SCIENTIFIC CONSIDERATIONS RELATED TO REGULATION DEVELOPMENT FOR CO_2 SEQUESTRATION IN BRINE FORMATIONS

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Introduction

Reduction of atmospheric emissions of CO_2 (DOE, 1999a) through injection of CO_2 into in deep brine formations is being actively studied both in the U.S. and internationally. If this technology is to be employed 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), and a coal-fired plant with 1000 MWe capacity generates about 30,000 tonnes of CO_2 per day (Hitchon, 1996). Careful evaluation of the issues that should be addressed by a regulatory framework for such a large-scale endeavor include (a) a realistic appraisal of the risks associated with CO_2 sequestration (b) recognition and incorporation of the best scientific understanding of the process of CO_2 injection and migration in subsurface formations into the regulatory approach and (c) innovations in monitoring technology to ensure that geologic sequestration is safe and effective.

The purpose of this paper is to review the Environmental Protection Agency's (EPA) Underground Injection Control (UIC) program in the context of CO_2 sequestration in brine formations. The Underground Injection Control Program, authorized under the Safe Drinking Water Act (SDWA) of December 1974, has extensive experience in regulating the injection of liquid waste in geologic formation in the United States. In this paper, we first give a history of liquid waste injection in the US and the essential elements for regulation and monitoring requirements. Then the special physical and chemical characteristics of CO_2 in contrast to liquid waste will be discussed. Implications for regulatory control and monitoring requirements based on these characteristics will be presented.

History of Waste Disposal by 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. 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, due to 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 due to precipitation of 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 facilitate minor earthquake activities.

Concerns about the safety of deep injection disposal led the U.S. EPA to issue a policy statement in 1974 that opposed storage or disposal of contaminants by subsurface injection “without strict control and clear demonstration that such wastes will not interfere with present or potential use of subsurface water supplies, contaminate interconnected surface waters or otherwise damage the environment.” In December 1974, Congress enacted the Safe Drinking Water Act (SDWA), which ratified U.S. EPA’s policy and required the agency to promulgate minimum requirements for state programs that would prevent endangerment of underground sources of drinking water by well injection.

In 1980, pursuant to the mandate established by the Safe Drinking Water Act, the U.S. EPA promulgated federal regulations that established minimum requirements for state UIC programs. These regulations are implemented by individual states, where state laws and regulations are adequate, or by the U.S. EPA in states choosing not to obtain approval of their UIC program. In the former case, the state UIC program can be more restrictive than the minimum federal Class I requirements. Under the regulations developed in the 1980s and 1990s by the EPA and the individual states, no significant well failures have occurred. By 2000, there were 485 deep injection wells in the U.S. for disposal of industrial liquid waste.

When Congress enacted the Hazardous and Solid Waste Amendment in 1984 to the Resource Conservation and Recovery Act (RCRA), a new burden was imposed particularly on "hazardous" waste injection wells. The amendment specifically prohibits the continued injection of untreated hazardous waste beyond specified dates - unless the administrator determines that the prohibition is not required to protect human health and the environment for as long as the wastes remain hazardous. In 1988, the UIC regulations were amended to comply with this new mandate. Operators of hazardous waste injection wells must now demonstrate to the U.S. EPA, through the use of computer models, that hazardous wastes will not migrate out of the injection zone for at least 10,000 years. This demonstration can be based either on flow modeling or on the modeling of waste transformation within the injection zone.

Regulation of Underground Injection Wells

EPA-UIC regulations require protection of current and potential sources of drinking water. They define underground sources of drinking water (USDW) as aquifers that supply any public water system or contain water with less than 10,000 mg/liter total dissolved solids (TDS) in sufficient quantity to serve as a public water system.

All injection wells fall into five classes of wells according to regulations established by the federal UIC program:

Class I:	Injection of municipal or industrial waste (including hazardous waste) below the deepest USDW.
Class II:	Injection related to oil and gas production, including enhanced hydrocarbon recovery and hydrocarbon storage.
Class III:	Injection of fluids for the extraction of minerals.
Class IV:	Injection of hazardous or radioactive waste into or above a USDW (banned by regulation and statutes).

Class V: All other wells used for injection of fluids. These are generally shallow wells used to inject non-hazardous fluids into or above a USDW.

The regulations are tailored to the different classes of wells. In general, the regulations for Class I, II, and III wells establish siting, construction, operating, testing, monitoring, and reporting requirements. In addition, owners and operators of these injection wells must demonstrate the financial capability to properly plug and abandon the wells upon completion of operations. The regulations are stringent and specific for Class I wells, particularly those that inject hazardous wastes; they are more flexible for Class II wells. Class IV wells are banned, with the exception of wells used for remediation of aquifers that have been contaminated with hazardous wastes.

Among the five classes of injection wells the most relevant to CO_2 injection into brine formations is the Class I wells. It appears likely that CO_2 storage will be required to be below the deepest USDW whenever possible. This is consistent with the desire for deep injection to store CO_2 in a supercritical state, which avoids the adverse effects from the separation of CO_2 into liquid and gas phases in the injection zone. The critical point of CO_2 is at a pressure of 73.82 bars and temperature of 31.04°C (Vargaftik, 1975), which exists at a depth below about 800 m.

For Class I wells, UIC regulations require the submission of detailed geologic and hydrologic data. These data are used to determine whether injection will take place in a receiving formation that is: (1) relatively homogeneous and continuous, (2) free of transmissive faults, and (3) separated from USDWs by at least one, but preferably several, thick and relatively impermeable strata. It is required that the location of the injection well not be in a seismically active region. The regulations require the applicant to demonstrate that all unused abandoned wells in the vicinity of the proposed injection well are properly completed and plugged, so that they will not serve as a conduit for injected waste or displaced formation fluids.

Another important factor for Class I injection wells is proper well construction. The UIC requirements were designed to achieve two goals: protection of USDWs and successful emplacement of the waste in the chosen injection interval. A typical Class I injection well constructed according to UIC requirements has at least two strings of casing. The surface casing is designed to protect USDWs, and the long-string casing is extended to the injection zone. These casings must be cemented to the wellbore in order to prevent movement of fluid into or between USDWs. Ideally, wells are equipped with an injection tubing set on a packer located above the injection zone to prevent backflow of injected waste into the well. Materials used in well construction must be resistant to the proposed injected waste and to formation fluids. Before a well is put into operation, the effectiveness of the cementing program must be verified by logging the well (i.e., lowering tools into the well with electrical sensors that measure such variables as temperature, noise, and particle emissions). Similarly, the integrity of the well's tubular system must be verified by pressure tests.

For proper operation of Class I wells, the EPA regulates injection pressure to ensure that the well and the confining formations are not damaged. The regulations require the maximum injection pressure specified to be set below the fracture pressure of the injection zone, which ensures that the confining zone cannot fracture. Injection pressure, injection volume, and flow rate must be continuously monitored as any change in the relationship between these variables could indicate downhole problems. The tubing-casing annulus must be filled with fluid with an applied positive pressure. Continuous monitoring of this pressure is required to detect leaks in the tubing, packer, or long-string casing. If a pressure change indicates a leak, the well must be shut down, and further testing conducted to verify the cause of the pressure change. The well must remain shut down until all problems are resolved. A simultaneous failure of at least two of these elements would be necessary for waste fluid to escape the injection well; the conditions under which both these failures could lead to contamination of a USDW are unlikely.

Proper operation also requires the injected waste to be compatible with injection formation matrix and fluids. This requirement often works to the advantage of the operator, because incompatibility between these elements could cause the formation of precipitates that plug the formation face and reduce the useful life of the well. In some cases, however, such as injection of acid waste in carbonate formations (which can result in the formation of carbon dioxide), the waste injection must be managed to prevent sudden releases of gas and well blowout.

Finally, the EPA determined that proper plugging and abandonment of the wells was important in ensuring that injected wastes would not travel back to the surface when injection is terminated. Regulations require the operator to submit a plugging and abandonment plan as part of the permit application. This plan must identify the number and method of placement of plugs in the well. The operator must also demonstrate that he or she is, and will remain, financially capable of properly plugging the well.

Monitoring Requirements

Under current UIC regulations for Class I Injection wells, separate monitoring wells are not required. The argument is that the most potential leakage pathways are concentrated in or around the injection well, because the injection pressure decays rapidly with distance from the point of injection. Thus, even if there is a relatively high-permeability leakage path in the confining layer above the injection zone some distance from the injection well, the driving force (pressure at the location) is relatively small to cause a large leakage (Miller et al., 1986). Another argument is that a randomly placed monitoring well has statistically low probability of success, so that a monitoring well should only be placed on the basis of an identified potential leakage pathway (Warner, 1992).

The logs and tests required for Class I injection wells are outlined below:

1. Continuous Monitoring
   - Injection flow rates
   - Injection pressures
2. One-Year Intervals
   - Radioactive Tracer Log (RTS-I^{131})
     * Pathway of injected waste
     * No upward migration channels by casing/cement shoe
   - Annulus Pressure Testing
     * Pressure up annulus (500–1000 psi) to verify no casing, tubing and packer leaks
     * May also run OA log to verify leaks (optional). Temp and noise logs may be used in combination, especially where a RTS anomaly has been discovered.
   - Reservoir Testing
     * Pressure fall-off test to determine characteristics of injection zone, etc.
     * Well(s) must be shut in for a period of time to make valid observation
3. Five-Year Intervals
   - Temperature Log
     * Must run for entire length of casing
     * Check for inter-formational movement of fluids
   - Casing Inspection Log (CIL)
     * To check for loss of casing material
     * Check for corrosion
   - Cement Bond Log (CBL)
     * Check zone for isolation of waste
     * Well construction/loss of cement
4. Well Plugging
   - Run mechanical integrity test logs: RTS/Temp/Noise/OA

- For final well plugging run, CIL and CBL before plugging well

5. Other Logging Tools for Safety
   - Open-hole logs
     - E-logs, SP log (dual induction), Neutron logs, micro F—logs, Fracture logs
   - Repeat Formation Tester (RFT)
     - Open hole fluid sample
     - Sample injected water from other wells
     - Collar location (CBL, temp, casing, and CIL)
   - Thermal Decay Tool (TDT)
     - To determine cavity top outside casing
   - Sonar Caliper Log
     - To determine cavity size and direction

Note that nearly all the tests and logs except for "Reservoir Testing" under "One-year Intervals" and operational data under "Continuous Monitoring" are concerned with the mechanical integrity of the injection well construction and the conditions in the immediate neighborhood of the well.

Special Physio-chemical Properties of CO_2

Sequestered CO_2 will reside in a dense, supercritical gas phase; some will be dissolved in the aqueous phase and a small portion will react with the minerals in the rock matrix. The dense, supercritical gas phase will have a density and viscosity less than water, so that there is a strong tendency for it to flow to the top of the injection zone. Thus, the areal extent of the injected CO_2 will be larger than a neutrally buoyant fluid. For example, storage of 2.7×10^{11} kg of CO_2 in a 100-m thick formation, will have an increase in areal extent due to buoyancy of approximately 1.4 (Pruess et al., 2001). For the example presented here, because of the large volume of CO_2 involved, the areal extent of the CO_2 supercritical gas in the injection zone can be as much as ~ 120 km^2.

Now if there is a vertical leakage path in the caprock within this area, CO_2, with its low density (about 60-80% of that of water) and viscosity (about a factor of 10–40 less than that of water) would escape by buoyancy. Pruess and Garcia (2000) made a simple estimate of the leakage and found it to be significant, due not only to the lower density and viscosity, but also to the two-phase flow effect. The CO_2 effective permeability in the vertical leakage path will increase as the saturation of CO_2 in the vertical channel increases. This preliminary evaluation indicates that a more complete study of caprock leakage is needed to provide a full understanding of the process and its implication on CO_2 sequestration.

In any case, it is likely that a transmissive fault, vertical fracture or leaky abandoned well in the caprock will have a significant impact on the leakage of CO_2 in the injection zone. Thus, a much more careful evaluation of caprock integrity, and detection of possible faults or fractures are necessary. Methods for evaluating caprock integrity have been developed for aquifer gas storage applications (Witherspoon et al., 1967) and are likely to be applicable here. However, new methods that provide caprock characterization over very large areas are likely to be needed. Geophysical techniques, including satellite-based land surface deformation monitoring, are likely to be helpful.

Chemically there is also a difference between CO_2 injection and injection disposal of acidic liquid waste. For the latter, the liquid waste will interact with the formation system and its acidity will be neutralized after a time period. For the case of storage of supercritical CO_2, the acidity will stay for a long time, slowly degrading the rock matrix. The long-term impact still needs to be studied. Further, supercritical CO_2 is dissolved in hydrocarbons and reduces their viscosity, making them more mobile. Implication of such differences between liquid wastes and CO_2 on needed regulatory control and monitoring deserves further study.

Given the fact that monitoring wells are likely to be needed for CO_2 sequestration, an important issue is how to locate the optimal sites for monitoring wells. Warner (1996) discussed the use of monitoring wells (a) within the injection zone, (b) within the first aquifer above the injection zone caprock, and (c) in the USDW above the injection zone. Selection of their locations requires some indication of the possible locations of potential leakage paths. This can be obtained by a combination of reservoir modeling, geophysical surveys such as 3-D seismic, electrical imaging and gravity surveys. All of these technologies are fairly mature and are applicable here.

A useful point to note is that a minor leakage of CO_2 into an overlying aquifer or into the atmosphere may not be a major environmental problem. In fact, in some cases, slow leakage of CO_2 followed by dissolution and possibly even mineralization of the CO_2 in overlying formations may be a desirable strategy for controlling reservoir pressures and limiting long term impacts of CO_2 sequestration. Thus there is no need for a no-migration requirement for CO_2 sequestration in brine formations. An alternative approach would use a careful evaluation of the hydrogeologic setting and model simulations to ensure that cumulative and instantaneous releases of CO_2 to the environment are within prescribed limits and do not compromise the sequestration effectiveness. Models for making these types of calculations are currently available and are being improved through the efforts of many researchers around the world (Pruess et al., 2001). Model results are then used to support risk based approaches for environmental decision-making (Ruckelshaus, 1983; National Research Council, 1994; Kammen and Hassenzahl, 1999).

Concluding Remarks

This paper reviews current EPA-UIC regulations and monitoring requirements in light of potential applicability to large-scale geologic sequestration of CO_2 in brine formations. Special physio-chemical properties of CO_2 injection related to appropriate regulation are pointed out. These include:

(a) Density being lighter than surrounding fluids, resulting in buoyancy driven flow;
(b) CO_2 plume covering a large area, requiring caprock evaluation over an extensive area;
(c) Low concentrations of CO_2 being not harmful; and
(d) Some degree of leakage can be allowed and incorporated into regulatory approach.

It is suggested that, based on the extensive EPA-UIC experience, the regulatory framework for CO_2 injection should have the following elements:

(1) Evaluation of regional and local hydrogeologic setting; selection of location to avoid seismically active areas and areas with many potentially leaky abandoned wells;
(2) Detection of potential leakage paths in the caprock and planning for monitoring wells, either in the injection zone or in the upper aquifers;
(3) Evaluation of chemical interactions between CO_2 and the host formation and the caprock;
(4) Simulation studies to evaluate CO_2 migration to ensure that cumulative and instantaneous leakage is limited to prescribed levels under appropriate criteria;
(5) Injection well construction: guidelines, monitoring requirements (such as annulus pressure and periodic geophysical logs);
(6) Continuous monitoring of injection pressure and flow rates;
(7) Reservoir testing: periodic tests of formation permeability to detect any changes; and
(8) Mitigation plans to be employed in the event of unanticipated leakage at unacceptable rates.

While certain techniques are now available for many of the above elements, new or improved methods and testing techniques will be needed to enable large-scale geologic sequestration of CO_2. Furthermore, as pointed out in the last section, certain physical and chemical processes particular to CO_2 sequestration in brine formations still need careful studies to provide an advanced understanding so that appropriate regulatory guidelines and monitoring strategy can be determined.

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