Carbon Dioxide Capture for Storage in Deep Geologic Formations – Results from the CO_2 Capture Project

Geologic Storage of Carbon Dioxide with Monitoring and Verification

Volume 2

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Geologic Storage of Carbon Dioxide with Monitoring and Verification

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Chapter 27

THE REGULATORY CLIMATE GOVERNING THE DISPOSAL OF LIQUID WASTES IN DEEP GEOLOGIC FORMATIONS: A PARADIGM FOR REGULATIONS FOR THE SUBSURFACE STORAGE OF CO_2?

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ABSTRACT

Federal and state regulations covering the deep injection disposal of liquid waste have evolved over the last 30 years in response to legislation designed to protect underground sources of drinking water (USDW). These regulations apply to so-called Class I wells, and address issues relating to the confinement of hazardous and nonhazardous wastes below the lowermost USDW. They have been made progressively more stringent with time, and are now quite effective in protecting USDWs. The deep injection disposal of compressed carbon dioxide (CO_2) into similar environments will undoubtedly require similar regulation. Accordingly, the history relating to the development of legislation to protect groundwater supplies, and resulting regulations is reviewed and conclusions drawn regarding the extent to which these regulations might eventually be applied to CO_2 injection.

INTRODUCTION

The technology of deep well injection disposal of liquid wastes has many similarities to that envisioned for the storage of CO_2 in deep saline formations. The issues raised—technical, legislative, regulatory and social—would be similar to those relating to disposal of hazardous liquid wastes in comparable subsurface environments. However, stabilizing or halting the increasing United States inventory of CO_2 in the atmosphere by subsurface storage would require the disposal of volumes of CO_2 approximately two orders of magnitude larger than those required for hazardous liquid waste. Concerns over the consequences of storing such large volumes of CO_2 in deep geologic formations will likely generate public apprehensions similar to those raised over deep well injection disposal of hazardous liquid waste at so-called off-site facilities.

A review of deep well injection technology and the regulatory framework governing the disposal of liquid wastes by this method is particularly valuable in anticipating corresponding issues affecting the subsurface disposal of CO_2. In this chapter, we consider the historical, technical, and regulatory basis for deep injection disposal of liquid industrial and municipal wastes with particular emphasis on regulations governing hazardous waste disposal. We then consider the implications for the future regulatory climate governing CO_2 disposal by similar means.

STUDY METHODOLOGY

History of Underground Disposal of Liquid Wastes

Deep well injection storage of industrial wastes came into prominence in the United States following World War II. But the technology had its roots much earlier during the first part of the 20th century, when substantial quantities of saline brines were co-produced in oil and gas fields. The brines and associated oil field wastes were initially discarded in surface evaporation or infiltration pits. However, this disposal method compromised the integrity of shallow groundwater aquifers, and states banned the practice. The oil and gas industry therefore turned to injection of liquid wastes. Currently, more than 300 billion gallons (1.1 billion m^3) of brine are injected yearly into approximately 175,000 wells [1,2]. The disposal of oilfield brines is still not without attendant risks of groundwater pollution. In fact, according to an earlier report by Gordon and Bloom [3] 17 of the 32 oil and gas producing states had reported groundwater contamination resulting from the storage of these brines.

By the early 1970s, nearly 90% of the US population had become dependent on groundwater for domestic use and for agricultural irrigation. At the same time, industry was increasingly looking for alternatives to surface effluent discharges, which had become an undesired focus of attention under the Clean Water Act of 1972. The disposal of any liquid waste by injection down wells was technically feasible, and particularly attractive, for the chemical and petrochemical industries, which produced large-volume, dilute hazardous waste streams that were difficult to dispose of by other means. Furthermore, although the capital cost of developing an injection facility was high, the operating costs were usually low. The lack of public awareness of this disposal method initially allowed industry to proceed without close scrutiny or adequate regulation.

The number of deep disposal facilities for hazardous liquid waste initially grew rapidly. In 1950, there were only five such facilities. By 1963, there were 30, [4], and between 1973 and 1975 the number peaked at about 270 following passage of the Clean Water Act of 1972. Ten years later, the total number of wells injecting hazardous waste had fallen slightly to 252 at 95 facilities. Since then, with implementation of more stringent regulations in 1988 following passage of the Resource Conservation and Recovery Act (RCRA) in 1984, the number of facilities had fallen to about 50, comprising 163 so-called Class I wells (i.e. wells injecting below the lowest aquifer containing a potential source of drinking water) injecting hazardous waste. Most of these wells are found in Texas (78) and Louisiana (18). Another 221 facilities comprising 366 Class I wells injecting nonhazardous waste are also in operation, the majority of which are found in Florida (112) and Texas (110). Of those operating in Florida, 104 are dedicated to the disposal of municipal waste, the only state operating this class of well [26]. Figure 1 illustrates the variation in the number of deep well injection facilities over time.

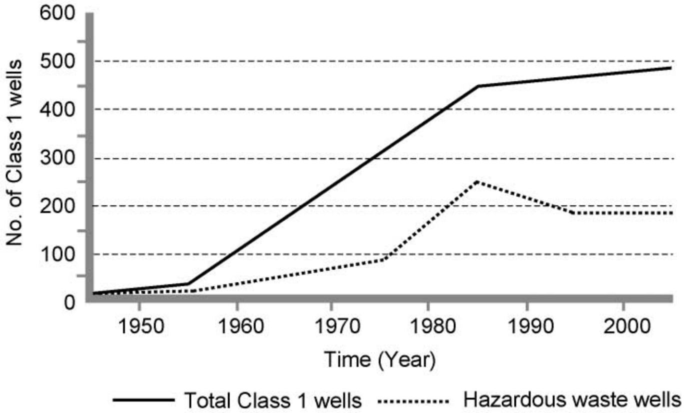


Figure 1: Number of Class I wells operating in the United States on a yearly basis since 1950 (from Ref. [13]).

Sites favorable for deep well disposal commonly overlie sedimentary basins, where deep formation waters are highly saline, and where permeable aquifers are interspersed with relatively impermeable shale "confining beds". The 48 contiguous states are endowed with several such basins, some of which are strategically located with respect to centers of industrial development, especially those in the raw materials sector. Figure 2 illustrates the distribution of these major sedimentary basins.

Figure 2: Map of the contiguous 48 states, showing major stratigraphic features in relation to the location of deep injection disposal wells (after Warner [29]).

Most of the deep injection disposal wells are located on the coastal plain of the Gulf Coast, and in states surrounding the Great Lakes. In the Great Lakes region, deep injection well depths range from 1700 to 6000 ft (520–1830 m), whereas those along the Gulf Coast range from 2200 to 9000 ft (670–2740 m) [5]. About 60% of the wells are located within the EPA jurisdiction of Region VI, which includes Texas and Louisiana. According to Gordon and Bloom [3], manufacturers of organic chemicals account for nearly 65% of the injected volume, while the petroleum refining and petrochemical industries account for a further 25%.

The quantities of hazardous liquid waste injected at deep well disposal facilities are enormous. By 1985, 11.5 billion gallons (43.5 million m^3) of industrial liquid wastes were injected annually [28]. At the time, this was 10 times the amount going to landfills and twice that going to surface impoundments [3]. By 1990, the quantity injected had fallen to 9 billion gallons (34 million m^3) [6] and currently remains at about the same level [2,7]. The injected hazardous liquid waste constitutes approximately 60% of all such waste generated in the United States.

Deep well injection disposal of hazardous waste remains a viable method of disposal, particularly on the basis of cost. In 1987, the cost of liquid hazardous waste disposal ranged from \$49 to \$207 per ton [8]. This compared with \$776–1426 per ton for incineration, \$85–394 per ton for chemical treatment, and \$131–329 per ton for resource recovery (in the case of organics from the aqueous phase). Brower et al. [9] estimated that the pre-treatment of injected waste to remove the hazardous components could increase the operating costs 3–40 times. Furthermore, alternative disposal methods, involving treatment and surface disposal, increase the potential risks of adverse consequences to the environment and public health. Thus, subsurface injection will remain a preferred method of hazardous liquid waste disposal for the foreseeable future.

Legislative history governing deep well injection disposal

Early deep well disposal practices commonly resulted in poorly engineered or constructed facilities, which were carelessly operated, and resulted in an increasing number of reported occurrences of potable aquifer contamination. Consequently, the Federal Water Quality Administration (FWQA) published policy guidelines governing the deep well injection of hazardous wastes [10], which "opposed the disposal or storage of wastes by subsurface injection without strict controls and a clear demonstration that such [injected] wastes will not interfere with present or potential use of subsurface water supplies" [11]. Furthermore, the policy provided for critical evaluation by the FWQA of all proposals for subsurface injection of wastes to ensure that the fate of the wastes could be predicted, and that the waste would not interfere with the use of water resources or cause environmental hazards. Waste injection had also to be continuously monitored and the injection well properly plugged following cessation of operations. The FWQA emphasized that subsurface disposal of wastes was to be considered a temporary expedient until alternative methods providing better environmental protection were developed.

With the reorganization in 1970 of federal government agencies charged with protection of the environment, the FWQA was absorbed by the United States Environmental Protection Agency (EPA), which subsequently issued a Technical Studies Report concerning deep well injection disposal [27]. This report noted that many problems arising through the use of this technology could be avoided if the fate of the injected wastes could be monitored. The report concluded that deep well injection should be regulated through a system of laws, and that a permitting process should be implemented, based on both injection site and the nature of waste injected (as noted in Ref. [11]).

EPA eventually set forth its own policies regarding deep well injection [12]. EPA was also opposed to the 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" [13]. But EPA also recognized that for some industries, such practice was then the only feasible means of disposal as was clearly the case in the oil and gas and geothermal industries where reinjection of large volumes of liquid wastes had been a standard practice for several decades.

Shortly after the EPA had published its policy on deep well injection, Congress passed the Safe Drinking Water Act (SDWA) of 1974. Part C of the SDWA is the Underground Injection Control (UIC) program, which implemented EPA's policy concerning deep well injection and mandated controls on injection practices. According to Herbert [11], the SDWA was essentially the first federal statute to address deep well injection practices. Furthermore, it provided for a joint system involving both state implementation and federal oversight, in which EPA would implement the policy guidelines set forth by the federal government by setting minimum requirements for state programs. EPA was to be allowed discretion in requiring states to use a permit system, rule making, or both to control underground injection. The reason for this discretion was to allow compatibility with permit provisions already in place under the Federal Water Pollution Control Act (FWPCA) of 1970.

EPA responded with the publication of technical UIC regulations in June 1980. It was also in these regulations that an Underground Source of Drinking Water (USDW), as set forth in 40 CFR Part 144.3, was first defined as containing fewer than 10,000 mg/L of dissolved solids, and was capable of providing a sufficient quantity of groundwater to supply a public water system. The regulations also categorized injection wells into five classes to deal with the multiplicity of waste streams and well functions, as set forth in 40 CFR Part 144.6—Classification of Wells. The classes most relevant to deep injection disposal of CO_2 are Class I, that class of wells injecting waste below the deepest USDW, and Class II, in which fluids relating to oil and gas production can be injected. Under certain circumstances, however, CO_2 could be injected into wells under the Class V designation.

Although the SDWA was promulgated to ensure the protection of the nation's water supplies, it did not specifically address the improper handling of hazardous waste. This omission was rectified through passage of RCRA in 1976. With this act, Congress made it a national policy to eliminate, or at least reduce, hazardous waste generation as expeditiously as possible. The act also designated responsibility to EPA for promulgating regulations governing the treatment, storage, and disposal of hazardous waste, including hazardous waste injection wells.

EPA classified hazardous wastes in 40 CFR Part 261—Identification and Listing of Hazardous Waste. In general, hazardous wastes are either "listed" or identified by their "characteristics". The characteristics are subdivided into six groups and given respective Hazard Codes. Each characteristic causes or significantly contributes to increased mortality or serious illness, or possesses a substantial present or potential threat to human health and the environment. The criteria for listing a hazardous waste are extensive and are provided in Subpart C of Part 162. Waste that is not classified as hazardous is, by default, nonhazardous. However, such waste cannot be allowed to contaminate a USDW unless it meets the criteria set forth in 40 CFR Part 141—National Primary Drinking Water Regulations. These criteria are sufficiently restrictive that most wastes would not be eligible for direct injection into a USDW.

Because of the technical complexity of the issues involved, and an overlap between SDWA and RCRA, EPA decided to coordinate their implementation by regulating aboveground facilities under RCRA, but injection wells under SDWA. However, deficiencies in EPA's coordination of SDWA and RCRA with respect to well disposal of hazardous wastes and protection of USDWs were revealed by the discovery of groundwater contaminated with hazardous chemicals due to malfunctioning and poorly regulated hazardous-waste injection wells [14]. In 1982, therefore, Congress gave EPA specific directives regarding the implementation of its UIC program to ensure that vulnerable subsurface drinking water supplies were adequately protected as specified in the Hazardous and Solid Waste Amendments (HSWA) to RCRA in 1984. Congress further mandated that land disposal of hazardous waste was allowed only if an applicant for a permit exempting restriction on land disposal could demonstrate that no migration of the waste would occur [11].

EPA responded to the 1984 RCRA amendments in 1988 with revised UIC regulations governing hazardous-waste injection, otherwise known as the "Land Ban" regulations. Henceforth, the subsurface injection of hazardous wastes would be prohibited unless EPA was to issue a permit exempting the operator of a deep well injection facility from the prohibition. To obtain a permit, the operator had to petition EPA and provide supporting documentation demonstrating that the injected waste would not migrate outside of a designated injection zone within 10,000 years, or that the waste would become nonhazardous. As noted above, Congress allowed EPA to delegate responsibility to the states to administer their own UIC programs, should a state wish to assume primacy. States also had the option of administering all or part of the UIC program. To date, 34 states have been delegated full authority to regulate Class I wells within their territory, and two share responsibility with the federal government. The remainder is administered under the federal program [15]. Four states have placed an outright ban on Class I wells. Figure 3 illustrates the distribution of states with primacy.

Although states with primacy follow federal regulations quite closely, specific variations do occur. These variations are generally more restrictive than the corresponding parts of federal regulations [16,17]. For example, several states require that a critical area surrounding the injection well must be established, based on logging and testing the injection well and surrounding formation, known as an "Area of Review" (AoR), which is larger than required by federal regulations, e.g. Texas requires 2.5 mile (4 km), Louisiana requires 2 mile (3.2 km), and Florida and Kansas require a 1 mile minimum (1.6 km) [17].

Current regulations have generally proven effective in protecting USDWs, as shown by relatively recent independent investigations, e.g. see Ref. [17]. There has been no evidence of subsurface leakage into USDWs from Class I hazardous waste injection wells since 1988, and no evidence of contamination of USDWs due to the migration of hazardous waste from well injection zones. With respect to the disposal of nonhazardous wastes, only one serious problem has arisen; that concerning the disposal of sewage waste in Class I wells in Florida where leakage outside the confining zone has been observed in several instances.

Difficulties remain, however, in providing a technically convincing demonstration of waste containment in the injection zone. These deficiencies have been exploited by environmental groups in their opposition to the underground disposal of hazardous liquid wastes. Opposition is not limited to technical issues related to the ultimate fate of the injected waste, but to environmental, social and quality of life issues arising from surface facilities. Off-site injection facilities are particularly subject to criticism, because the hazardous waste must be trucked in from various sources and transferred and temporarily stored in surface tanks or impoundments. Wastes from different sources may vary widely in chemical composition and react with undesired consequences when mixed. Off-site facilities are commonly prone to toxic releases to the atmosphere and to contamination of surface waters and shallow ground waters. They also tend to be more frequently in violation of federal and state regulations governing deep well injection disposal. Recently, the General Accounting Office [18] has questioned the adequacy and timing in soliciting public

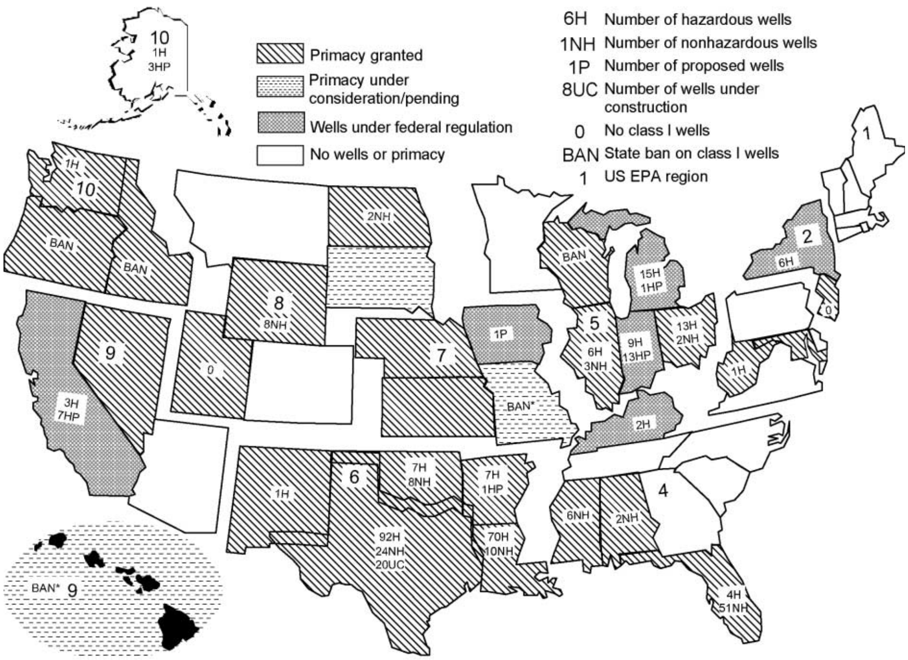


Figure 3: Regulatory status of Class I wells in the U.S. (from Ref. [9]).

comments during the permitting process of off-site Class I hazardous waste wells, and has recommended that the public be involved at an earlier stage in the process (see below). EPA, in response, believes that many of the issues raised by local communities are not relevant to the mission of the UIC program.

For the foreseeable future, deep well injection disposal will continue to be the technology of choice for the elimination of liquid wastes. Despite impediments to its use, regulatory policy, which considers deep injection waste disposal as an interim expedient, owner liability, and opposition from environmental groups, the technology remains one of the cheapest, safest, and most convenient disposal options for many hazardous waste generators. CO_2 storage in deep geologic formations by injection would similarly be the technology of choice, particularly as current estimates suggest a cost of between only \$3 and \$10 per ton CO_2 injected.

Current Regulations Governing Deep Well Injection Disposal of Liquid Wastes

Current regulations governing the deep well disposal of wastes are found in the Code of Federal Regulations, Chapter 40, Parts 144–148:

- Part 144—Underground Injection Control Program
- Part 145—State UIC Program Requirements
- Part 146—Underground Injection Control Program: Criteria and Standards
- Part 147—State Underground Injection Control Programs
- Part 148—Hazardous Waste Injection Restrictions.

In addition, 40 CFR Part 124—Procedures for Decision-Making, includes public-participation requirements that must be met by UIC programs.

This section focuses on regulations pertaining to Class I wells, because these wells usually penetrate to considerable depths and discharge their waste below aquifers containing potable water. Operating conditions are therefore somewhat similar to those expected of wells injecting supercritical CO_2, where the optimum depth range would fall between 3000 and 6000 ft (915–1830 m).

The following discussion refers only to federal regulations; where states have primacy, the regulations sometimes differ. The criteria and standards applicable to Class I wells are very stringent, and even more so for those Class I wells injecting hazardous waste. Those applicable to wells injecting nonhazardous waste are given in Subpart B of Part 146, and those for wells injecting hazardous waste are given in Subpart G of Part 146. Each subpart is loosely subdivided into seven categories covering the following requirements:

- Information Required for Authorization (Permitting) by the Director of EPA.
- Siting
- Construction
- Operation
- Monitoring
- Ambient monitoring
- Reporting
- Closure and post-closure requirements.

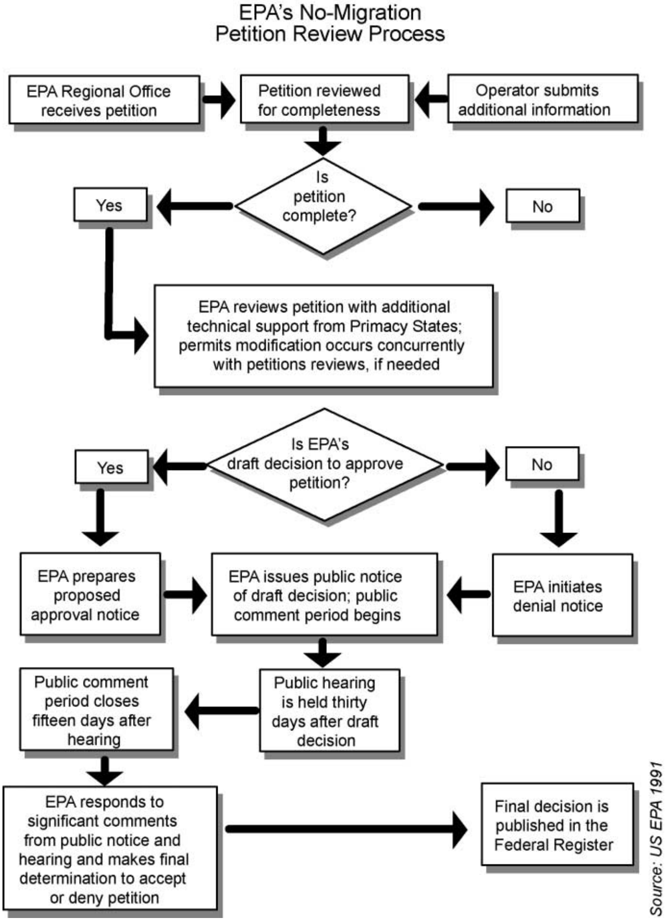
Application for a permit to operate a Class I well

For authorization to operate a Class I hazardous waste well, the owner or operator must first submit a so-called "No-Migration Petition" to EPA describing all aspects of the proposed operation, including well siting, design and operation, and conduct hydrologic modeling and geochemical modeling (if feasible) to demonstrate that migration will not occur beyond a defined injection zone. The need for adequate site characterization, especially for Class I hazardous waste wells, is particularly critical to ensure that no failure occurs for whatever reason, and that hazardous waste will be contained for at least 10,000 years or become nonhazardous during that period.

Because of the 10,000-year period required for post-closure regulatory compliance, experimental verification is not feasible, and therefore much of the justification necessary to demonstrate waste containment must depend on predictive modeling. This modeling usually takes the form of numerical simulations, and conceptual models based on an understanding of the hydrologic and chemical processes occurring in the subsurface environment. The no-migration petition could take one or both of two forms: "A Fluid Flow Petition," or a "Waste Transformation Petition" [17]. Because quantitative information describing the chemical processes that render waste nonhazardous is usually understood only qualitatively, geochemical arguments supporting the fate or attenuation of hazardous wastes are not normally invoked, and therefore waste transformation petitions are rarely submitted. Instead, most modeling invokes hydrologic arguments to demonstrate confinement over the 10,000-year period. Furthermore, because many parameters used in the models are not precisely known, limiting conservative values are usually selected, leading to modeling results that represent worst-case scenarios. If these results show satisfactory containment, then it can be argued that a more realistic assessment would predict an even smaller likelihood of failure. A flowchart illustrating the permitting process is given in Figure 4.

The EPA regional offices are responsible for reviewing all no-migration petitions for Class I hazardous waste wells. The review process takes the best part of a year to accomplish, owing to the vast quantity of information required, the interdisciplinary nature of the technical arguments presented, and the inevitable challenges regarding the adequacy of information presented. Brasier and Kobelski [13], citing an earlier report [6], noted that industry spent $343,000 in preparation and the EPA dedicated over 2000 employee hours to the review of each demonstration. According to USEPA [17], factoring in the costs for geologic testing and modeling, a no-migration petition can cost in excess of $2,000,000.

Each petition is subject to public notice and comment. Notice of the final decision regarding the petition is published in the Federal Register [17]. The duration of the permit for a Class 1 well does not exceed 10 years. The permit may be reissued for a new term, but the entire permit application must be reopened and is subject to revision.



Source: US EPA 1991

Figure 4: A flowchart illustrating EPA's no-migration review process for Class I deep well injection disposal facilities (from Ref. [16]).

Information required in a permit application. The information needed prior to construction of a disposal well is concerned with the suitability of the subsurface environment to contain the injected waste. Of particular importance is the identification of any potential conduits for the migration of waste, such as other wells in the vicinity, whether operational or abandoned, and geologic faults. To this end, suitable maps and cross sections providing topographic, geologic and hydrologic information are required to show the locations of wells and faults in relation to the proposed injection well and the injection well to USDWs. A plan is required to ensure that any abandoned wells in the vicinity that penetrate the injection zone will be properly plugged prior to waste injection. Details are also required concerning the construction, operation, monitoring, and periodic testing of the well as well as contingency plans in the event of well failure. Finally, EPA requires delivery of a performance bond for its final closure and abandonment.

After construction of the well, EPA requires the submission of the results of a comprehensive test program demonstrating that the well is safe to operate, a description of specific injection procedures, and corrective actions concerning improperly abandoned wells in the vicinity. In addition, an AoR surrounding the injection well must be established.

Siting requirements. All Class I wells must be sited in such fashion that they inject into a formation that is beneath the lowermost formation containing a USDW. Class I hazardous waste injection wells must be restricted to geologically suitable areas. The geology of the area must be described with sufficient confidence that the limits of waste fate and transport can be accurately predicted. The injection zone must have characteristics that prevent migration of fluids into USDWs. The confining zone must also have sufficient structural integrity to prevent the movement of fluids into a USDW, and it must contain at least one formation of sufficient thickness and characteristics to prevent vertical propagation of fractures. Furthermore, the confining zone must be separated from the base of the lowermost USDW by at least one sequence of permeable and less permeable strata, to provide an added layer of protection for the USDW in the event of fluid movement in an undetected transmissive pathway. Finally, within the AoR, the piezometric surface of the fluid in the injection zone must be less than the piezometric surface of the lowermost USDW, or a USDW must be absent.

Construction requirements. The requirements for construction of a Class I well vary somewhat, depending on the nature of the waste, i.e. whether hazardous or nonhazardous, and if nonhazardous, whether or not the waste is treated sewage. The most stringent requirements pertain to wells injecting hazardous waste, and a design incorporating all of the desired features for such wells is illustrated in Figure 5.

All Class I wells must be cased and cemented to prevent the movement of fluids into or between USDWs. Materials used in construction must be designed for the life expectancy of the well and to prevent potential

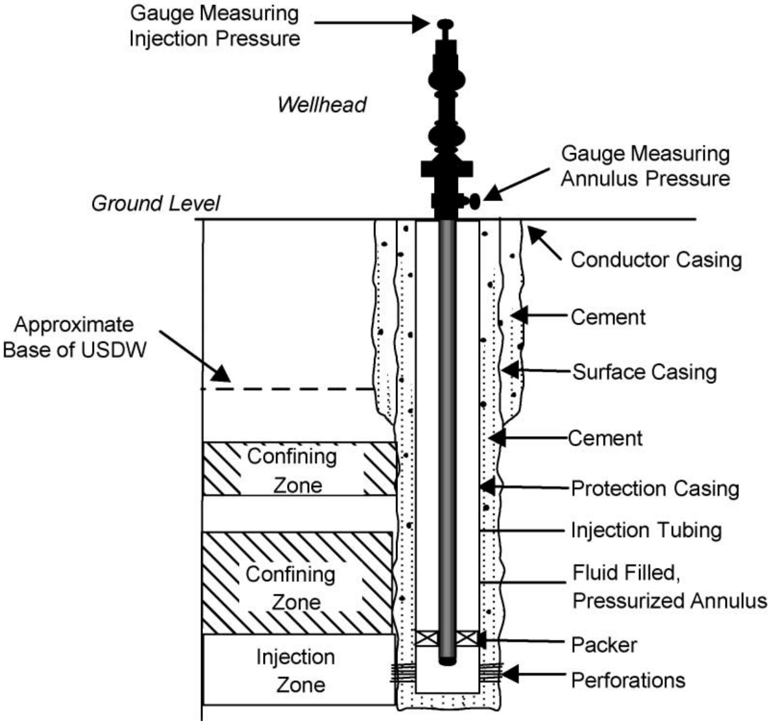


Figure 5: A typical configuration of a Class I hazardous waste injection well (from Ref. [16]).

leaks. Hazardous waste wells must also be constructed and completed to prevent the movement of fluids into any zones other than that selected for injection, and allow continuous monitoring of injection tubing and long-string casing. All Class I injection wells, except those municipal wells injecting noncorrosive wastes, must inject fluids through tubing with a fluid seal or packer set immediately above the injection zone.

Appropriate logs and other tests must be conducted during the drilling and construction of new Class I wells to characterize comprehensively the subsurface environment. Such logs and tests are also needed to establish accurate baseline data against which future measurements may be compared. Numerous logs and tests must also be made to ensure that casing intended to protect USDWs will retain its integrity. Upon completion of a Class I well injecting hazardous waste, pump or injectivity tests must be conducted to verify the hydrogeologic characteristics of the injection zone.

Operating requirements. During operation of a Class I well, the injection pressure at the wellhead must not be so high as to cause hydrofracturing of the injection zone or confining beds, in order to prevent migration of the waste into an overlying USDW. In general, the annulus fluid between the tubing and the casing must be maintained at a suitable overpressure to prevent leakage of waste from the tubing. For hazardous-waste injection, an approved plan for chemical and physical analysis of the waste must be followed. The hazardous waste stream and its anticipated reaction products must not affect the properties of the confining or injection zones.

Monitoring requirements

The operator must monitor both the operation of a Class I well and the volume and composition of the waste stream to ensure compatibility with the well construction materials. He must also monitor injection pressure, and "ambient" conditions in the injection zone, confining beds and adjacent USDWs. For hazardous waste injection, the injection pressure, flow rate and temperature of injected fluids, and the fluid pressure in the annulus, must be monitored and recorded continuously with automatic alarm and shut-off systems in the event of deviation from operating conditions.

The extent of "ambient" monitoring depends upon the potential for fluid movement from the well or injection zone, and on the potential value of monitoring wells to detect such movement. At a minimum, annual monitoring of the pressure buildup in the injection zone is required. EPA may also require continuous monitoring for pressure changes in the first aquifer overlying the confining zone and, if a well is installed, the aquifer must be periodically sampled for chemical analysis. If a well is installed in the lowermost USDW, it must also be analyzed periodically for water quality. If additional wells are available for monitoring contaminant migration or detecting communication with the injection zone through pressure testing, EPA can also mandate the monitoring of these wells.

Reporting requirements

The EPA and state agencies responsible for environmental protection specify minimum reporting requirements for monitoring the operation of deep injection wells. These requirements are specified in 10 CFR Part 146, Subparts B and G. Reports must be submitted quarterly to EPA. They must include the physical and chemical characteristics of injection fluids, monthly average, maximum and minimum values for injection pressure, flow rate and volume, and annular pressure and monitoring results. In addition, results of periodic mechanical-integrity tests or any well workover must be reported to EPA. For wells injecting hazardous waste, the quarterly reports must also include information on the operating conditions and any alarms or shutdowns, and the responses taken. Extensive monitoring is required to ensure the continuing integrity of the well components. However, required ambient monitoring is restricted only to periodic pressure testing using the injection well.

Closure and post-operational monitoring

The EPA is particularly concerned that deep injection wells, especially those that have injected hazardous waste, are properly plugged and abandoned. The owner or operator of a well that injected hazardous waste must, therefore, not only be responsible for proper closure, but also assume responsibility in perpetuity for any contamination to a USDW. At least 60 days beforehand, EPA must be notified of the intended well closure. The owner or operator of a Class I hazardous waste injection well must comply with a closure plan as part of the permit application. Prior to granting approval for the plugging and abandonment, EPA must review details concerning the method of closure and receive information on the casing and any other materials to be left in the well, and any proposed tests or measurements. A Class I hazardous waste well must be plugged with cement in a manner that will not allow the movement of fluids into or between USDWs. Before closing the well, the pressure decay must be recorded and mechanical integrity testing conducted to ensure the integrity of any long-string casing and cement that will be left in the ground after closure.

After closure, the owner must also submit a closure report to EPA. For a Class I hazardous waste well, the owner must prepare and comply with a plan for post-closure care. The plan must also include the predicted position of the waste front at closure, the status of any cleanups required, and the estimated cost of proposed post-closure care. The plan must also assure financial responsibility. The owner or operator must continue groundwater monitoring until pressure in the injection zone decays to the point that waste migration into a USDW would not occur. A number of administrative requirements must be met including submission of a survey plan to the local zoning authority with a copy to EPA, and notification of state and local authorities having cognizance over drilling activities, to enable them to impose appropriate conditions on subsequent drilling activities in the vicinity of the abandoned well.

Reliability of Deep Well Injection Facilities

The purpose of existing federal (and state) regulations and standards governing deep well injection disposal is to ensure protection of USDWs. The effectiveness of these regulations in protecting USDWs serves as a basis for deciding whether corresponding regulations governing CO_2 injection are promulgated, what modifications to these regulations would be necessary to ensure containment of this less dense fluid. This subject can be considered from several perspectives. We can establish from monitoring programs, the frequency and nature of injection facility failures. Such failures can be broadly classified into two categories: those relating to the well failure, and those where the ambient environment has failed to prevent migration of the waste from the injection zone as a result of confining bed failure. The experience thus gained will allow estimates to be made of future system failures. The extent of operator or owner compliance can be assessed, and what enforcement remedies are necessary in the event of noncompliance. Enforcement will in turn ensure the minimization of component failures and increase reliability.

Two studies were conducted prior to 1988 (when more stringent regulations were introduced) to assess the nature and frequency of operational problems [19,20]. According to USEPA [17], the CH2M Hill study identified 26 malfunctions involving 43 wells, suggesting an overall malfunction rate of 9%. Only six wells injecting nonhazardous waste (or 2% of all Class I wells) experienced malfunctions that resulted in contamination of a USDW. The GAO study reported only two cases of USDW contamination and eight cases of contamination of nonpotable aquifers. In all cases, contamination occurred prior to 1980.

Since 1988, when more stringent regulations were introduced, reported substantive incidents involving contamination of formations or USDWs not designated as injection zones have been rare. Of those few known violations since that time, all but one can be traced to actual contamination when less stringent regulations were in force. Contamination of USDWs by Class I nonhazardous waste injection facilities in Florida injecting treated sewage waste is unusual in that violations have occurred more recently. The reasons for the failure of some of the Florida waste wells are discussed elsewhere [21]. These reasons, and the environmental consequences, are relevant to the proposed CO_2 injection into saline aquifers, because the density of the injected sewage, like that of CO_2 is less than the ambient ground waters of the injection zone. Furthermore, the scale of Florida sewage injection would be comparable in size and density to CO_2 injection facilities throughout the United States.

EPA has analyzed mechanical integrity (MI) failures in all Class I wells in selected states between 1988 and 1991 [17]. One hundred and thirty internal MI failures were attributed to leakage from the injection tubing or failure of the long-string casing. Only one external MI failure occurred, involving flow along the outside of the casing. There were four cases of nonhazardous waste migration, three of which were detected by monitoring wells and a fourth during the drilling of a new injection well. A second EPA analysis of MI failures for the time period 1993–1998 [22] showed that the overall rate of failures had declined to half the rate in all states except Texas, where failures increased by 65%.

Cases of noncompliance or violations are handled at a level commensurate with the nature of the violation [28]. However, the extent to which UIC regulations are enforced is not adequately known.

Since 1988, EPA has also pursued, through the US Justice Department, two cases of purported contamination of USDWs through deep well injection. In both cases, the alleged violators were charged with injecting hazardous waste into an aquifer that was claimed by EPA to be a USDW. Continuing operation would, under RCRA, subject each company to substantial fines. In one case, total potential fines could have been several hundred million dollars and would have been, if successfully levied, the largest environmental fine in history. Plans for litigation were abandoned, however, because the evidence was insufficient to make a case that the aquifer was a USDW. In the other case, the company settled with a $3,500,000 fine, which was imposed for both surface and subsurface contamination [23]. In contrast, EPA's response to contamination of potable aquifers in Florida by Class I wells injecting nonhazardous treated sewage was to propose amended regulations rather than mandate cessation of injection and costly remediation.

In summary, the present regulatory climate regarding USDW contamination by waste, whether hazardous or not, is first and foremost to operate a Class I facility in such a manner that the risk of failure is extremely small. Secondly, the operation of the well should be such that failures that can be easily and effectively demonstrated should be tightly regulated. The preferred enforcement approach is through consent decrees and fines, rather than by requiring remediation. The status of deep aquifers in relation to their classification as USDWs is sometimes difficult to establish in the absence of direct evidence from pumping tests. Furthermore, in the event that monitoring wells do suggest contamination, existing remedies can prove to be politically unacceptable.

RESULTS AND DISCUSSION

The experience gained from the regulation of deep well injection of both hazardous and nonhazardous wastes will inevitably be carried over in the regulation of deep injection of supercritical CO_2. There are, however, several major distinctions between CO_2 and hazardous wastes, which will necessitate the promulgation of regulations that recognize these distinctions. Firstly, CO_2 is generally considered to be nonhazardous. Secondly, the volumes of CO_2 being considered for interception prior to atmospheric release exceed by at least two orders of magnitude the quantities of hazardous waste currently being injected. Thirdly, while current regulations require isolation of hazardous waste within the confining zone of an injection well for the lesser of 10,000 years, or that length of time before it is rendered nonhazardous, these restrictions are hardly relevant to supercritical CO_2 injection. Fourthly, regulations governing the diversion of CO_2 production from the atmosphere to the subsurface environment must take into account the extent to which CO_2 can be contained in the subsurface environment over long periods of time and the more stringent monitoring requirements necessary to ensure confinement. Finally, the question arises as to the class under which CO_2 injection wells should be categorized, or whether a special class should be designated. The classification question is complicated by the fact that CO_2 is also used in the tertiary recovery of oil, and its injection for that purpose is regulated under Class II wells.

Compressed carbon dioxide is a relatively benign chemical substance when pure, and is not considered to be hazardous, except under certain environmental conditions. It is limited in its capacity to corrode well tubing and casing, and carbonates casing cements relatively slowly. For these reasons, current regulations specifying the design of nonhazardous injection wells would likely suffice. A critical aspect of well design would be to prevent leakage of CO_2 along the casing and its consequent migration into shallow aquifers or cause surface blowouts. Rigorous monitoring of tubing annulus pressure and proper testing of casing and cement grout integrity would therefore be mandatory. If, however, CO_2 containing significant sulfur dioxide and water vapor were to be injected tubing and casing corrosion could become an issue. Furthermore, the presence of sulfur dioxide could require that the injected gas mixture be subject to regulations similar to those for injection of hazardous waste. Therefore, we can conclude that existing regulations relating to the design and operation of Class I wells could be adapted to CO_2 injection with relatively minor modifications.

If all CO_2 generated by fossil fuel power plants in the United States were to be recovered for sub-surface disposal, approximately 3 Gton/yr would have to be injected [2,24]. Suitable sedimentary formations for CO_2 storage exist under only about half of the land area of the 48 contiguous states, and not all sedimentary formations would be suitable for injection for various geologic, hydrologic and societal reasons. Quantitative estimates of the total volume of CO_2 that could be injected into formations that could contain indefinitely the injected CO_2 have not been made, but rough calculations would suggest that disposal capacity would permit injection for about 500 years. However, although the injection rate would be comparable in tonnage to that of oilfield brines, the latter are essentially refilling a void from which they were previously extracted, whereas CO_2 would eventually require the displacement of a corresponding volume of brine or volumetric compensation by other means.

CO_2 confinement within an injection zone is far more challenging from the regulatory point of view. Supercritical CO_2 is less dense and has substantially lower viscosity than the ambient brine of the injection zone. It will therefore tend to concentrate beneath any confining zone, and spread laterally over a substantial area. In the case of a 1000 MWe plant injecting into a 100 m thick aquifer, the areal extent of the injected plume could attain 120 km^2 [24]. The CO_2 could migrate buoyantly upwards through structural defects into overlying aquifers. The substantial lateral spreading of the CO_2 fluid increases the likelihood that such defects will be encountered. Given the lateral extent to which CO_2 can migrate, it would be important to use whatever means are feasible to monitor potential leakage into formations overlying the injection zone. According to the EPA [28], the installation of monitoring wells is not required for Class I wells, as there was no technology available that would define the siting of these wells. Furthermore, the drilling of multiple monitoring wells into a very deep interval would be prohibitively costly. Available monitoring wells have been limited, mainly to hydrologic testing [25].

Although regulations require containment of hazardous waste within the injection zone of a Class I well for 10,000 years, such a stringent requirement would be unnecessary for the interim storage of CO_2, unless mandated by social, technical and scientific considerations. The argument implicit in CO_2 capture is that this activity would be conducted only until alternative energy sources, conservation, or longer term natural processes would lead to a stabilization of the ambient CO_2 concentration in the atmosphere. Therefore, total confinement of injected CO_2 for very long periods, i.e. over 10,000 years could be unnecessary. Unlike hazardous waste, supercritical CO_2 storage could be considered as a form of interim storage, rather than disposal. Controlled leakage of the stored CO_2 might therefore be acceptable, provided it were sufficiently slow to allow the goals of carbon dioxide capture to be met. However, controlled leakage would invariably result in migration into overlying USDWs where present.

The preceding review is predicated on the assumption that CO_2 injection would be governed by regulations developed and implemented for the protection of USDWs from contamination by injected liquid wastes, particularly those classified as hazardous. However, the cost associated with the petitioning process to obtain a permit for the operation of a Class I hazardous waste injection well is substantial. It can be argued that much of the cost might be avoided through classification of a CO_2 injection well under the Class I nonhazardous category. But in doing so, many of the protections would be lost, which are afforded by the requirements for the injection of hazardous waste, and which would be applicable for the safe operation of a well dedicated to CO_2 injection.

The nonhazardous nature of CO_2 might justify its injection into deep aquifers meeting the definition of a USDW, but which would otherwise be economically unsuitable for exploitation of potable water, and therefore CO_2 injection could be permitted under Class V. Allowing this flexibility would enhance the opportunities for locating injection facilities in regions where USDWs occupy the whole sedimentary sequence above basement rocks, or where aquifers of optimal depth for CO_2 injection, while saline, would still fall within the classification as a USDW. Future regulations could well take into account the potential opportunity to utilize USDWs for injection, provided such sources have no likelihood of being used for potable water. Caution must necessarily be exercised, however, because the consequences of compressed CO_2 penetration into a USDW have not yet been assessed. Although such contamination, whether as a gaseous fluid or dissolved in potable water, may not be particularly hazardous, CO_2 can act as an organic solvent and react with host rock minerals causing some chemical constituents to exceed drinking water standards. Clearly, in formulating future regulations, these issues must be considered.

Given that CO_2 is currently permitted under Class II, a special class designated exclusively for subsurface CO_2 storage might be designated. This class should take into account the current experience relating to Class II injection, and the demonstrated protections afforded by Class I, while permitting restricted operation under what would normally be Class V for the reasons given above. Finally, past experience with off-site hazardous waste facilities indicates that timely input from a concerned public would facilitate acceptance. On-site facilities within the boundaries of existing coal-fired plants would be more likely accepted, particularly if instituted in conjunction with more effective pollution control.

CONCLUSIONS

Regulations designed to protect USDW from contamination by injected industrial and municipal wastes will serve as a basis for regulations governing subsurface disposal of CO_2. Large volumes of CO_2 would require disposal, exceeding by about two orders of magnitude the amount of hazardous liquid waste that is currently injected, only a small portion of which will be diverted for tertiary oil recovery under Class II well regulations. Therefore, injection of the remainder will most likely be subject to federal regulations similar to those promulgated for Class I wells. However, these regulations should not be adopted without modifications to account for the different physical and chemical properties of CO_2 compared with existing wastes disposed by deep well injection.

Pure compressed CO_2 is generally considered in the context of deep well injection disposal to be a nonhazardous noncorrosive chemical compound, and therefore regulations governing the design and operation of nonhazardous Class I wells may be followed. If by-products of the combustion of coal, such as sulfur dioxide and water vapor are not removed special precautions mandated for hazardous waste disposal could be required. The lower density of CO_2 in relation to brines of the injection zone, and its tendency to migrate buoyantly, poses potential problems of containment that are not adequately addressed by Class I well regulations governing the disposal of hazardous waste. Thus, the siting of compressed CO_2 injection wells, like those for the injection of hazardous waste, will be critically dependent on the geology. Furthermore, Class I well hazardous waste ambient monitoring requirements are insufficient to guarantee the protection of USDWs from CO_2 intrusion. Therefore, additional ambient monitoring techniques not currently required for Class I wells may be imposed. The solvent properties and chemical interactions of compressed CO_2 with the subsurface environment and its potential to transport co-contaminants into USDWs are not fully understood. Thus, further study to assess the significance of co-contamination will be necessary before promulgation of regulations could be promulgated.

Opposition to CO_2 injection disposal by environmental groups and local communities could be as vehement as has been the case regarding some off-site Class I well hazardous waste disposal facilities. Prior experience would indicate that on-site disposal at sources of CO_2 generation would mitigate potential opposition and potential litigation. The permitting process for Class I hazardous waste wells under Land-Ban regulations could be adapted to regulate the siting of CO_2 injection wells provided there is timely input to the satisfaction of affected local communities.

RECOMMENDATIONS

If CO_2 deep subsurface storage and storage is to become a reality, the consequence of high pressure CO_2 intruding an overlying USDW must be considered. The buoyant nature of compressed CO_2 could result in preferential migration even to the surface through along faults, fractures and incompletely plugged and abandoned wells. Without a clear understanding of the risks entailed in deep subsurface disposal, the drafting of regulations would necessarily require a degree of conservatism that could inhibit further consideration of this means of managing greenhouse gases. Therefore, first and foremost, comprehensive investigations must be conducted of migration mechanisms and probabilities of USDW contamination by CO_2 and displaced brines from underlying compressed CO_2 reservoirs. Secondly, potential contamination of USDWs by co-contaminants due to the solvent properties and reactivity of compressed CO_2 should be investigated. With such information in hand, appropriate risk analyses should be conducted to assess the probability of barrier failure in the ambient environment. Thirdly, minimum barrier requirements and specifications should be defined for acceptable risk. Finally, minimum ambient monitoring requirements should be formulated to ensure that any potential threat to the integrity of a USDW is identified in a timely manner.

The integrity of natural barriers of the ambient environment and protection of USDWs in the event of failure of these barriers is the most important issue requiring definition. But current practices relating to Class I injection well design construction, operation and monitoring must also be reviewed, and modified to account for the physical and chemical characteristics of compressed CO_2. In particular, the corrosive characteristics of CO_2 containing minor concentrations of sulfur dioxide and water vapor should be investigated, improved casing cement formulations and inclusion of blow-out preventers should be reviewed in the light of current Class I well regulations.

Following the technical definition stage, current regulations governing the injection of both hazardous and nonhazardous waste in Class I wells should be reviewed in relation to CO_2 storage by similar means. Although existing regulations provide a substantial basis for regulating the future disposal of CO_2 will be necessary, and must be debated and evaluated. Consideration should be given to regulations governing CO_2 injection under Class II, and the feasibility of allowing CO_2 injection into USDWs under restricted circumstances. The urgency of such an evaluation will depend on government policy, but in any event, it would be reasonable for EPA either to perform the evaluation in-house, or contract with a suitable company in the private sector.

Finally, due consideration should be given to perceived environmental and social impacts of the subsurface storage of such large anticipated quantities of CO_2. The public comment period for proposed regulations governing CO_2 injection disposal will inevitably become a venue for opponents. However, current regulations should be modified to allow timelier and sufficiently comprehensive input from affected communities. A proactive stance should therefore be taken by evaluating a priori the environmental and social issues arising from CO_2 injection disposal.

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REFERENCES

1. Ground Water Protection Council, Florida ground water conditions, Ground Water Report to Congress, 2000, pp. 19–20, www.gwpc.site.net/gwreport/states.htm.
2. E.J. Wilson, T.L. Johnson, D.W. Keith, Regulating the ultimate sink: managing the risks of geologic CO_2 storage, *Environ. Sci. Technol.* **37** (2003) 3476–3483.
3. W. Gordon, J. Bloom, Deeper problems: limits to underground injection as a hazardous waste disposal method, Natural Resources Defense Council, 1985, p. 82, Available From NRDC, NY.
4. E.C. Donaldson, Surface disposal of industrial wastes in the United States, US Bureau of Mines Information Circular 8212, 1964.
5. T. Kozlowski, Waste Goes Well Underground, CMA News, November 1997. (Document #2333122), p. 3, 1997, Available from PolicyFax at (312) 377-3000.
6. USEPA, Analysis of the effects of epa restriction on the deep injection of hazardous waste, EPA 570/9-91-031, 1991.

7. Ground Water Protection Council, Underground Injection Fact Sheet, 2001, www.site.net/factshee.htm.
8. H. Sigman, Reforming Hazardous Waste Policy. Essays in Public Policy, Hoover Institution, Stanford, CA, 2001, www-hoover.stanford.edu/publications/epp/93/93a.html.
9. R.D. Brower, I.G. Krapac, B.R. Hensel, A.P. Visocky, G.R. Peyton, J.S. Nealon, M. Guthrie, Evaluation of Current Underground Injection of Industrial Waste in Illinois, Final Draft report HWRIC RR, Hazardous Waste Research and Information Center, State Water Survey Division, Illinois Department of Energy and Natural Resources, 1986.
10. USFWQA, Policy on disposal of wastes by subsurface injection, COM 5040.10, October 15, 1970.
11. E.A. Herbert, The regulation of deep-well injection: a changing environment beneath the surface, *Pace Environ. Law Rev.* **14** (1) (1996) 169–226. www.law.pace.edu/pacelaw/pelr/herbert.htm.
12. USEPA, Subsurface emplacement of fluids by well injection, 39 Fed. Reg. at 12,922, 1974.
13. F.M. Brasier, B.J. Kobelski, Injection of industrial wastes in the United States, in: J.A. Apps, C.F. Tsang (Eds.), Deep injection Disposal of hazardous and Industrial Waste: Scientific and Engineering Aspects, Academic Press, San Diego, CA, 1996, pp. 1–8, Chapter 1.
14. J. Bloom, Resource Conservation and Recovery Act Reauthorization Hearings, supra note 5, at 263 (Statement of Jane Bloom, NRDC) citing General Accounting Office, Hazardous Waste Facilities with Interim Status may be Endangering Public Health and the Environment, 1981. (Cited in Herbert, 1996), 1982.
15. USEPA, State UIC Programs, 2002a, www.epa.gov/safewater/uic/primacy.html..
16. J.E. Clark, An overview of injection well history in the United States, American Institute of Hydrology, *4th USA/CIS Joint Conference*, November 9, Cathedral Hill Hotel, San Francisco, California, 1999.
17. USEPA, Class I underground injection control program: study of risks associated with Class I underground injection wells, Office of Water, EPA 816-R-01-007, 2002b.
18. U.S. General Accounting Office, Deep injection wells. EPA needs to involve communities earlier and ensure that financial assurance requirements are adequate. Report to the Honorable Lynn C. Woolsey, House of Representatives, GAO-03-761, 2003, p. 36.
19. CH2M Hill, A Class I injection well survey, Report Prepared for the Underground Injection Practices Council, 1986.
20. U.S. General Accounting Office, Hazardous waste: controls over injection well disposal operations, Report to Chairman, Environment, Energy, and Natural Resources Subcommittee, Committee on Government Operations, House of Representatives, GAO/RCED-87-170, August 8, 1987.
21. D.F. McNeill, A review of upward migration of effluent related to subsurface injection at Miami-Dade Water and Sewer South District plant, Final Report Prepared for the Sierra Club—Miami Group, 2000, p. 30.
22. ICF Inc., Class I mechanical integrity failure analysis: 1993–1998, Prepared by ICF, Inc., Fairfax, Virginia, for USEPA, Office of Ground Water and Drinking Water, Underground Injection Control Program, 1998.
23. USDOJ, Zeneca Agrees to Pay Civil Penalty, Cease Deep Well Injection, Press release, http://ww.usdoj.gov/opa/pr/1998/388enr.html, 1998, p. 2.
24. C.-F. Tsang, S.M. Benson, B. Kobelski, R.E. Smith, Scientific considerations related to regulation development for CO_2 sequestration in brine formations, *Environ. Geol.* **42** (2002) 275–281.
25. D.L. Warner, Monitoring of Class I injection wells, in: J.A. Apps, C.-F. Tsang (Eds.), Deep Injection Disposal of Hazardous and Industrial Waste: Scientific and Engineering Aspects, Academic Press, San Diego, CA, 1996, pp. 421–432, Chapter 25.
26. USEPA, Deep Wells (Class I), Office of Water, UIC Program, 2001, www.epa.gov/safewater/uic/classi.html.
27. USEPA, Subsurface pollution problems in the united states, technical studies, Report: U.S. EPA Office of Water Programs TS-00-72-02, at 8-9 (May 1972).
28. USEPA, Report to Congress on Injection of Hazardous Waste, EPA 570/9-85-003, With corrections, 2nd printing (May 1985), 1983.
29. D.L. Warner, American Association of Petroleum Geologists, Memoir No. 10, 1968, p. 11.