extensional stress regime (Figure 11), the shear slip is likely to occur in subvertical fractures in the uppermost aquifer and in the overburden rock. An extensional stress regime may also allow for hydraulic fracturing at the bottom of the uppermost caprock. The analysis by Rutqvist et al. (2006a) thus demonstrates that for evaluation of the maximum sustainable CO_2-injection pressure at a particular site, it is essential to have a good estimate of the three-dimensional *in situ* stress field.

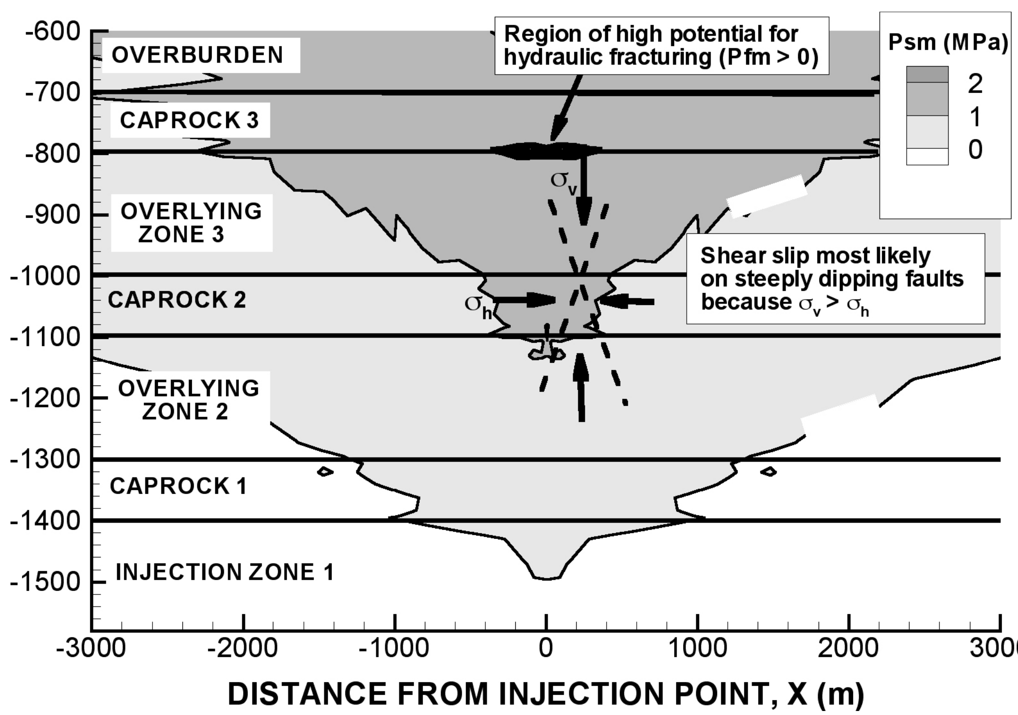


Figure 11. Calculated pressure margin for shear slip along pre-existing fractures after 30 years of CO_2 injection for extensional stress regime (with horizontal stress magnitude being 0.7 times the vertical). The region of high potential for hydraulic fracturing is also indicated in the figure.

Overall, the various analyses of both single-caprock and multilayered systems show that the magnitude and the anisotropy of the initial stress field is an important factor in determining where and how failure could occur. A site with a horizontal stress much lower than the vertical (i.e., a strongly anisotropic, extensional stress regime) would be most unfavorable for safe and effective CO_2 storage, since subvertical fractures could be more easily reactivated by shear or hydraulic fracturing. A site with a horizontal stress approximately equal to the vertical (i.e., an isotropic stress regime) might be the most favorable situation, because an isotropic stress regime tends to prevent shear stress, and hence shear failure along pre-existing fractures, from occurring.

3.8 Site Characterization and Monitoring

The criteria for selecting a site suitable for CO_2 injection have been discussed by Bachu (2000) and Bachu and Gunter (1999). They are largely similar to those of deep injection of liquid wastes (Warner and Lehr, 1977), except for the areal extent at the site being considered for injection and storage. As was mentioned above, the scale of CO_2 storage is much larger than that of liquid waste disposal, and also, some leakage into upper layers is allowed, so long as leakage to the atmosphere is limited. This means that characterization of the sites suitable for CO_2 storage has a much larger scope, both horizontally and vertically than that for liquid waste disposal.

This larger scope can be illustrated by the case studied by Haidl et al. (2005), who conducted a regional geological mapping over a scale of 200 × 200 km, with depth ranging from 1.5 to 3.5 km, for site characterization, as part of a CO_2 storage demonstration project. The objectives of the geological mapping included:

- The distribution of strata comprising the geologic container, identifying and characterizing primary and secondary seals or caprock units
- Mapping aquifers and aquitards, particularly local thinning or absence of aquitards
- Determining whether discontinuities are present in the system

Haidl et al. (2005) used the data generated by their investigation to construct a 3D geologic model that can be used in numerical simulations of risk and performance assessment. This geologic model is also a key ingredient needed to design baseline studies and develop long-term monitoring strategies.

With respect to monitoring of liquid-waste disposal, the need has been discussed by Warner (1992, 1996) and Gerrish and Cooper (1996). The monitoring requirement tends to be very limited. Nearly all the required monitoring (Brasier and Kobelski, 1996; Tsang et al., 2002) involves tests and well logs that focus on the mechanical integrity of the injection well and the conditions in the immediate vicinity of the well. The only exceptions are reservoir testing at one-year intervals to ensure continuing injectivity (i.e., formation permeability having not changed significantly), and recording of operational data, such as injection rates and pressures. Furthermore, no monitoring wells away from the injection well are required. There had been the suggestion that the monitoring wells should be required to perhaps enhance confidence that no migration from the defined disposal zone has occurred. However, Warner (1992) argued that the main hydrologic perturbation caused by liquid-waste injection occurs close to the injection well, and that any monitoring well at some distance away from the well has a high likelihood of missing any of the injection plume, owing to flow-channeling effects caused by formation heterogeneity and the presence of fractures, making such an effort of minor value.

Monitoring of CO_2 injection and storage, on the other hand, is more complex and demanding (see e.g., Lewicki et al., 2005). This is because of the large area covered by the CO_2 plume, and because some level of leakage could be allowed without compromising the atmospheric CO_2 emission reduction goals or endangering the environment. Chalaturnyk and Gunter (2005) have considered the problem in some detail. They advocate that the complete monitoring program should not just involve some measurements over the site area, but rather involve a number of steps:

- Define project conditions
- Understand the mechanisms that control fluid flow

- Specify the technical questions to be answered and parameters to be measured
- Predict the magnitude of changes to be expected in these parameters
- Select monitoring systems and their implementation locations and frequency

In Figure 12, Chalaturnyk and Gunter (2005) define three monitoring periods and levels: namely, operational, verification, and environmental. The first and second levels are, respectively, the monitoring needed during the CO_2 injection phase and during the following period of performance confirmation. (see also Oldenburg and Unger, 2003, 2004; Oldenburg and Lewicki, 2006) The third level, environmental monitoring, includes monitoring of potential seepage to ensure it to be acceptable. The figure also shows the links between the consequences or potentials for leakage and the three levels of monitoring stages. A decision framework has to be developed to provide decision criteria for moving from one level of monitoring to another.

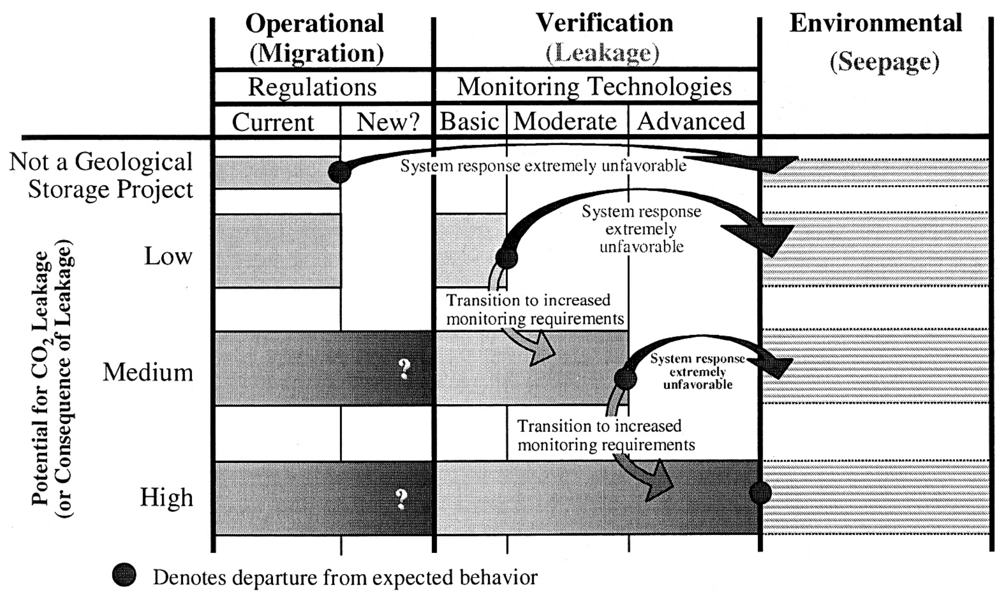


Figure 12. Monitoring phases, leakage potential, and level of monitoring technologies needed (from Chalaturnyk and Gunter, 2005)

Various monitoring methods, ranging from air-borne surveys, soil gas sampling, *in situ* tracers, seismic, electromagnetic, ultra-sonic, gravity, to transient-pressure testing methods, are being studied for particular application to CO_2 injection and subsurface migration (e.g., Vrignaud et al., 2006; Strazisar et al., 2006; Mishra et al., 2006; Pickles and Cover, 2006; Huang and Fehler, 2006). Figure 13 shows the various monitoring methods in perspective (Chalaturnyk and Gunter, 2005) according to time frame and the respective needs to monitor migration of CO_2 in the storage formation, leakage of CO_2 upwards, and seepage of CO_2 on the ground surface.

	0.1 − 1 year	1 − 10 years	10 − 100 years	100 − 1000 years
Seepage	Aircraft Soil Gas Insitu Tracers	Aircraft Soil Gas Insitu Tracers	Aircraft Soil Gas Insitu Tracers	Aircraft ------------------ Insitu Tracers
Leakage	3D-Seismic Tilt Meter Pressure Insitu Tracers Logs Passive Seismic	3D-Seismic Tilt Meter Pressure Insitu Tracers Logs Passive Seismic	3D-Seismic Tilt Meter Pressure Insitu Tracers Logs Passive Seismic	3D-Seismic Tilt Meter ------------------ ------------------ ------------------ ------------------
Migration	3D-Seismic Passive Seismic X-Well Seismic Tilt Meter Pressure ------------------ Insitu Tracers Logs ------------------	3D-Seismic Passive Seismic X-Well Seismic Tilt Meter Pressure Injected Tracers Insitu Tracers Logs Injection Rates	3D-Seismic Passive Seismic X-Well Seismic Tilt Meter Pressure Injected Tracers Insitu Tracers Logs ------------------	3D-Seismic ------------------ ------------------ Tilt Meter ------------------ ------------------ ------------------ ------------------ ------------------

Figure 13. Monitoring methods according to time frame and the respective needs to monitor (i) migration of CO_2 in the storage formation, (ii) leakage of CO_2 upwards and (iii) seepage of CO_2 to the ground surface (from Chalaturnyk and Gunter, 2005)

3.9 Effects of CO_2 Storage on Groundwater Resources

Because of the potentially large quantity of CO_2 to be stored, there arises the question of where the displaced *in situ* brine would flow, with the more specific concern of how that would affect the shallower drinking and groundwater resources. Considerations include, for example, the possible changes in chemical composition of a shallower aquifer resulting from inflow of high-concentration or CO_2-saturated brine. As discussed in Jaffe and Wang (2003) and Wang and Jaffe (2004), the increased acidity after CO_2 intrusion may enhance the solubility of heavy metals present in minerals or adsorbed on mineral surfaces. Dissolution of heavy metals into the groundwater could then lead to contaminant concentrations above health-based limits. Another concern is the potential impact of added fluid volumes on surface discharge and recharge of groundwater systems. As an example, Nicot et al. (2006) presented a fictitious case study with CO_2 injection into a deep brine aquifer in the Texas Gulf Coast area, which hydraulically interacts with a distant groundwater regime. These issues are not of concern in liquid waste disposal because of the relatively small volume involved.

4. SUMMARY AND CONCLUDING REMARKS

This paper presents a comparison of hydrologic issues and technical approaches used in injection and disposal of liquid wastes using deep wells, and those associated with injection and storage of CO_2 in deep brine formations.

Overall, CO_2 injection involves more complex hydrologic processes than liquid-waste injection. These complications include effects such as multiphase flow interference and hysteresis in relative permeability functions, as well as much stronger buoyancy flow and flow fingering. However, this may not have practical implications for the performance of a CO_2 injection-storage operation. Additional analyses have to be made to assess the impact at the CO_2 storage scale.

From a practical standpoint, hydrologic concerns for liquid injection are more localized, since the main cause for leakage is injection pressure, which is significantly large only in the area close to the injection well. Within the so-called area of review, strict requirements are necessary for the construction of injection wells and for detection of abandoned wells. As a general rule, numerical modeling is used to estimate the migration of the liquid-waste plume based on site-specific data. The driving forces for leakage of

CO_2, on the other hand, include not only the near-field injection pressure, but also the buoyancy force, because of the low density and low viscosity of the stored supercritical CO_2. This consideration means that the potential for leakage is present over the whole area of the injected CO_2 plume, which will be very extensive because of the large volume of CO_2 to be stored. This, in turn, means that assessing the effects of abandoned wells and defects (fractures and spill points) of caprocks above the storage zone will be a much more intensive task.

Hydromechanically, the concern for liquid injection is mainly the potential of hydrofracturing caused by injection pressure around the injection well. For CO_2 injection, the presence of buoyancy pressure implies that the hydromechanical effects on low-permeability caprocks must be assessed along potential leakage paths, all the way from the storage formation to the shallow subsurface. The need can be seen if we consider the significant driving buoyancy force associated with an isolated column of CO_2, from a storage formation (at, say, 1,000 m) to the land surface. Of course, in practical cases, this column is not isolated and communicates with the shallower brine formations, which would moderate this effect.

An interesting point is that in contrast to liquid waste, a low level of CO_2 leakage into the near-surface environment does not present a serious environmental problem, as evidenced by natural analogs (Lewicki et al., 2006). It has also been discussed that a useful CO_2 storage system can accommodate such a leakage up to a certain level. Hydrologically, this leads to the question of estimating the potential leakage level of a CO_2 storage system. Such an estimation would require appropriate site-specific data and numerical modeling, It also implies that there is a need for a properly designed site-specific monitoring system, so that any leakage can be detected and evaluated as to whether it is within the range predicted by the model of the site.

Acknowledgments

The authors would like to gratefully thank Bruce Kobelski (US EPA/HQ), Bill Gunter (Alberta Research Council, Canada), Richard Metcalfe (Quintessa, UK) and Curt

Oldenburg (LBNL, US) for their careful review and very useful comments. The paper was much improved in its English language by Dan Hawkes. The work was supported by U.S. Environmental Protection Agency, Office of Air and Office of Ground Water and Drinking Water, through an Interagency Agreement with the US Department of Energy under the auspices of Lawrence Berkeley National Laboratory Contract Number DE-AC02-05CH11231.

References

Akervoll, I., P. Zweigel, and E. Lindeberg, CO_2 storage in open, dipping aquifers, *Proceedings of GHGT-8 8th International Conference on Greenhouse Gas Control Technologies*, (2006); Trondheim, Norway, June 19-22, 2006.

Ambrose, W.A., Lakshminarasimhan, S., Holtz, M.H., Núñez-López, V., Hovorka, S.D., and Duncan, I., Geologic factors controlling CO_2 storage capacity and permanence—Techniques and case studies based on experience with heterogeneity in oil and gas reservoirs applied to CO_2 storage, *Proceedings of CO2SC Symposium*, Lawrence Berkeley National Laboratory, Berkeley, California, March 20–22, p. 9, 2006.

Apps, J.A., and C-F. Tsang (eds), Deep injection disposal of hazardous and industrial waste, Academic Press, San Diego, 775 pp., 1996.

Bachu, S., Sequestration of CO_2 in geological media: Criteria and approach for site selection in response to climate change, *Energy Convers Manage*, **41**:953–970, 2000.

Bachu, S., and Gunter, W.D., Storage capacity of CO_2 in geological media in sedimentary basins, with application to the Alberta Basin, in: Eliasson B., Riemer P.W.F., Wokaun A. (eds.) *Greenhouse Gas Control Technologies*. Elsevier Science, Amsterdam, pp 195-200, 1999.

Bachu, S., Gunter, W.D., and Perkins, E.H., Aquifer disposal of CO_2: hydrodynamic and mineral trapping, *Energy Convers Manage* 35:269–279, 1994.

Bachu, S., Haug, K., Michael, K., Buschkuehle, B.E., and Adams, J.J., Deep injection of acid gas in Western Canada, in: Tsang C.F. and Apps J.A., (eds.), *Underground Injection Science and Technology*. Advances in Water Sciences, Volume 52, Elsevier, pp., 623-636, 2005.

Brasier, F. and Kobelski, B., Injection of Industrial Wastes in the United States. in: Apps J.A. and Tsang C-F. (eds.) *Deep Injection Disposal of Hazardous and Industrial Waste*, Academic Press, San Diego, pp. 1-8, 1996.

Bundy, J.D. and Fizer, L.A., Mechanical integrity analysis and evaluation of long-term, low-rate annulus fluid loss in class I waste injection wells, in: Apps J.A. and Tsang C-F. (eds.) *Deep Injection Disposal of Hazardous and Industrial Waste*, Academic Press, San Diego, pp. 211-224, 1996.

Celia, M.A., Bachu, S., Nordbotten, J.M., Gasda, S.E., and Dahle, H.K., Quantitative estimation of CO_2 leakage from geological storage: Analytical models, numerical models, and data needs," *Proceeding Greenhouse Gas Control Technologies*, Volume I, E.S. Rubin, D.W. Keith and C.F. Gilboy (eds.), p. 663, 2005.

Celia, M.A., Kavetski, D., Nordbotten, J.M., Bachu, S., and Gasda, S., Implications of abandoned wells for site selection, *Proceedings of CO2SC Symposium*, Lawrence Berkeley National Laboratory, Berkeley, California, March 20-22, 2006a,

Celia, M.A., Bachu, S., Nordbotten, J.M., Kavetski, D., and Gasda, S., A risk assessment modeling tool to quantify leakage potential through wells in mature sedimentary basins, *Proceedings of GHGT-8 8th International Conference on Greenhouse Gas Control Technologies*, (2006); Trondheim, Norway, June 19–22, 2006b.

Chadwick, R.A., Zweigel, P., Gregersen, U., Kirby, G.A., Holloway, S., and Johannessen, P.N., Geological reservoir characterization of a CO_2 storage site: The Utsira Sand, Sleipner, Northern North Sea, *Energy* **29**, pp. 1371-1381, 2004.

Chalaturnyk, R. and Gunter, W.D., Geological storage of CO_2: time frames, monitoring and verification, in *Proceedings of 7th International Conference on Greenhouse Gas Control Technologies*, Volume I, E.S. Rubin, D.W. Keith and C.F. Gilboy (eds.), 623-631, 2005.

Chalbaud, C., Robin, M., and Egermann, P., Interfacial tension of brine/CO_2 systems at reservoir condition, in *Proceedings of GHGT-8 8th International Conference on Greenhouse Gas Control Technologies*, Trondheim, Norway, June 19–22, 2006.

Chang, Y.-B., Lim, M.T., Pope, G.A., and Sepehrnoori, K., CO_2 flow patterns under multiphase flow: field-scale conditions, *SPE Reservoir Eng* 9:208–216, 1994.

Clark, J.E., Bonura, D.K. and Van Voorhees, R.F., An overview of injection well history in the United States of America, in Tsang C.F. and Apps J.A., eds., Underground Injection Science and Technology. *Advances in Water Sciences, Volume 52*, Elsevier, pp. 1–12, 2005.

DOE, Carbon sequestration research and development, in: Reichle, D. and others (eds), U.S. Dept Energy, Washington, DC, Rep DOE/SC/FE-1, 1999a.

DOE (1999b) Inventory of electric utility power plants in the United States, Energy Information Administration, U.S. Dept Energy, Washington, DC, 1999b.

Donaldson, E.C., Surface disposal of industrial wastes in the United States, *US Bureau Mines Inf Circ*, 8212, 1964.

Doughty, C, Pruess, K, Benson, S.M., Hovorka, S.D., and Green, C.T., Capacity investigation of brine-bearing sands of the Frio Formation for geologic sequestration of CO_2, *Proc 1st National Conference on Carbon Sequestration*, National Energy Technology Laboratory, Washington, DC, May 14–17, 2001.

Ennis-King, J., and Paterson, L., Reservoir engineering issues in the geological disposal of carbon dioxide, in: Williams, D.J., Durie, R.A., McMullan, P., Paulson, C.A.J., and Smith, A.Y., (eds.), *Proc 5th Int Conf Greenhous Gas Control Technologies*, Cairns, Australia, , pp. 290–295, 2000.

Flett, M.A., Gurton, R.M., and Taggart, I.J., Heterogeneous saline formations: Long-term benefits for geo-sequestration of greenhouse gases, in: *Proceedings of 7th International Conference on Greenhouse Gas Control Technologies*, Volume I, E.S. Rubin, D.W. Keith and C.F. Gilboy (eds.), 501-509, 2005.

Flett, M., Gurton, R., and Weir, G., Reservoir performance of disposed carbon dioxide in saline formations: Impact of heterogeneity and dip, *Proceedings of GHGT-8 8th International Conference on Greenhouse Gas Control Technologies*, p. 281, Trondheim, Norway, June 19–22, 2006.

Gallo, Y.L., Trenty, L., Michel, A., Vidal-Gilbert, S., Parra, T., and Jeannin, L., Long-term flow simulations of CO_2 storage in saline aquifer, in *Proceedings of GHGT-8 8th International Conference on Greenhouse Gas Control Technologies*, p. 284 (2006); Trondheim, Norway, June 19–22, 2006.

Gerard, B., Frenette, R., Auge, L., Barlet-Gouedard, V., Desroches, J., and Jammes, L., Well integrity in CO_2 environments: Performance, risk, and technologies, *Proceedings of CO2SC Symposium*, Lawrence Berkeley National Laboratory, Berkeley, California, p. 160, March 20–22, 2006.

Gerrish, H.W. and Cooper, K.J., Monitoring waste movement at industrial waste disposal well sites, in: Apps, J.A., and Tsang C.-F. (eds), *Deep Injection Disposal of Hazardous and Industrial Waste*, Academic Press, San Diego, pp. 433-448, 1996.

Haidl, F.M., Whittaker, S.G., Yurkowski, M., Kreis, L.K., Gilboy, C.F., and Burke, R.B., The importance of regional geological mapping in CO_2 storage site characterization: Examples from the IEA Weyburn CO_2 monitoring and storage project, in *Proceedings Greenhouse Gas Control Technologies*, Volume I, E.S. Rubin, D.W. Keith and C.F. Gilboy (Eds.), 751-759, 2005.

Harlow, I.F., Waste problem of a chemical company, *Ind Eng Chem* 31:1345–1349, 1939.

Hellström, G., Tsang, C-F., and Claesson, J., Combined forced-convection and buoyancy flow at a two-fluid interface in a porous medium: analytical studies, *Water Resour Res* 24(4): 407–515, 1988.

Hendriks, C.A., and Blok, K., Underground storage of carbon dioxide, *Energy Convers Manage* 34:949-947, 1993.

Hitchon, B. (ed) Aquifer disposal of carbon dioxide, *Geoscience Publishing*, Sherwood Park, Alberta, 1996.

Hovorka, S.D., Doughty, C., Benson, S.M., Pruess, K, and Knox, P.R., The impact of geological heterogeneity on CO_2 storage in brine formations: a case study from the Texas Gulf Coast. In: Baines SJ, Worden RH (eds.) Geological Storage of Carbon Dioxide. Geological Society of London Special Publication 233:147–163, 2004.

Hsieh, P.A. and Bredehoeft, J.S., A reservoir analysis of the Denver earthquakes—A case study of induced seismicity, *J. Geophys. Res*. 86, 903-920, 1981.

Huang, L. and Fehler, M., Detecting faults in the caprock using seismic imaging, *Proceedings of the CO2SC Symposium*, Lawrence Berkeley National Laboratory, Berkeley, California, p. 43, March 20–22, 2006.

IEA. Wellbore Integrity Workshop, October 2005. IEA Greenhouse Gas R&D Programme, Report No. 2005/12, 2005.

Jaffe, P.R. and Wang, S., Potential effect of CO2-releases from deep reservoirs on the quality of fresh-water aquifers, *Proceedings 6th International Conference on Greenhouse Gas Control Technologies*, Eds. J. Gale and E. Kaya, October 2002, Kyoto, Japan, 1657-1660, 2003.

Kelly, S.L. and Fleniken, J.A., Development of cement evaluation quality control measures for Class I injection wells, in Apps J.A. and Tsang C-F. (eds) (1996) Deep Injection Disposal of Hazardous and Industrial Waste, Academic Press, San Diego, pp. 165–200, 1996.

Lehr, J.H., Underground injection: A positive advocate, *Ground Water Monitoring Rev* 6(3):4–6, 1986.

Lewicki, J.L., Birkholzer, J.T., and Tsang, C.-F., Natural and industrial analogs for leakage of CO_2 from storage reservoirs: identification of features, events, and processes and lessons learned, *Environmental Geology*, doi:10.1007/s00254-006-0479-7, 2006.

Lewicki, J.L., Hilley, G.E., and Oldenburg, C.M., An improved strategy to detect CO_2 leakage for verification of geologic carbon sequestration, *Geophys. Res. Letts.*, *32*, L19403, 2005.

Mathis, R.L., and Sears, S.O., Effect of CO_2 flooding on dolomite reservoir rock, Denver Unit, Wasson (San Andres) Field, TX. In: *SPE Annual Technical Conference and Exhibition*, Houston, Texas, September 16–19, 1984.

Mercer, J.W., Faust, C.R., Brown, C., and Clark, J.E., Analysis of injectate location at Dupont Beaumont Works, in: Tsang C.F. and Apps J.A., Eds (2005) *Underground Injection Science and Technology*. *Advances in Water Sciences, Volume 52*, Elsevier, pp. 51–64, 2005.

Miller, C., Fischer, T.A., II, Clark, J.E., Porter, W.M., Hales, C.H., and Tilton, J.F., Flow and containment of injected wastes, *Ground Water Monitoring Rev* 6(3): 37–48, 1986.

Mishra, S., Pickens, J.F., and Delay, J., New approaches for transient testing and long-term pressure monitoring of low-permeability caprocks, *Proceedings* of *CO2SC*

Symposium, Lawrence Berkeley National Laboratory, Berkeley, California, p. 46, March 20-22, 2006.

Nicot, J., Hovorka, S., and Lakshminarasimhan, S., Impact of carbon storage on shallow groundwater and pressure-controlled regional capacity for brine aquifers, Abstract, Proceedings of AGU Fall Meeting, San Francisco, December 20066.

Oldenburg, C.M., and Unger, A.J.A., On leakage and seepage from geologic carbon sequestration sites: unsaturated zone attenuation, *Vadose Zone Journal*, 2(3): 287-296, August 2003. LBNL-51928

Oldenburg, C.M., and Unger, A.J.A., Coupled vadose zone and atmospheric surface-layer transport of CO_2 from geologic carbon sequestration sites, *Vadose Zone Journal*, *3*, 848–857, 2004, LBNL-55510

Oldenburg, C.M., and Lewicki, J.L., On leakage and seepage of CO_2 from geologic storage sites into surface water, *Environmental Geology*, *50*(5), 691-705, 2006, LBNL-59225

Pickles, W.L., and Cover, W.A., Hyperspectral geobotanical remote sensing for CO_2 storage monitoring, *Proceedings* of *CO2SC Symposium*, Lawrence Berkeley National Laboratory, Berkeley, California, p. 176, March 20–22, 2006.

Platt, S. S. and Rectenwald, D., The appropriate methodology for determining the use of a fixed-radius area of review or zone of endangering influence, when conducting an area-of-review analysis for underground injection control operations, in: Tsang C.F. and Apps J.A., (eds.) *Underground Injection Science and Technology. Advances in Water Sciences, Volume 52*, Elsevier, pp., 45–50, 2005.

Pozdniakov, S.P., Bakshevskay, V.A., Zubkov, A.A., Danilov, V.V., Rybalchenko, A.I., and Tsang, C.-F., Modeling of waste injection in heterogeneous sandy clay formations, in: Tsang C.F. and Apps J.A., eds., *Underground Injection Science and Technology*. *Advances in Water Sciences, Volume 52*, Elsevier, pp., 203-220, 2005.

Pruess, K., On leakage from geologic storage reservoirs of CO_2, *Proceedings* of *CO2SC Symposium*, Lawrence Berkeley National Laboratory, Berkeley, California, p. 178, March 20–22, 2006.

Pruess, K., and Garcia, J., Multiphase flow dynamics during CO_2 disposal into saline aquifers, *Environ Geol* **42**, 282, 2002.

Pruess, K., Garcia, J., Kovscek, T., Oldenburg, C., Rutqvist, J., Steefel, C. and Xu, T., Code intercomparison builds confidence in numerical simulation models for geologic disposal of CO_2, *Energy* **29**, pp. 1431–1444, 2004.

Pruess, K., Xu, T., Apps, J.A., and Garcia, J., Numerical modeling of aquifer disposal of CO_2, *SPE/EPA/DOE Exploration and Production Environmental Conf*, San Antonio, TX, 26-28, SPE 66537, February 26–28, 2001a.

Pruess, K., Tsang C-F., Law D.H-S., and Oldenburg, C.M., An intercomparison study of simulation models for geologic sequestration of CO_2. *Proceedings of the First National Conference on Carbon Sequestration*, Washington, DC, 2001b.

Rish, W.R., A probabilistic risk assessment of Class I hazardous waste injection wells, in : Tsang C.F., Apps J.A. (eds), *Underground Injection Science and Technology*. *Advances in Water Sciences*, *Volume 52*, Elsevier, pp. 93–138, 2005.

Ross, G.D., Todd, A.C., and Tweedie, J.A., The effect of simulated CO_2 flooding on the permeability of reservoir rocks, In: Fayers FY (ed), *Enhanced Oil Recovery*. Elsevier, Amsterdam, pp 351–366, 1981.

Rutqvist, J., Birkholzer, J., and Tsang, C-F., Modeling of geomechanical processes during injection in a multilayered reservoir-caprock system and implications on site characterization, *Proceedings of CO2SC Symposium*, Lawrence Berkeley National Laboratory, Berkeley, California, p. 230, March 20–22, 2006a.

Rutqvist J., Birkholzer J.T., and Tsang C.-F., Modeling hydrological and geomechanical processes related to CO_2 injection in a faulted multilayer system. *Proceedings of 8th International Conference on Greenhouse Gas Control Technologies*, Trondheim, Norway, June 19–22, 2006b.

Ruqvist J. and Stephansson O. The role of hydromechanical coupling in fractured rock engineering. *Hydrogeology Journal* 11:7–40, 2003.

Rutqvist J. and Tsang C.F. Coupled hydromechanical effects of CO_2 injection, in: Tsang C.F. and Apps J.A. (eds.), *Underground Injection Science and Technology*. *Advances in Water Sciences, Volume 52*, Elsevier, pp. 649–680, 2005.

Rutqvist J. and Tsang C.-F. A study of caprock hydromechanical changes associated with CO_2 injection into a brine aquifer. *Environmental Geology, 42*, 296–305, 2002.

Samsonova, L.M. and Drozhko, E., Migration of high-density industrial waste solutions through fresh groundwaters, in: Apps J.A. and Tsang C-F. (eds) Deep Injection Disposal of Hazardous and Industrial Waste, Academic Press, San Diego, pp. 669–680, 1996.

Strazisar, B.R., Wells, A.W., and Diehl, J.R., Near-surface monitoring of geologic carbon sequestration, *Proceeding of, CO2SC Symposium*, Lawrence Berkeley National Laboratory, Berkeley, California, p. 185, March 20–22, 2006.

Strazisar, B.R. and Kutchko, B.G., Degradation of wellbore cement due to CO_2 injection − Effects of pressure and temperature, *Proceeding of, CO2SC Symposium*, Lawrence Berkeley National Laboratory, Berkeley, California, p. 182, March 20–22, 2006.

Torp, T.A. and Gale, J., Demonstrating storage of CO_2 in geological reservoirs: The Sleipner and SACS Projects, *Energy 29*, 1361–1369, 2004.

Tsang, C-F., Some hydrologic factors affecting the safety of deep injection disposal of liquid wastes, In: Apps JA, Tsang C-F (eds), *Deep Injection Disposal of Hazardous and Industrial Waste*, Academic Press, San Diego, pp. 35–45, 1996.

Tsang C.F. and Apps J.A., editors. *Underground Injection Science and Technology*. *Advances in Water Sciences, Volume 52*, Elsevier, 704 pp., 2005.

Tsang, C.F., Benson S., Kobelski, B. and Smith R.E., Scientific considerations related to regulation development for CO_2 sequestration in brine formations, *Environmental Geology*, 42(2-3): 275-281, 2002

Tsang, C-F., Moreno, L., Tsang, Y.W., and Birkhölzer, J., Dynamic channeling of flow and trandsport in saturated and unsaturated heterogeneous media, in: *American Geophysical Union (AGU) Geophys Monograph* 42: Flow and Transport through Unsaturated Fractured Rock, eds. D. Evans, T. Nicholson and T. C. Rasmuson, pp. 33-44, 2001.

Van der Meer, L.G.H., The CO_2 storage efficiency of aquifers, *Energy Convers Manage*, 36:513–518, 1995.

Vargaftik, N.B., *Tables on the Thermophysical Properties of Liquids and Gases,* 2nd edition. Wiley, New York, 1975.

Vrignaud, Y., Jammes, L., Van Kuijk, R., Froelich, B., Schilling, K., Hori, H., and Pistre, V., Assessing the integrity of downhole CO_2 storage using in-situ sonic, advanced ultrasonic, and electromagnetic measurements, *Proceedings of GHGT-8 8th International Conference on Greenhouse Gas Control Technologies*, (2006); Trondheim, Norway, June 19–22, 2006.

Wang, S. and P.R. Jaffe, Dissolution of a mineral phase in potable aquifers due to CO_2 releases from deep formations: Effect of dissolution kinetics, *Journal of Energy Conversion and Management*, 45(18-19), 2833-2848, 2004.

Warner, D.L., Survey of industrial waste injection wells, Final Rep US Geol Surv Contract no 14-08-0001-12280, University of Missouri, Rolla, 1972.

Warner, D.L., Monitoring of Class I injection wells with monitor wells and by other means, Report to Chemical Manufacturers Association, Washington, DC, 1992.

Warner, D.L., Monitoring of Class I injection wells, in Apps J.A. and Tsang C-F. (eds), *Deep Injection Disposal of Hazardous and Industrial Waste*, Academic Press, San Diego, pp 421-432, 1996.

Warner, D.L.and Lehr, J.H., An introduction to the technology of subsurface wastewater injection, U.S. Environmental Protection Agency Rep 600/2-77-240, 1977.

Wesson, R.L. and Nicholson, C., Earthquake Hazard Associated with Deep Well Injection, Report to EPA by USGS, Reston, VA, March 1987.

Whiteside, Jr., R.F., Roth, T.P., and Creech, J.R., Applications of corrosion-resistant materials and cement in the design and construction of Class I injection wells, in Apps J.A. and Tsang C-F. (eds), *Deep Injection Disposal of Hazardous and Industrial Waste*, Academic Press, San Diego, pp. 145–164, 1996.

Yamamoto, K., Site characterization of CCS: Geomechanical aspects, *Proceedings* of *CO2SC Symposium*, Lawrence Berkeley National Laboratory, Berkeley, California, p. 26, March 20–22, 2006.