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EPA

Class I Underground Injection Control Program: Study of the Risks Associated with Class I Underground Injection Wells

Contents

Preface

The Land Disposal Program Flexibility Act of 1996 (Public Law 104-119) requires the United States Environmental Protection Agency (EPA) to complete a study of the risks to human health and the environment associated with hazardous waste disposal practices and directly related to *decharacterized* wastes managed by surface impoundments and Class I injection wells regulated under the Underground Injection Control (UIC) program. EPA has been charged with compiling information on these waste disposal activities and making a determination on whether existing programs administered by the Agency or the states are adequately protective or new regulations are needed to ensure safe management of these wastes.

Two offices within EPA are tasked with this response. The Office of Solid Waste and Emergency Response, Office of Solid Waste (OSW) is preparing a study on surface impoundments to be completed within 5 years of the enactment of this legislation. The Office of Water, Office of Ground Water and Drinking Water (OGWDW) is conducting a study on Class I injection wells in a similar timeframe. This *Study of the Risks Associated with Class I Underground Injection Wells* is OGWDW's response to Congress' request.

Direction of the Class I *Study*

In the Act, Congress did not ask EPA to do an entirely new study regarding Class I UIC wells that would have required a re-collection of the large amount of report data and information already compiled. Nor did Congress require the states to contribute new field data or tabulations of data already being reported.

EPA decided that the Class I *study* would describe the current Class I UIC Program, document past compliance incidents involving Class I wells, and summarize studies of human health risks associated with Class I injection conducted for past regulatory efforts and policy documentation. This compilation would serve as the basis for the Agency's decision either to promulgate new regulations, or determine that existing Class I controls are adequate. This *study* would be submitted to appropriate members of Congress and their staffs and to fulfill the Agency's commitment under the Act.

The *Study* Report

As stated above, this study is a compilation of existing information on the Class I UIC injection program. Much program data has been gathered on Class I hazardous and nonhazardous injection wells, and each type of well is regulated separately, but stringently. In the *study*, the hazardous and nonhazardous Class I requirements are presented together to give a complete picture of the UIC program. Many UIC Primacy states place requirements on Class I nonhazardous waste disposal wells under their jurisdiction that are equivalent to, or stricter than, the federal Class I hazardous well requirements. Moreover, the Agency believes, from information collected in past studies and reports related to rulemaking, that substantial volumes of *decharacterized* wastewaters are being managed in Class I hazardous injection wells, thus providing a significant degree of protection to human health and the environment. Any different requirements between Class I non-hazardous and hazardous wells are described and compared to give the reader a more complete perspective of the preventative aspects of the entire UIC Class I program.

Based on the recommendations of expert reviewers, and to be consistent with the June 1998 memorandum from President Clinton to all federal agencies to take steps to improve the clarity of government writing, this report is written in "plain English." In addition, the authors assume that the audience is a mixture of educated non-scientists and people with a more sophisticated understanding of geology, risk analysis, and other relevant sciences. As a result, the report tries to educate the audience on the basic principles of geology, modeling, etc., and some portions could be considered repetitive by more knowledgeable readers.

Data Needs and Initial Steps

The *study* relies on secondary data, that is, existing information such as studies, reports, and background information documents prepared by EPA, the states, and others. By using existing information, OGWDW becomes bound by certain limitations, such as data accuracy, quality, soundness of methodology, and other pertinent technical data. However, EPA believes that such data are usually very accurate given the finite universe of Class I wells and the history of regulation of these wells by EPA and the states, among other things. EPA Regional Offices and the states have collected operational and construction-related data for these wells for a fairly long time, and such data are compiled and reviewed on a regular basis. Thus, the documents upon which the *study* is based are reliable. While many of these documents have not been peer reviewed, *per se*, they were subject to technical and policy review by informed individuals including regional staff, state staff, and other technical stakeholders. In most cases, they were developed to support Agency rulemakings and were therefore subject to public comment. A large library of such documents existed in EPA files and dockets as of 1996.

As the initial step in conducting the *study,* in September 1996 EPA prepared a paper titled *Class I Underground Injection Control Program: Background Document and Assessment of Risks Associated with Class I Underground Injection Wells*. Prior to completion of this paper, OGWDW decided to investigate and apply the Office of Water Peer Review Process to ensure that the scientific and technical "underpinnings" of any decisions involving Class I UIC wells meet two important criteria:

- They should be based on the best current knowledge from science, engineering, and other domains of technical expertise.
- They should be judged credible by those who deal with the Agency.

Although the Background Document, which represented a compilation of existing documents related to Class I UIC wells, was not judged to be a "major scientifically and technically based work product," OGWDW determined that it would benefit from some form of technical review. Although the *study* addresses controversial issues, supports a policy decision, and could have significant impact on the investment of Agency resources, other tempering factors (i.e., it is not a new data collection but a compilation of existing studies and it represents an "update" of progress in the UIC Class I program) suggest that it is not a candidate for *bona fide* peer review.

Expert Panel Process

OGWDW chose to seek external review of the initial draft of the *study* document primarily to ensure scientific and technical accuracy. To do this, EPA engaged a contractor to convene a panel of experts in the scientific and technical subject matter. The panel was balanced to encompass a multi-disciplinary group of experts in other disciplines who could contribute to the full range of issues concerning Class I wells.

The five-member panel's experts have many years of experience with deep well injection and related technology. Panel members represented a variety of perspectives on Class I wells, including industry and consulting, state regulatory agencies, and academia. They have experience with development and oversight of EPA and state UIC programs, as well as permit preparation and review. Their technical expertise spans aquifer characterization, geohydrologic model development, no-migration petition demonstrations, well siting and construction, and well testing including mechanical integrity. The expert panel's primary goal is to serve as peer reviewers and to further acknowledge that information and data collected is technically sound, appropriate, and accurate.

OGWDW distributed the first draft of its work product on the Class I *study* to the expert panel in April 1998. After initial review, the entire panel met in Alexandria, Virginia, in late April 1998 to begin discussions. The panel provided substantial comment and recommended several changes to the text of the report, including reordering the presentation, adding a discussion on modeling methodology, and writing the report in plain English. EPA revised the draft based on the expert panel members' comments and edits. A follow-up draft of the *study* was prepared and sent to the members for review in December 1998. The panel then met for a second time prior to a Ground Water Protection Council Meeting in New Orleans, Louisiana, in January 1999. Additional edits and comments were compiled via teleconferences and electronic mailings, and EPA prepared a third and final draft product in December 1999.

Distribution of the *Study* Document

The Office of Water (OW) is providing the Class I *study* to Congress for its consideration. OW is also making the study available to states and other stakeholders, including the interested public through a number of mechanisms. As part of the communication strategy for such studies, EPA will place it on a list of UIC documents on OGWDW's Web site, and make it available to the general membership of the Ground Water Protection Council and the National Drinking Water Council and via general Water Program announcements.

Exhibits

Executive Summary

In 1996, Congress enacted the Land Disposal Program Flexibility Act, which exempted Class I underground injection wells disposing of decharacterized hazardous wastes from the provisions of the Resource Conservation and Recovery Act (RCRA) Land Disposal Restrictions (LDRs). This legislation also required the U.S. Environmental Protection Agency (EPA) to conduct a study of such wastes and disposal practices to determine whether Class I wells pose risks to human health and the environment, and if current state or federal programs are adequate to address any such risks. EPA must also determine whether such risks could be better addressed under existing state or federal programs. Upon receipt of additional information or upon completion of such study and as necessary to protect human health and the environment, the Administrator may, but is not required to, impose additional requirements under existing Federal laws, including subsection (m)(1), or rely on other state or federal programs or authorities to address such risks.

EPA's *Study of the Risks Associated with Class I Underground Injection Wells* describes the Class I UIC Program, injection well technology, the Land Disposal Restrictions, and the 1996 legislation; documents past failures of Class I wells; and summarizes studies of human health risks associated with injection via Class I wells, including non-hazardous and hazardous wells. The study also includes an updated risk analysis using Class I injection well data and an annotated bibliography of literature on injection via Class I wells.

Class I wells inject industrial or municipal wastewater beneath the lowermost underground source of drinking water (USDW).[1] Class I wells are designated as hazardous or nonhazardous, depending on the characteristics of the wastewaters injected. (Wastewaters are considered to be hazardous wastes if they demonstrate a hazardous characteristic of ignitability, corrosivity, reactivity, or toxicity, or are a listed waste as determined by EPA.) This designation affects the stringency of the requirements imposed on operators of Class I wells. The wastewater injected into Class I wells typically is associated with the chemical products, petroleum refining, and metal products industries.

History: Early Concerns, EPA's Response

The practice of underground injection of wastewater began in the 1930s as oil companies began disposing of oil field brines and other waste products into depleted reservoirs. In the mid 1960s and 1970s, injection began to increase sharply, growing at a rate of more than 20 new wells per year. In 1974, responding to concerns about underground injection practices, including failure of some wells, EPA issued a policy statement in which it opposed underground injection

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[1] EPA defines an underground source of drinking water as an aquifer or portion of an aquifer that supplies a public water system (PWS) or contains enough water to supply a PWS; currently supplies drinking water for human consumption or contains water with less than 10,000 milligrams/liter of total dissolved solids (TDS); and is not exempted by EPA or state authorities from protection as a source of drinking water (40 CFR 144.3).

without strict control and clear demonstration that the wastes will not adversely affect ground water supplies. In December 1974, Congress enacted the Safe Drinking Water Act (SDWA), which required EPA to set requirements for protecting USDWs; EPA passed its Underground Injection Control (UIC) regulations in 1980.

In 1984, Congress enacted the Hazardous and Solid Waste Amendments (HSWA) to RCRA, which banned the land disposal of hazardous waste, unless the hazardous waste is treated to meet specific standards. EPA amended the UIC regulations in 1988 to address the Hazardous and Solid Waste Amendments. Operators of Class I wells are exempt from the ban if they demonstrate that the hazardous constituents of the wastewater will not migrate from the disposal site for 10,000 years or as long as the wastewater remains hazardous. This demonstration is known as a no-migration petition. HSWA also requires EPA to set dates to prohibit the land disposal of all hazardous wastes: EPA has instituted the LDRs in a phased-in schedule. The Phase III LDR rule implemented the Land Disposal Program Flexibility Act.

Class I Technology Ensures Safe Disposal

Class I fluids are injected into brine-saturated formations thousands of feet below the land surface, where they are likely to remain confined for a long time. The geological formation into which the wastewaters are injected, known as the injection zone, is sufficiently porous and permeable so that the wastewater can enter the rock formation without an excessive build up of pressure. The injection zone is overlain by a relatively nonpermeable layer of rock, known as the confining zone, which will hold injected fluids in place and restrict them from moving vertically toward a USDW.

EPA requires that Class I wells be located in geologically stable areas that are free of transmissive fractures or faults through which injected fluids could travel to drinking water sources. Well operators must also show that there are no wells or other artificial pathways between the injection zone and USDWs through which fluids can travel. The site-specific geologic properties of the subsurface around the well offer another safeguard against the movement of injected wastewaters to a USDW.

All Class I wells are designed and constructed to prevent the movement of injected wastewaters into USDWs. Their sophisticated multi-layer construction has many redundant safety features. The well's casing prevents the borehole from caving in and contains the tubing, or injection string. Constructed of a corrosion-resistant material such as steel or fiberglass-reinforced plastic, the casing consists of an outer surface casing, which extends the entire depth of the well; and an inner long string casing that extends from the surface to or through the injection zone. The innermost layer of the well, the injection tubing, conducts injected wastewater from the surface to the injection zone. All of the materials of which injection wells are made are corrosion-resistant and compatible with the wastewater and the formation rocks and fluids into which they come in contact. A constant pressure is maintained in the annular space and is continuously monitored to verify the well's mechanical integrity and proper operational conditions. Trained operators are responsible for day-to-day injection well operation, maintenance, monitoring, and testing.

EPA's Requirements Minimize Risk

There are two potential pathways through which injected fluids can migrate to USDWs. First, wells could have a loss of waste confinement; second, improperly plugged or completed wells or other pathways near the well can allow fluids to migrate to USDWs. EPA's extensive technical requirements for Class I wells at 40 CFR 146 (for all Class I wells) and 148 (for hazardous waste wells) are designed to prevent contamination of USDWs via these pathways. The requirements for hazardous wells are more stringent than those for nonhazardous wells.

Class I wells must be sited so that wastewaters are injected into a formation that is below the lowermost formation containing, within one-quarter mile of the well, a USDW. Class I well operators must demonstrate via geologic and hydrogeologic studies that their proposed injection will not endanger USDWs. Operators must identify all wells in the vicinity that penetrate the injection or confining zone, determine whether they could serve as pathways for migration of wastewaters, and take any corrective action necessary. In addition, Class I operators seeking to inject hazardous wastewaters must demonstrate via a no-migration petition that the hazardous constituents of their wastewaters will not migrate from the disposal site for as long as they remain hazardous.

EPA requires that Class I wells be designed and constructed to prevent the movement of injected wastewaters into USDWs. These requirements specify the multi-layer design of Class I wells. Class I wells must be operated so that injection pressures will not initiate new fractures or propagate existing fractures in the injection or confining zones. Class I hazardous wells must be equipped with continuous monitoring and recording devices that automatically sound alarms and shut down the well whenever operating parameters exceed permitted ranges.

Operators of Class I wells must continuously monitor the characteristics of the injected wastewater, annular pressure, and containment of wastewater within the injection zone. Operators also must periodically test the well's mechanical integrity.

Upon closing their wells, operators must flush the well with a non-reactive fluid, and tag and test each cement plug for seal and stability before the closure is completed. Operators must submit a plugging and abandonment report when closure is complete.

Studies Assess the Safety of Class I Practices

EPA and others have performed numerous studies to assess the risks associated with disposal via Class I wells. Early studies of the effectiveness of the 1980 UIC regulations looked at ways in which Class I wells fail.[2] Many of the failures documented in these studies were a result of historic practices that are no longer acceptable under the UIC regulations.

Although studies emphasizing risk of injection practices have primarily focused on Class I hazardous waste injection wells, EPA believes such studies to be very relevant to all Class I wells, including those managing decharacterized wastewaters. The Agency believes that a substantial volume of decharacterized wastewaters are, in fact, injected into Class I hazardous waste wells, thus affording a particularly strong level of public health protection from these activities.

Studies performed in anticipation of the 1988 updates to the UIC regulations assessed the risks associated with disposal of hazardous wastewater via Class I wells. These include a two-phase qualitative assessment of waste confinement potential in the Texas Gulf Coast geologic setting given either a grout seal failure or the presence of an unplugged abandoned borehole. An additional study assessed the difference in risk among various geologic settings.

In support of EPA's Phase III LDR rulemaking, the Office of Ground Water and Drinking Water (OGWDW) prepared a draft Benefits Analysis estimating the risks associated with injection of Phase III wastes into Class I hazardous wells; EPA revised the Benefits Analysis in response to comments in 1995. To provide a quantifiable analysis in support of the *de minimis* requirements in the proposed Phase III rule, EPA in 1996 analyzed cancer and noncancer risks of varying the underlying hazardous constituent concentrations for five Phase III LDR waste constituents.

In the most recent studies of the risks posed by Class I wells, data on Class I wastewaters have been used to refine models of well failure scenarios. And failure-tree scenarios have been used to estimate quantitatively the risk that waste would no longer be contained based on the probabilities that sequences of events leading to containment loss would occur.

Conclusions: Current Class I Regulations are Adequately Protective of Human Health and the Environment

Since the early days of Class I injection, EPA has learned much about what makes Class I wells safe and what practices are unacceptable. The UIC regulations are based on the concept that injection into properly sited, constructed, and operated wells is a safe way to dispose of wastewater.

Class I injection practices offer multiple safeguards against failure of Class I non-hazardous and hazardous waste wells, or the migration of injected fluids. For example, EPA requires operators to identify and address all improperly abandoned wells in the area of review

[2] Failures are defined by two potential pathways through which injected fluids can migrate to USDWs: failure of the well or improperly plugged or completed wells or other pathways near the well.

(AoR) around the injection well, because studies show that an unplugged abandoned borehole may contribute significantly to the migration of injected fluids from the injection zone. (Many of the states that oversee a large proportion of the Class I well inventory have even more stringent AoR requirements than does EPA.) In addition to the AoR requirement, Class I wells are sited to minimize the potential for waste migration and designed to minimize the possibility that the wells will fail. Inspections and well testing, along with passive monitoring systems, can detect malfunctions before wastewaters escape the injection system. Several decades of well operation bear this out: only four cases of significant wastewater migration from underground injection wells have been documented (none of which affected a drinking water source).

Under EPA's UIC regulations, the probability of loss of waste confinement due to Class I injection has been demonstrated to be low. The early problems with Class I wells were a result of historic practices that are not permissible under the UIC regulations. Class I wells have redundant safety systems and several protective layers to reduce the likelihood of failure. In the unlikely event that a well should fail, the geology of the injection and confining zones serve as a final check on movement of wastewaters to USDWs.

Through modeling and other studies of Class I injection, EPA has learned much about the fate and behavior of hazardous wastewater in the subsurface. The 1988 UIC regulations implementing the HSWA offer additional protection by requiring operators of Class I hazardous wells to complete no-migration petitions to demonstrate that the hazardous constituents of their wastewater will not migrate from the injection zone for 10,000 years, or that characteristic hazardous wastewater will no longer be hazardous by the time it leaves the injection zone. EPA believes that a substantial volume of decharacterized wastewaters are being injected into Class I hazardous wells (which require a no-migration petition) because industrial, manufacturing, and petrochemical facilities typically do not segregate waste streams. Therefore, an extremely high level of protection, even above minimum federal requirements, is given by these practices. But, even the disposal of decharacterized wastewaters into a typical Class I non-hazardous well affords the public and the environment an extremely low level of risk from injection due to the multiple levels of safety features outlined in this study.

Class I Expert Panel

EPA prepared the *Study of the Risks Associated with Class I Underground Injection Wells* in consultation with a panel of experts on Class I deep well injection practices. These experts were selected because of their experience with deep well injection and related technology; they represent industry and consulting, state regulatory agencies, and academia. The experts attended two working sessions on drafts of the study report, discussed the preliminary findings, and reviewed and offered comments on the technical accuracy of the study.

E. Scott Bair, Ohio State University, Department of Geological Sciences

Professor E. Scott Bair is chair of the Department of Geological Sciences at Ohio State University. He teaches courses on quantitative groundwater flow modeling, hydrogeology, field methods in hydrogeology, contaminant hydrogeology, science in the courtroom, and water resources. He has worked with the U.S. Geological Survey and as a consultant on groundwater monitoring and groundwater modeling issues. Dr. Bair has written or co-written more than 40 books, papers, and government-sponsored reports on groundwater monitoring, aquifer investigations, groundwater flow modeling, aquifer management, and wellhead protection area delineation. He was a 1998 fellow of the Geological Society of America and the 2000 Birdsall-Dreiss Distinguished Lecturer sponsored by the society. He is a member of the American Geophysical Union's Horton Scholarship Committee and an associate editor of the journal *Ground Water* published by the National Ground Water Association. Dr. Bair earned his Ph.D. and Master's degrees in Geology from the Pennsylvania State University and his Bachelor's degree in Geology from the College of Wooster.

Larry Browning, P.E., Geological Engineering Specialties

A Principal with Geological Engineering Specialties, Larry Browning is an expert in every aspect of the UIC program. As a consultant or an EPA employee, Mr. Browning has supported virtually every UIC regulatory initiative since the program began and has in-depth knowledge of all classes of UIC wells. He was appointed special technical advisor to EPA's landmark Class I Regulatory Negotiation Committee. For EPA's Class I petition review process, Mr. Browning developed training documents and performed technical reviews of important petitions. He performed two analyses of Class I mechanical integrity failures, spanning 1988 through 1991 and 1991 through 1998. Since 1975, he has performed over 120 technical studies for EPA, including a two-volume technical manual on wireline testing of Class II injection wells which is used in all 10 EPA regions. Mr. Browning worked with EPA Region 6 and supported writing of the original UIC regulations. He has also performed ground water investigations, well testing, and investigations of injection wells and hazardous waste disposal facilities. Mr. Browning earned a Master's degree in Geology from the University of Texas at Austin and a Bachelor's degree in Geology from Northern Kentucky University.

James Clark, DuPont Engineering

James Clark has over 25 years' experience, including 18 years with DuPont working on groundwater issues. As a senior leader for DuPont, he works on Class I UIC issues spanning well construction, permitting, testing, and no-migration petitions. In this capacity, he has written numerous publications on injection issues and regulatory requirements for Class I wells. For the past 14 years, Mr. Clark has served as a technical representative to the Chemical Manufacturers Association's UIC Group; in this capacity, he worked on an assessment of the risk associated with Class I injection. Prior to joining DuPont, Mr. Clark worked as a geohydrologist with Law Engineering Testing Co. where he gained 4 years' experience on suitability studies of salt domes as repositories for nuclear waste. He also served as Chief Geologist for the Georgia Department of Transportation. Mr. Clark has written over 20 publications on Class I injection, waste confinement, aquifer monitoring, and groundwater flow. Mr. Clark has a Master's degree in geophysical sciences from the Georgia Institute of Technology and a Bachelor's degree in geology from Auburn University.

Ben Knape, TNRCC, UIC Permit Team

For over 20 years, Ben Knape has worked with the Texas Natural Resource Conservation Commission (TNRCC) and its predecessors on regulation of Class I injection wells and oversight of the state's UIC program. As a UIC Program geologist, Mr. Knape focuses on ground water studies and the use of Class I wells for industrial waste disposal. As UIC program administrator, he served as project coordinator on revising the commission's UIC program to reflect a significant rulemaking, which included strengthening construction and performance standards for Class I wells and interpreting and implementing the commission's program standards for Class I well monitoring and inspections. Mr. Knape has served as co-chair of the Ground Water Protection Council's Division I, representing Class I injection issues, and is a board member of the Underground Injection Practices Research Foundation. He is leader of TNRCC's UIC Permits Team for Class I and Class III wells. Mr. Knape holds degrees in Geology and Zoology from the University of Texas at Austin.

David Ward, Michael Baker Jr., Inc.

David Ward recently joined Michael Baker Jr., Inc. as Director of the Technology Applications Division. He has over 20 years of experience as a consultant, with expertise in hydrogeologic modeling of groundwater flow and hazardous waste transport in porous and fractured media. He has managed projects for EPA and industrial clients on deep well injection of hazardous wastes, including well test interpretation, groundwater flow and waste confinement, and no-migration petition preparation. Mr. Ward performed numerical simulations of well failures in a variety of geologic settings. He has prepared applications of flow and transport codes for many hydrogeologic models, including SWIFT and MODFLOW, including applications to geochemical analyses and no-migration demonstrations. He has written more than 80 publications on groundwater flow, waste transport, and well failure simulations. Mr. Ward holds a Master's degree in Water Resources from Princeton University and a Bachelor's degree in Civil Engineering from Lehigh University.

Abbreviations

ACC	American Chemistry Council
AoR	Area of Review
BDAT	Best Demonstrated Available Technology
CFR	Code of Federal Regulations
CMA	Chemical Manufacturers Association
DI	Direct Implementation
EPA	U.S. Environmental Protection Agency
GAO	General Accounting Office
GWPC	Ground Water Protection Council
HSWA	Hazardous and Solid Waste Amendments
HWIR	Hazardous Waste Identification Rule
LDR	Land Disposal Restriction
MI	Mechanical Integrity
MIT	Mechanical Integrity Test
OAL	Oxygen Activation Log
OGWDW	Office of Ground Water and Drinking Water
OSWER	Office of Solid Waste and Emergency Response
PWS	Public Water System
RCRA	Resource Conservation and Recovery Act
RIA	Regulatory Impact Analysis
RTS	Radioactive Tracer Survey
SDWA	Safe Drinking Water Act
TDS	Total Dissolved Solids
TRI	Toxic Release Inventory
UHC	Underlying Hazardous Constituent
UIC	Underground Injection Control
UIPC	Underground Injection Practices Council
USDW	Underground Source of Drinking Water
UTS	Universal Treatment Standards

I. Introduction

The U.S. Environmental Protection Agency (EPA) regulates Class I underground injection wells under the Safe Drinking Water Act (SDWA) and the Hazardous and Solid Waste Amendments of the Resource Conservation and Recovery Act (RCRA). These regulations establish siting, design, construction, and monitoring requirements for Class I injection wells to ensure protection of underground sources of drinking water (USDWs) from injected wastewater. HSWA prohibits injection of certain hazardous wastewater[3] unless the well operator can prove that the injected wastewater will not migrate out of the injection zone for as long as the wastewater remains hazardous.

Under the Land Disposal Program Flexibility Act of 1996,[4] Congress declared that wastewaters considered hazardous only because they exhibit a hazardous characteristic (ignitability, corrosivity, reactivity, or toxicity) are not prohibited from land disposal if they do not exhibit the characteristic (i.e., decharacterized) at the point of disposal. Class I well operators do not, therefore, have to identify and treat underlying hazardous constituents in these decharacterized wastewaters prior to injection. This legislation effectively overturned the D.C. Circuit Court's opinion in *Chemical Waste Management v. EPA*, 976 F. 2d 2 (D.C. Cir. 1992). EPA had interpreted the D.C. Circuit Court's opinion to require that hazardous constituents in characteristic wastes be removed, destroyed, or immobilized through treatment before the wastewaters were available for land disposal.

In passing the Land Disposal Program Flexibility Act, Congress stated the following (see Appendix A for the complete text of the Act):

> Not later than 5 years after the date of enactment of this paragraph, the Administrator shall complete a study of hazardous waste managed pursuant to paragraph (7) or (9) to characterize the risks to human health or the environment associated with such management. In conducting this study, the Administrator shall evaluate the extent to which risks are adequately addressed under existing state or federal programs and whether unaddressed risks could be better addressed under such laws or programs. [PL 104-119 s 2 (10)]

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[3] In order for a waste to be a hazardous waste, it must not be excluded by EPA under 40 Code of Federal Regulations (CFR) 261.4(a) or through the delisting process under 40 CFR 260.22. There are two major categories of hazardous wastes: listed wastes and characteristic hazardous wastes. The listed hazardous wastes are described in Subpart D of 40 CFR 261. The second major category of hazardous wastes includes any wastewater that exhibits any or all of the four characteristics of hazardous waste (i.e., ignitability, corrosivity, reactivity, and toxicity) described in Subpart C of 40 CFR 261. Characteristic wastes are identified by sampling a wastewater, or using appropriate company records concerning the nature of the wastewater, to determine whether a wastewater has the relevant properties.

[4] Public Law 104-119, March 26, 1996.

In response to Congress' requirement for such a study, EPA identified the need for a document that synthesizes existing information on the Class I program, including documented studies of the risks to human health or the environment posed by Class I injection wells. This document presents this information by:

- Providing an overview and history of EPA's Class I Underground Injection Control (UIC) program.

- Summarizing the geologic, engineering, and modeling sciences as they relate to Class I injection and outlining the risks associated with Class I wells.

- Describing the regulations designed to minimize the potential threat Class I wells pose to human health or the environment, and reviewing the Land Disposal Restrictions, the D.C. Circuit Court's opinion, and the 1996 legislation.

- Presenting studies that document Class I well failures, synthesizing various studies of human health risks associated with Class I injection wells, and updating a risk analysis using recent Class I injection well data.

- Providing an annotated bibliography of documents related to Class I injection wells.

I.A Overview of Class I Wells

By definition, Class I wells inject industrial or municipal wastewater beneath the lowermost USDW.[5] An **underground source of drinking water** is an aquifer or portion of an aquifer that supplies a public water system (PWS) or contains enough water to supply a PWS, supplies drinking water for human consumption or contains water with less than 10,000 milli-grams/liter of total dissolved solids (TDS), and is not exempted by EPA or state authorities from protection as a source of drinking water.[6] Class I wells are classified as hazardous or nonhazardous, depending on the characteristics of the wastewaters injected.[7] Class I wells

[5] The UIC Program oversees four other classes of wells, in addition to Class I wells. Class II wells are used to dispose of fluids which are brought to the surface in connection with oil or natural gas production, to inject fluids for enhanced recovery of oil or natural gas, or to store hydrocarbons. Class III wells inject fluids for the extraction of minerals. Class IV wells inject hazardous or radioactive waste into or above strata that contain a USDW (these wells are banned). Class V includes wells not included in Classes I, II, III, or IV. Typical examples of Class V wells are agricultural drainage wells, storm water drainage wells, industrial drainage wells, untreated sewage waste disposal wells, and cesspools.

[6] 40 CFR 144.3.

[7] Hazardous wastes are defined at 40 CFR 261.

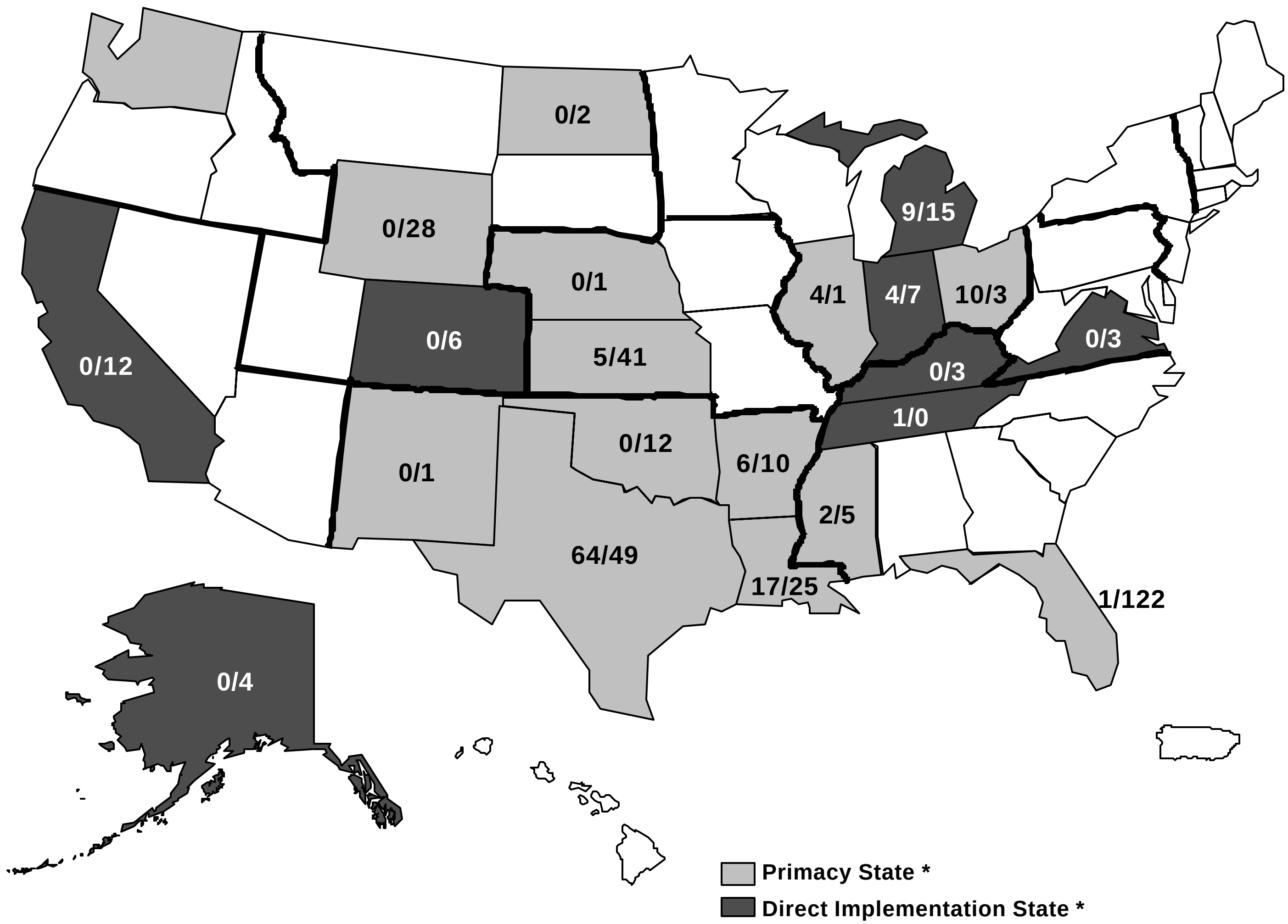
permitted to inject hazardous wastewater are referred to as hazardous wells; those that inject only nonhazardous wastewater are known as nonhazardous wells. Class I wells used for disposal of treated municipal sewage effluent are referred to as Class I municipal wells.

Many Class I wells inject wastewater associated with the chemical products, petroleum refining, and metal products industries. Injected wastewaters vary significantly based on the process from which they are derived. Some of the most common wastewaters are manufacturing process wastewater, mining wastes, municipal effluent, and cooling tower and air scrubber blowdown.

Class I municipal wells are found only in Florida, primarily due to a shortage of available land for waste disposal, strict limitations on surface water discharges, the presence of highly permeable injection zones, and cost considerations. Class I municipal wells inject sewage effluent that has been subject to at least secondary treatment. These wells have been constructed with well casings up to 30 inches in diameter to allow injection of large volumes of water (e.g., over 19 million gallons per day) at low pressures (e.g., about standard atmospheric pressure). Class I municipal wells are not subject to the same strict requirements as other Class I wells. This study does not address Class I municipal wells because they are not included in the Land Disposal Program Flexibility Act's mandate to Study Class I injection.

Currently, there are 473 Class I wells in the United States, of which 123 are hazardous, and 350 are nonhazardous or municipal wells. Most Class I wells are located in EPA Regions 6 (184 wells), 4 (134 wells), and 5 (53 wells). Texas has the greatest number of Class I hazardous wells (64), followed by Louisiana (17). Florida has the greatest number of nonhazardous wells (the majority of which are municipal wells), followed by Texas and Kansas. Exhibit 1 presents the national distribution of hazardous and nonhazardous Class I wells; Exhibit 2 shows the relative numbers of hazardous and nonhazardous Class I wells.

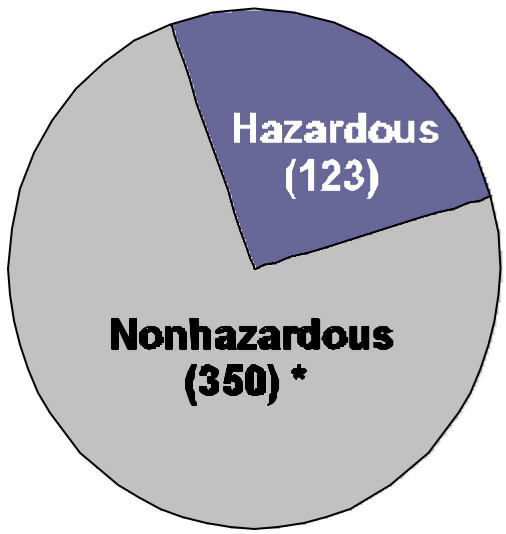
Exhibit 1
Number of Class I Wells by State



* See Section IV.B for explanation.
EPA Regions are outlined.
Number of wells in State denoted: Hazardous/Nonhazardous.

Source: EPA's Class I Well Inventory, 1999.

Exhibit 2
Hazardous and Nonhazardous Class I Wells



* 122 nonhazardous are municipal
waste disposal wells

I.B History of the UIC Program and Rulemakings Related to Class I Injection

Underground injection of wastewater began in the 1930s when oil companies began disposing of oil field brines and other oil and gas waste products into depleted reservoirs. Most of the early injection wells were oil production wells converted for wastewater disposal. In the 1950s, injection of hazardous chemical and steel industry wastes began. At that time, four Class I wells were reported; by 1963, there were 30 wells. In the mid 1960s and 1970s, Class I injection began to increase sharply, growing at a rate of more than 20 wells per year.

The 1980 UIC Regulations

Prior to EPA's regulation of Class I injection wells, several cases of well failures occurred. The Hammermill Paper Company in Erie, PA, and the Velsicol Chemical Corporation in Beaumont, TX, are two examples.

- In April 1968, corrosion caused the casing of Hammermill Paper Company's No. 1 well to rupture and spent pulping liquor to flow onto the land and enter Lake Erie. Additionally, a noxious black liquid seeped from an abandoned gas well at Presque Isle State Park, 5 miles away. The Pennsylvania Department of

Environmental Resources suspected (though never conclusively determined) that wastewaters from Hammermill's injection well migrated up the unplugged, abandoned well bore.

- In 1974 and 1975 the Velsicol Chemical Company noted lower than normal injection pressures in one of its two injection wells, which was designed without tubing. In 1975, Velsicol shut down the well to determine the cause of the decreased injection pressures, and an inspection revealed numerous leaks in the well's casing. The company decided to plug the well and drill a new one. During the course of the abandonment, Velsicol determined that contaminated wastewater had leaked to a USDW. The wastewater was pumped from the aquifer.

In 1974, responding to concerns about underground injection practices, EPA issued a policy statement in which the Agency opposed underground 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 SDWA, which required EPA to set requirements for protecting USDWs.

EPA promulgated the UIC regulations in 1980 based on the idea that, properly constructed and operated, injection wells are a safe mechanism for disposing of liquid waste. The SDWA provided a definition of an underground source of drinking water; the 1980 UIC regulations categorized injection wells into five classes. The regulations established technical requirements for siting, construction, operating, and closure of injection wells. These regulations are described in section IV.A.

The RCRA Hazardous and Solid Waste Amendments

In 1984, Congress enacted the Hazardous and Solid Waste Amendments (HSWA) to RCRA, which banned the land disposal of hazardous waste, unless the hazardous waste is treated to meet specific concentration-based or technology-based standards, or unless the hazardous waste is injected into a land disposal unit that has an approved "no-migration" exemption. Underground injection is included in the definition of land disposal methods that require regulation at section 3004(k) of HSWA.

EPA amended the UIC regulations in 1988 to address the amendments to RCRA. The 1988 changes require operators of Class I hazardous wells to demonstrate through sophisticated models that the hazardous constituents of the wastewater will not migrate from the disposal site for 10,000 years, or as long as the wastewater remains hazardous. This demonstration is known as a no-migration petition, which may be in the form of a fluid flow petition or a waste transformation petition (see section IV.A for more on these demonstrations).

Once a no-migration petition is approved, an operator may inject only wastes that are listed in the petition. Operators who do not successfully complete the petition process must either treat their wastewater to acceptable levels, stop injecting, or implement pollution prevention measures, as specified by EPA in the regulations. EPA's treatment standards are based on the performance of the best demonstrated available technology (BDAT). EPA may also set treatment standards as constituent concentration levels, and the operator may use any technology not otherwise prohibited to treat the wastewater.

The Land Disposal Restrictions

HSWA also requires EPA to set dates to prohibit the land disposal of all hazardous wastes (40 CFR 148 and 40 CFR 268). EPA was required to promulgate, by May 8, 1990, land disposal prohibitions and treatment standards for all wastes that were either listed or identified as hazardous at the time of the 1984 amendments. The Agency was also required to promulgate prohibitions and standards for wastes listed or identified as hazardous after the 1984 amendments, within 6 months of the listing or identification of these wastes. EPA did not meet all of these deadlines and, as a result, the Environmental Defense Fund (EDF) filed a lawsuit which resulted in a consent decree outlining a schedule for adoption of prohibitions and treatment standards for hazardous wastes (*EDF v. Reilly*, Cir. No. 89-0598, D.D.C). Various wastes have been listed or identified as hazardous, and Congressionally mandated prohibitions on land disposal of these wastes have been instituted in a phased-in schedule. Progress on each phase of the Land Disposal Restriction (LDR) rulemakings is described below.

Phase I Rulemaking

Phase I included Congressionally mandated restrictions on spent solvents and dioxins, hazardous wastes that were banned from land disposal by the State of California (known as "California list" wastes), and an assessment of all the hazardous wastes listed in 40 CFR 261. Since there were a large number of these wastes, this requirement was divided into three parts, referred to as the first, second, and third-thirds wastes. The Third-Thirds rule, published in June 1990 (55 *FR* 22520, June 1, 1990), addressed regulation of characteristic wastes (i.e., wastes considered hazardous because they exhibit a characteristic of ignitability, corrosivity, reactivity, or toxicity). This rulemaking did not require treatment of underlying hazardous constituents (UHCs) in these characteristic wastes, and it generally allowed for the use of dilution to remove the characteristic in order to meet disposal standards.

In 1992, the D.C. Circuit court's opinion in *Chemical Waste Management v. EPA*, 976 F.2d 2 (D.C. Cir. 1992) essentially negated the 1990 Third-Thirds rule. In this decision, the court made a number of rulings pertaining to treatment standards for characteristically hazardous wastes. First, the court held that LDR requirements can continue to apply to characteristic hazardous wastes even after they no longer exhibit a hazardous characteristic. Second, to satisfy the requirements of RCRA section 3004(m) that address both short-term and long-term threats posed by land disposal, the court held that it is not enough that short-term threats are addressed (e.g., waste is rendered no longer corrosive). Instead, the court believed that long-term threats posed by toxic underlying hazardous constituents contained in the characteristically hazardous wastewater must be addressed. Third, the court held that dilution was not an acceptable means of treating hazardous constituents because it did not remove, destroy, or immobilize hazardous constituents.

This decision would have far-reaching implications for operators of Class I nonhazardous wells because a large number of these wells inject decharacterized wastewaters (e.g., wastewaters rendered nonhazardous through treatment or commingling with other wastewaters). These operators would have to reduce the UHCs to treatment standard levels through source reduction and waste segregation and remove the characteristic which rendered the waste hazardous.

Phase II and III Rulemakings

EPA published the Phase II LDR rule in September 1994. It established concentration-based "universal treatment standards" (UTS) for 216 characteristic and listed wastes. The UTS simplified treatment standards by setting uniform constituent concentration levels across all types of wastes and replacing concentration standards, which could vary based on the type of waste containing the constituents. These technology-based UTS may eventually be superseded, or capped, by the proposed risk-based exit levels in the Hazardous Waste Identification Rule (HWIR) (60 *FR* 66344, December 21, 1995).

In the Phase III Rule, as proposed in March 1995, the Agency suggested that Class I operators could segregate their characteristically hazardous wastes and treat just that volume of the wastewater to treatment standard levels in order to meet the treatment requirements. However, a number of commenters on the proposed rule indicated segregation was both technically and economically impractical due to the way wastewater is handled at Class I facilities. Commenters also noted that segregation and treatment could pose greater human health risks than underground injection. The other alternatives available to these operators were to seek a no-migration variance, apply for a case-by-case capacity variance (in addition to an existing national capacity variance), or reduce mass loadings of hazardous constituents by instituting pollution prevention measures.

On March 26, 1996, President Clinton signed the Land Disposal Program Flexibility Act. In effect, this legislation put back in place the approach adopted by EPA in the Third-Thirds rule of 1990 on the disposal of decharacterized wastewater. The new legislation stated, in essence, that hazardous wastes which are hazardous only because they exhibit a characteristic are not prohibited from Class I nonhazardous well disposal if they no longer exhibit the characteristic at the point of injection. The characteristic can be removed by any means, including dilution or other deactivation through aggregation of different wastewaters. Operators of Class I nonhazardous wells do not, therefore, have to identify and treat underlying hazardous constituents. Nonhazardous Class I facilities injecting decharacterized wastewater would not be reclassified as hazardous and would not have to make no-migration demonstrations or treat underlying hazardous constituents in order to keep injecting these wastes. The legislation also called for a study, to be completed within 5 years of the Act's passage, which would assess the risks of land disposal and Class I underground injection of decharacterized wastes.

The final Phase III LDR rule, published in April 1996, implemented the Land Disposal Program Flexibility Act by narrowing the applicability of UTS to decharacterized wastewaters managed in Class I wells. The Phase III rule also addressed issues related to small quantity generators by establishing a *de minimis* volume exclusion. Under this approach, Class I operators could continue injecting small volumes of characteristically hazardous wastewaters when mixed with a greater volume of nonhazardous waste. Class I facility wastewaters that meet the *de minimis* standard must have hazardous waste constituent concentrations of less than 10 times the established UTS at the point of generation. In addition, the facility's hazardous wastewater must account for less than 1 percent of the total flow at the point of injection and after commingling with the nonhazardous streams. Finally, the total volume of the hazardous streams must be no more than 10,000 gallons per day.

Phase IV Rulemaking

EPA published the Phase IV LDR rule on May 12, 1997 and May 26, 1998, establishing treatment standards and land disposal restrictions for wood preserving, toxicity characteristic metals, and mineral processing wastewaters. EPA estimated that the economic impact of restricting these wastes from disposal in Class I wells is minimal. Although the annual volume of Phase IV wastes is small, treatment capacity is not readily available or applicable because Phase IV wastes are process wastes injected on-site. Meeting no-migration demonstrations or other proposed management options may be difficult for most facilities at this time. A 2-year capacity variance has been granted to deal with the lack of treatment capacity.

II. Technology Summary

Injection engineering technology, regional and local geologic characterization, and site-specific mathematical modeling are combined to ensure that injected fluids from Class I wells travel to their intended location safely away from USDWs, and remain there for as long as they pose a risk to human health or the environment.

II.A Injection Well Technology

Class I wells are designed and constructed to prevent the movement of injected wastewaters into USDWs. Wells typically consist of three or more concentric layers of pipe: surface casing, long string casing, and injection tubing.[8] Exhibit 3 shows the key construction elements of a typical Class I well.

The well's **casing** prevents the borehole from caving in and contains the tubing. It typically is constructed of a corrosion-resistant material such as steel or fiberglass-reinforced plastic. **Surface casing** is the outermost of the three protective layers; it extends from the surface to below the lowermost USDW. The **long string casing** extends from the surface to or through the injection zone. The long string casing terminates in the injection zone with a screened, perforated, or open-hole **completion**, where injected fluids exit the tubing and enter the receiving formation. The well casing design and materials vary based on the physical and chemical nature of injected and naturally occurring fluids in the rock formation, as well as the formation's characteristics. The wastewater must be compatible with the well materials that come into contact with it. Cement made of latex, mineral blends, or epoxy is used to seal and support the casing.

The characteristics of the receiving formation determine the appropriate well completion assembly—a perforated or screen assembly is appropriate for unconsolidated formations such as sand and gravel, while an open-hole completion is used in wells that inject into consolidated sandstones or limestone.

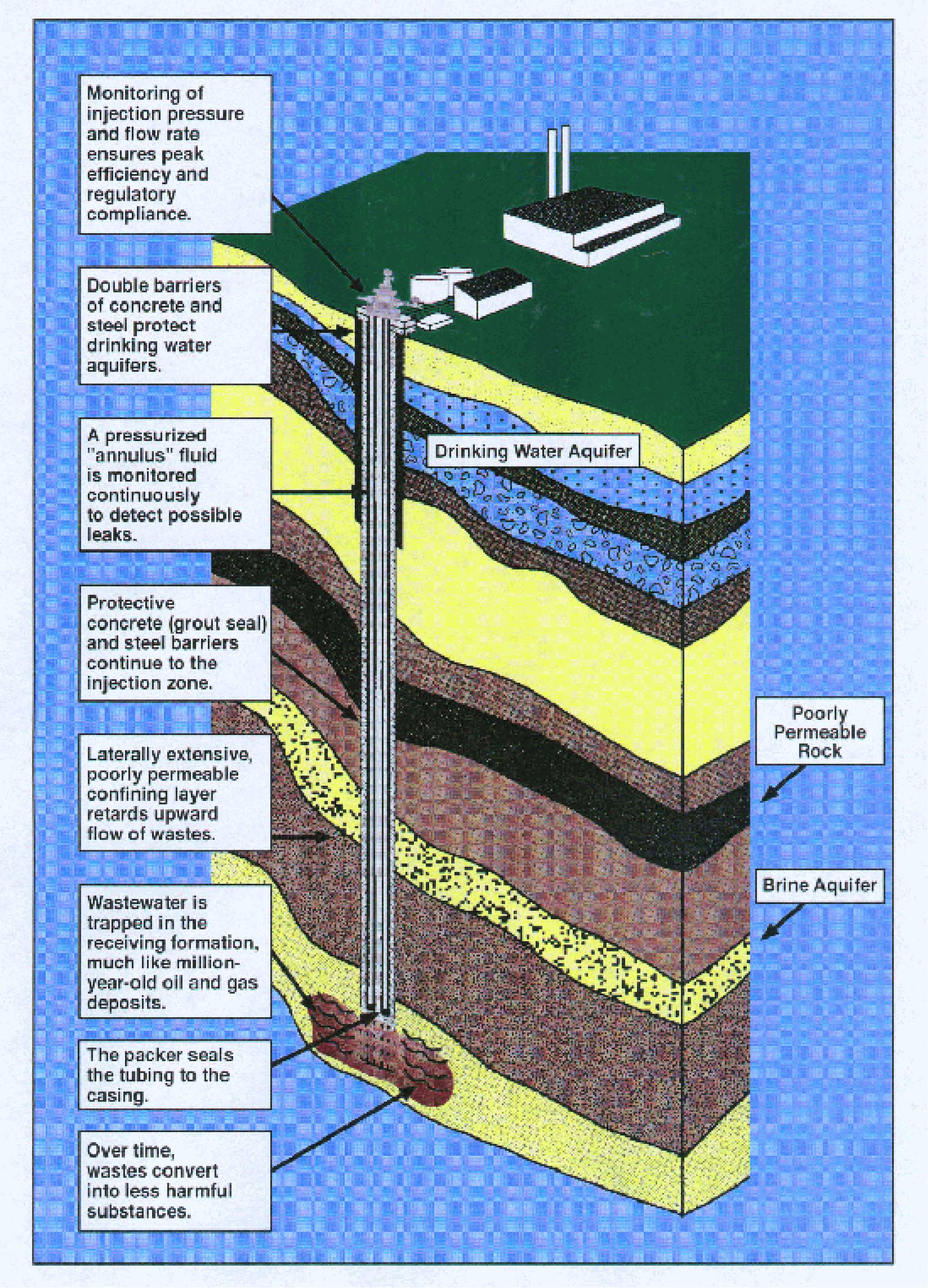
The innermost layer of the well, the **injection tubing**, conducts injected wastewater from the surface to the injection zone. Because it is in continuous contact with wastewater, the tubing is constructed of corrosion-resistant material (e.g., steel and high-nickel alloys, fiberglass-reinforced plastic, coated or lined alloy steel, or more exotic elements such as zirconium, tantalum, or titanium).

The annular space between the tubing and the long string casing, sealed at the bottom by a packer and at the top by the wellhead, isolates the casing from injected wastewater and creates a fluid-tight seal. The **packer** is a mechanical device set immediately above the injection zone that seals the outside of the tubing to the inside of the long string casing. The packer may be a simple mechanically set rubber device or a complex concentric seal assembly. Constant pressure is maintained in the annular space; this pressure is continuously monitored to verify the well's mechanical integrity and proper operational conditions.

[8] All three layers are required of Class I hazardous wells [40 CFR 146.65(c)].

Exhibit 3

A Typical Class I Injection Well



II.B Geologic Siting

In addition to the multiple safeguards of the injection well design, the geologic properties of the subsurface around the well offer a final safeguard against the movement of injected wastewaters to a USDW. Class I wells are sited so that, should any of their components fail, the injected fluids would be confined to the intended subsurface layer.

Class I wells inject into zones with the proper configuration of rock types to ensure that they can safely receive injected fluids. The geological formation into which the wastewaters are injected is known as the **injection zone**. Extensive pre-siting geological tests confirm that the injection zone is of sufficient lateral extent and thickness and is sufficiently porous and permeable so that the fluids injected through the well can enter the rock formation without an excessive build up of pressure and possible displacement of injected fluids outside of the intended zone. The injection zone is overlain by one or more layers of relatively impermeable rock that will hold injected fluids in place and not allow them to move vertically toward a USDW; this rock layer(s) defines the **confining zone**. Confining zones are typically composed of shales, which are "plastic," meaning they are less likely to be fractured than more brittle rocks, such as sandstones.

Class I fluids are injected deep into the earth into brine-saturated formations or non-freshwater zones. The typical Class I well injects wastewaters into geologic formations thousands of feet below the land surface. In the Great Lakes region, injection well depths typically range from 1,700 to 6,000 feet; in the Gulf Coast, depths range from 2,200 to 12,000 feet or more. Fluids at these depths move very slowly, on the order of a few feet per hundred or even thousand years, meaning that fluids injected into the deep subsurface are likely to remain confined for a long time.

Class I hazardous wells are located in geologically stable areas. The operator of a well must demonstrate that there are no transmissive fractures or faults[9] in the confining rock layer(s) through which injected fluids could travel to drinking water sources. Well operators also must show that there are no wells or other artificial pathways between the injection zone and USDWs through which fluids can travel. EPA regulations prevent Class I hazardous wells from being sited in areas where earthquakes could occur and compromise the ability of the injection zone and confining zone to contain injected fluids.

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[9] A transmissive fracture or fault is one that has sufficient permeability and vertical extent to allow movement of fluids between formations.

II.C Class I Well Risks

There are two potential pathways through which injected fluids can migrate to USDWs: (1) failure of the well or (2) improperly plugged or completed wells or other pathways near the well. EPA's extensive technical requirements for Class I wells are designed to prevent contamination of USDWs via these pathways.

Well Failure

Contamination due to well failure is caused by leaks in the well tubing and casing or when injected fluid is forced upward between the well's outer casing and the well bore should the well lose mechanical integrity (MI). **Internal mechanical integrity** is the absence of significant leakage in the injection tubing, casing, or packer. An internal mechanical integrity failure can result from corrosion or mechanical failure of the tubular and casing materials. **External mechanical integrity** is the absence of significant flow along the outside of the casing. Failure of the well's external mechanical integrity occurs when fluid moves up the outside of the well due to failure or improper installation of the cement. To reduce the potential threat of well failures, operators must demonstrate that there is no significant leak or fluid movement through channels adjacent to the well bore before the well is issued a permit and allowed to operate. In addition, operators must conduct appropriate mechanical integrity tests (MITs) every year (for hazardous wells) and every 5 years (for nonhazardous wells) thereafter to ensure the wells have internal and external MI and are fit for operation. It is important to note that failure of an MIT, or even a loss of MI, does not necessarily mean that wastewater will escape the injection zone. Class I wells have redundant safety systems to guard against loss of waste confinement (see section III.A for further discussion).

Pathways for Fluid Movement in the Area of Review

The **Area of Review** (AoR) is the zone of endangering influence around the well, or the radius at which pressure due to injection may cause the migration of the injectate and/or formation fluid into a USDW. Improperly plugged or completed wells that penetrate the confining zone near the injection well can provide a pathway for fluids to travel from the injection zone to USDWs. These potential pathways are most common in areas of oil and gas exploration. Because the geologic requirements for Class I hazardous injection activities are similar to those for oil and gas exploration, these activities often take place in the same areas. EPA estimates that there may be as many as 300,000 abandoned wells and 100,000 producing wells potentially in the AoRs of Class I injection wells.

To protect against migration through this pathway, wells that penetrate the zone affected by injection pressure must be properly constructed or plugged. Before injecting, operators must identify all wells within the AoR that penetrate the injection or confining zone, and repair all wells that are improperly completed or plugged before a permit is issued.

Fluids could potentially be forced upward from the injection zone through transmissive faults or fractures in the confining beds which, like abandoned wells, can act as pathways for waste migration to USDWs. Faults or fractures may have formed naturally prior to injection or may be created by the waste dissolving the rocks of the confining zone. Artificial fractures may also be created by injecting wastewater at excessive pressures. To reduce this risk, injection wells are sited such that they inject below a confining bed that is free of known transmissive faults or fractures. In addition, during well operation, operators must monitor injection pressures to ensure that fractures are not propagated in the injection zone or initiated in the confining zone.

II.D Introduction to Modeling

Site-specific modeling of wastewater migration is the foundation of a no-migration demonstration that hazardous wastewaters will remain in the injection zone for as long as they remain hazardous. Models are also the basis on which the requirements for hazardous and nonhazardous waste disposal were developed. A long-term analysis is the only way to know with absolute certainty what will happen to injected fluids; however this is impractical, given the time frames involved in movement of deep-injected fluids. The purpose of modeling is to provide long-term prediction of the extent of injected wastewater migration at great depths and demonstrate, using conservative assumptions, that the wastewater will remain contained or rendered nonhazardous. Modeling is based on rigorous science, and models are well-established scientific tools. All of the models on which studies and no-migration petitions are based are accepted by the scientific and regulatory communities.

The modeling process has several components: the conceptual model, the mathematical model or equations, and the numerical model or computer code used to solve the equations. In general, modeling is a conceptual representation, using simplifying assumptions about the injection well, the surrounding formation, and well operations. The mathematical model involves equations to represent the conservation of mass and momentum. The equations simulate fluid pressure and chemical or constituent concentration levels changes over time. Because of the difficulty in measuring the slow movement of fluids over long time periods (i.e., 10,000 years at great depths), the injection and emplacement of the wastewater is modeled mathematically using complex computer simulations.

The conceptual model is a simplified representation of the geologic strata in the vicinity of the injection well. It is envisioned that the well operations include wastewater injection operations, based on both the actual operational history of the site and future injection conditions. In addition, the model includes a post-operation period of 10,000 years in which the wastewater will migrate from the point of emplacement in the injection zone. Several processes are considered in the conceptual model, including pressure build-up, fluid displacement, mixing or dispersion of the injected wastewater and the native formation fluids, and fluid density differences.

Mathematical models are used to simulate the injection and migration of fluids within the injection zone. These models include fluid flow and dissolved contaminant transport within geologic materials using mathematical expressions based on the physical principles associated with the geology and the native (*in situ*) and injected fluids. Within the model, the injection zone and the confining zone are defined by subdividing the region into series of adjoining "cells." The lateral extent of the model is often several miles wide. The cells or blocks are defined in order to segment the region both vertically and laterally. Each cell within the modeled region has defined geologic parameters and fluid properties including permeability, porosity, compressibility, dispersivity, fluid density and viscosity. The mathematical models solve for the fluid pressure and chemical concentration. Realistic modeling requires considerable knowledge about the fluid properties of the injectate and the physical properties of the rock formation, all of which serve as inputs to the model. It is also possible to mathematically simulate chemical interactions between the injected fluids, the native fluids, and the geologic formation. More complex models also include a representation of the complex geologic structure through a series of surface and subsurface maps.

The models or computer codes are used to simulate the effects of injecting fluids at some initial time into one or more of the cells and predict the flow and chemical concentration transferred from cell to cell over an extended period of time. Many calculations take place in the model. At each time step (i.e., from the start of the injection operations to 10,000 years), the model must track the new amount of wastewater injected, the flow and chemical flux into adjacent cells, and the subsequent flow and chemical flux from cell to cell. There may be thousands of cells in a model, and the flow and chemical flux must be calculated for every side of each cell. The model tracks the mass of the fluids, the fluid density and viscosity, chemical concentrations, and temperature of rock and water within every cell at specified times.

Models are constructed based on field observations and measurements of downhole pressure, surface injection pressure, geophysical logs, rock cores extracted from depth, injectivity tests, pressure fall-off test, tracer surveys, injection chemical concentration, and fluid density. The process of model calibration is a fitting of the input parameters in order to match field conditions. For example, pressure fall-off tests may be analyzed using analytical tools for injection zone permeability. The values for permeability are used as inputs from one fall-off test and then compared with field observations from another test. The input parameters are then adjusted to afford the best possible match with field conditions. Conservative assumptions are embedded throughout the model construction, so that the model predicts the maximum extent of wastewater migration.

The results of the model are verified against actual data from the field (i.e., data from pressure tests, drawdown or build-up tests). Typically, model verification does not address concentration levels. Occasionally, new wells are constructed near existing injection wells, and model verification of the existing wastewater plume can be performed. Because the model is predictive over a long time scale and the geologic materials are naturally variable, a conservative model is designed to address the issue of variability in the model parameters and fluid motion within the injection zone through a series of analyses. Multiple simulations or computer runs using differing input parameters are generally performed to assess variations in the predicted outcome. Moreover, it is preferable for the models to use conservative assumptions to predict worse-case scenarios and reflect the high degree of uncertainty in the no-migration demonstrations (40 CFR 148.21). This worst-case scenario brackets the outer limits of the fluid migration within the area of investigation.

When the modeling analysis is complete, the output is typically a series of graphs and maps that depict the amount of fluid pressure increase and the concentration of the injected fluid within the injection zone. Although the conditions at the final time step (10,000 years) are the objective, it is possible to show the physical position of injected fluids at any specified time.

Numerous models or codes are based on work by the United States Geologic Survey, EPA, U.S. Department of Defense, U.S. Army Corps of Engineers, many universities and colleges, and the oil and gas industry. These are distributed commercially, and many are available for free on the Internet. The models have evolved in their complexity and ability to represent the real world, from simple displacement approaches to models incorporating molecular diffusion and variable pressure responses.

III. Options for Decharacterized Wastewaters

Under RCRA, wastewaters that demonstrate the characteristic of ignitability, corrosivity, reactivity, or toxicity are considered to be hazardous wastes.

- **Ignitable wastes** are capable of causing fire through friction at standard temperature or pressure. Ignitable wastes are produced by the organic chemical production, laboratories and hospitals, paint manufacturing, cosmetics and fragrances, pulp and paper, and construction industries.

- **Corrosive wastes** are extremely acidic or alkaline (i.e., have a pH less than or equal to 2 or greater than or equal to 12.5). The organic chemical production, laboratories and hospitals, paint manufacturing, cosmetics and fragrances, equipment cleaning, soaps and detergents, electronics manufacturing, iron and steel, and pulp and paper industries produce corrosive wastes.

- **Reactive wastes** are normally unstable wastes that react violently or form potentially explosive mixtures with water. Examples of industries that produce reactive wastes include organic chemical production and petroleum refining.

- **Toxic organic wastes** contain toxic constituents in excess of a regulatory level. They are produced by organic chemical production, petroleum refining, and waste management and refuse systems.

Characteristic hazardous wastes are identified with waste codes D001 through D043. These waste codes are used for record keeping, tracking off-site shipments, and determining the applicability of the LDR program.

Prior to disposal in a Class I nonhazardous well, hazardous wastewaters must be decharacterized (i.e., the hazardous characteristic must be removed) by any means including treatment, dilution, or other deactivation through aggregation of different wastewaters, including commingling with nonhazardous or exempt wastewaters. The Class I nonhazardous wells, into which the decharacterized wastewater is injected, must conform with all federal and state UIC regulations. The management of these wastewaters by Class I injection well operators provides a low-risk option, as will be described in the next sections of this study.

In addition, from a general analysis of data from previous studies, including databases specific to Class I nonhazardous and hazardous injection wells, EPA believes that a substantial volume of decharacterized waste is being injected into Class I hazardous wells. Facilities using Class I injection wells, including industrial, manufacturing, petrochemical, and refinery operations, will generally use their Class I hazardous wells to dispose of wastewaters from their process operations which may not be amenable to segregation. They can use their Class I hazardous wells for disposal of any wastewaters allowed by their permits, and included in their no-migration petition demonstration (permitting and no-migration petitions will also be discussed later in this study). This practice affords an even greater (though not essential) level of protection, as the Class I hazardous waste wells have additional operating, monitoring, and other redundant safety requirements beyond the already protective requirements of the Class I nonhazardous wells.

IV. Oversight of Class I Wells

This section describes how EPA oversees the Class I program. Section IV.A describes the Agency's regulations for siting, constructing, operating, monitoring and testing, and closing Class I wells. Section IV.B describes how EPA Headquarters and regions oversee Class I injection practices.

IV.A Regulations and Criteria for Class I Wells

EPA's siting, construction, operating, monitoring, and closure requirements for Class I wells provide multiple safeguards against well leakage or the movement of injected wastewaters to USDWs. The following sections describe the Class I Program regulations (40 CFR 146 and 148).

Siting Requirements

Class I wells must be sited so that wastewaters are injected into a formation that is below the lowermost formation containing, within one-quarter mile of the well, a USDW [40 CFR 146.12(a); 40 CFR 146.62(a)]. In siting Class I wells, operators must use geologic and hydrogeologic studies and studies of artificial penetrations of the injection and confining zones to demonstrate that their proposed injection will not endanger USDWs. In addition, Class I operators seeking to inject hazardous wastewaters must demonstrate via a no-migration petition that the hazardous constituents of wastewaters will not migrate from the disposal site for as long as the wastewaters remain hazardous.

Additional siting requirements are imposed on Class I hazardous wells to ensure that they are located in geologically stable (e.g., low risk of earthquakes) formations that are free of natural or artificial pathways for fluid movement between the injection zone and USDWs.

Geologic Studies

Studies of the injection and confining zones are conducted to ensure that Class I wells are sited in geologically suitable areas. Well permitting decisions are based on whether the receiving formations are sufficiently permeable, porous, and thick to accept the injected fluids at the proposed injection rate without requiring excessive pressure. The injection zone should be homogeneous. It should also be of sufficient areal extent to minimize formation pressure buildup and to prevent injected fluids from reaching aquifer recharge areas. The confining zone should be of relatively low permeability to prevent upward movement of injected materials.

For Class I hazardous wells, additional structural studies must demonstrate that the injection and confining formations in the area around the well are free of vertically transmissive fissures or faults, and that the region is characterized by low seismicity and a low probability of earthquakes. The operator must demonstrate that the proposed injection will not induce earthquakes or increase the frequency of naturally occurring earthquakes.

Injected fluids must be geochemically compatible with the well materials and the rock and fluids in the injection and confining zones. The injection zone must have no economic value (i.e., be unfit for drinking or agricultural purposes and lack dissolved minerals in economically valuable quantities).

Operators must demonstrate that the wastewater and its anticipated reaction products are compatible with both the geologic material of the injection zone and any native (naturally occurring) or previously injected fluids. Water analyses must be performed to characterize the geochemistry of the native water to predict potential interactions, and to provide a baseline to determine whether contamination has occurred.

Area of Review

The AoR, or the zone of endangering influence (the radius at which injection can affect a USDW), must be determined by either a fixed radius or mathematical computation.[10] When a fixed radius is used, the AoR for Class I nonhazardous wells and municipal wells must be, at a minimum, one-quarter mile [40 CFR 146.69(b)]; for hazardous wells, the AoR is extended to, at a minimum, 2 miles [40 CFR 146.63]. It is important to note, however, that for many Class I nonhazardous wells, the radius of the AoR studied was larger than the federally-required one-quarter mile. Seventy-six percent of the wells studied by the Underground Injection Practices Council (UIPC) had an area of review that exceeded one-quarter mile.[11] Several states require an AoR for all Class I wells that is larger than that required under the federal regulations. For example, Texas requires a minimum 2½-mile AoR; Louisiana requires a 2-mile AoR; and Florida and Kansas regulations establish a 1-mile minimum. These four states collectively account for nearly 70 percent of the Class I well inventory.

Operators must identify all wells within the AoR that penetrate the injection or confining zone, and determine whether any of these wells are improperly completed or plugged and thus could serve as pathways for migration of wastewaters. Along with the permit application, the operator must submit a corrective action plan containing the necessary steps or modifications to address improperly completed or plugged wells [40 CFR 144.55(a)]. The plan must take into account the nature of native fluids or injection byproducts, potentially affected populations, geology and hydrogeology, and the history of injection activities. Prior to commencing injection, the operator must demonstrate that all potential pathways for migration have been adequately addressed.

[10] The zone of endangering influence may be determined via computations as specified at 40 CFR 146.6 for Class I nonhazardous wells, or at 40 CFR 146.61(b) for Class I hazardous wells. For hazardous wells, the computations specified in 40 CFR 146.6 are superseded by the requirement for a 2-mile radius, at 40 CFR 146.63 (whichever is greater).

[11] Underground Injection Practices Council. *A Class I Injection Well Survey (Phase I Report): Survey of Selected Sites.* D19976.S1. Prepared by CH2M Hill, Gainesville, Florida. April 1986.

No-Migration Petition

In addition to geological and AoR studies, operators of Class I hazardous waste injection wells must demonstrate with reasonable certainty that the hazardous components of their wastewaters will not migrate from the injection zone [40 CFR 148.20].

To qualify for this exemption from the ban on disposal of certain wastes, EPA requires operators to show that the wastewaters will remain in the injection zone for as long as they remain hazardous, or that the wastes will decompose or otherwise be attenuated to nonhazardous levels before they migrate from the injection zone. A detailed hydrogeological and geochemical modeling study, known as a **no-migration petition**, may take one of the following forms:

- A **Fluid Flow Petition** demonstrating that for at least 10,000 years[12] no lateral movement to a pathway to a USDW or vertical movement out of the injection zone will occur. Petitioners must demonstrate that the strata in the injection zone above the injection interval are free of transmissive faults or fractures and that a confining zone is present above the injection interval.
- A **Waste Transformation Petition** to demonstrate that attenuation, transformation, or immobilization will render wastes nonhazardous before they migrate from the injection zone. Petitioners must demonstrate that the zone where transformation, attenuation, or immobilization will occur is free of transmissive faults or fractures and that a confining zone is present above the injection interval.

Each petition is a multi-volume complex technical analysis which describes the well construction, the injected wastewater, and the local and regional geology and hydrogeology. It relies on conservative mathematical models demonstrating that the hazardous wastewater will not migrate from the injection zone into USDWs. Once a no-migration petition is approved, an operator may inject only those wastes that are listed in the petition. (See section II.D for a description of the modeling for no-migration petitions.)

Preparing a no-migration petition is a lengthy process which typically costs $300,000 and requires up to 11,000 hours of technical work by engineers, computer modelers, geochemists, geologists, and other scientists. Factoring in the cost of necessary geological testing and modeling, no-migration petitions can cost in excess of $2 million.

[12] The 10,000-year standard is considered sufficiently long to ensure that the no-migration standard would be met, and short enough to be within the abilities of predictive models. [NRDC v EPA, 907 F.2d at 1158 .]

Summary of Siting Requirements[13]	
Hazardous Wells	Nonhazardous Wells
• 2-mile AoR study performed. • No-migration petition demonstration required. • Sited in demonstrated geologically-stable areas. • Additional geologic structural and seismicity studies performed.	• ¼-mile AoR study performed (a larger AoR study may be conducted if required by state regulations). • Sited in demonstrated geologically-stable areas.

Construction Requirements

EPA requires that Class I wells be designed and constructed to prevent the movement of injected wastewaters into USDWs. Construction requirements for Class I nonhazardous wells and municipal wells are set forth at 40 CFR 146.12; construction requirements for hazardous wells are specified at 40 CFR 146.65 and 40 CFR 146.66. These requirements specify the multi-layer design of Class I wells, as described in section II.A.

During the permit application process, the permitting authority reviews and approves engineering schematics and subsurface construction details. The design of the casing, tubing, and packer must be based on the depth of the well; the chemical and physical characteristics of the injected fluids; injection and annular pressure; the rate, temperature, and volume of injected fluid; the size of the well casing [40 CFR 146.12(c)(2)]; and cementing requirements (40 CFR 146.65). Any changes to the proposed design during construction must be approved before being implemented.

During well construction, operators conduct deviation checks at sufficiently frequent intervals to ensure that there are no diverging holes which would allow vertical migration of fluids. Other logs and tests (e.g., resistivity or temperature logs) also may be required during construction. EPA or the permitting authority may witness portions of construction activities.

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[13] Decharacterized waste is injected into Class I nonhazardous wells (although it may be injected into both hazardous and nonhazardous wells). Requirements for both Class I hazardous and nonhazardous wells are presented in this report for comparison and to provide a complete portrayal of the UIC Program. It should be noted that some states impose some of the federal Class I hazardous well requirements on nonhazardous wells.

Summary of Construction Requirements	
Hazardous Wells	Nonhazardous Wells
• Well is cased and cemented to prevent movement of fluids into USDWs. • Detailed requirements for appropriate tubing and packer. • UIC Program director must approve casing, cement, tubing and packer design prior to construction.	• Well is cased and cemented to prevent movement of fluids into USDWs. • Constructed with tubing and packer appropriate for injected wastewater.

Operating Requirements

EPA's operating requirements for Class I wells provide multiple safeguards to ensure that injected wastewater is fully confined within the injection zone and the integrity of the confining zone is never compromised. At a minimum, all Class I wells must be operated so that injection pressures will not initiate new fractures or propagate existing fractures after initial stimulation of the injection zone during well construction.

The annular space between the tubing and the long string casing must contain approved fluids only and permitted pressures must be maintained.[14] Class I hazardous wells are subject to additional or more explicit permitting requirements and operating standards related to annular monitoring parameters and continuous demonstration of mechanical integrity.[15]

Class I hazardous wells must be equipped with continuous monitoring and recording devices that automatically sound alarms and shut-in the well whenever operating parameters related to the injection pressure, flow rate, volume, temperature of the injected fluid, or annular pressure exceed permitted ranges.[16] When this occurs, the owner or operator must cease injection; notify the Director within 24 hours; and identify, analyze, and correct the problem. Operators of Class I wells are required to notify the UIC Program Director and obtain approval before performing

[14] 40 CFR 146.13 (a).

[15] 40 CFR 146.67 (a) to (e).

[16] 40 CFR 146.67 (f), (g), and (j).

any workover or major maintenance on the well.[17] The operator may resume injection only upon approval of the Director.

Summary of Operating Requirements	
Hazardous Wells	Nonhazardous Wells
• Continuously monitor injection pressure, flow rate, and volume. • Install alarms and devices that shut-in the well if approved injection parameters are exceeded. • Maintain injection at pressures that will not initiate new fractures or propagate existing fractures.	• Continuously monitor injection pressure, flow rate, and volume. • Maintain injection at pressures that will not initiate new fractures or propagate existing fractures.

Monitoring and Testing Requirements

Operators of Class I wells must monitor and test for mechanical integrity, containment within the injection zone, and characteristics of the injected wastewater. They must also monitor USDWs within the AoR for indications of fluid migration and pressure changes indicating a potential for contamination.[18]

Class I well operators must continuously monitor injection pressure, flow rates and volumes, and annular pressure.[19] Monitoring requirements for Class I hazardous wells have explicit procedures for reporting and correcting problems related to a lack of mechanical integrity or evidence of wastewater injection into unauthorized zones. In addition to monitoring the well operation, operators of hazardous wells are required to develop and follow a waste analysis plan for monitoring the physical and chemical properties of the injected wastewater.[20] The frequency of these analyses depends on the parameters being monitored. Complete analysis of the injected wastewaters must be conducted at frequencies specified by the plan or when process or operating changes affect the characteristics of the wastewater.

[17] 40 CFR 146.67 (j).

[18] 40 CFR 146.13 (b) (4).

[19] 40 CFR 146.13 (b).

[20] 40 CFR 146.68 (a).

Operators of Class I hazardous wells must perform tests to demonstrate that the wastewater's characteristics remain consistent and compatible with well materials with the wastewater.[21]

Periodic testing of all Class I wells also is required.[22] The operator must develop a monitoring program that includes, at minimum, an annual pressure fall-off test in addition to an internal MIT every year and an external MIT every 5 years. (Texas and Michigan require external MITs every year.)

Class I operators must conduct tests to demonstrate that their wells have internal and external mechanical integrity.[23] Every year, operators of Class I hazardous wells must demonstrate internal mechanical integrity by conducting an approved pressure test to inspect the long string casing, injection tubing, and annular seal, as well as an approved radioactive tracer survey (RTS) or Oxygen Activation Log (OAL)[24] to examine the bottom hole cement. Operators of Class I nonhazardous wells must demonstrate internal MI every 5 years. Every 5 years, all Class I well operators must demonstrate external MI using noise, temperature, or other approved logs to test for fluid movement along the borehole. Casing inspection logs or noise, temperature, or other approved logs are also required when a well workover is conducted, or if the Director believes that the long string casing lacks integrity.

An internal or external MI failure does not imply failure of the injection well or loss of wastewater confinement. These are simply indicators that one of several protective layers in the injection well system has malfunctioned. As long as the other protective elements are intact, wastewaters would be contained within the injection system.

UIC regulations authorize the use of monitoring wells in the AoR to monitor fluids and pressure. Monitoring wells can be used to supplement required injection and pressure monitoring if needed. The location, target formation, and the types of monitoring wells should

[21] 40 CFR 146.68 (c).

[22] 40 CFR 146.13 (d) and 40 CFR 146.68 (e).

[23] 40 CFR 146.13 (b) and 146.68 (b).

[24] The OAL has been approved as an alternative to the RTS to test for movement of fluids between the casing and the well bore. Case studies by EPA Region 6 indicate that the RTS and the OAL are equally effective in identifying channels behind the casing, which are in hydraulic communication with the injection zone. The OAL is a preferred method where channeling is not in hydraulic communication with the injection interval. EPA Region 6 has also requested the use of the OAL to increase confidence in MIT results.

be based on potential pathways of contaminant migration. Monitoring within the USDW can provide geologic data or evidence of contamination.[25]

Summary of Monitoring and Testing Requirements	
Hazardous Wells	Nonhazardous Wells
• Follow approved waste analysis plan. • Conduct internal MIT every year and external MIT every five years. • Monitoring wells to supplement required monitoring are authorized.	• Conduct internal and external MITs every 5 years. • Monitoring wells to supplement required monitoring are authorized.

Reporting and Record Keeping Requirements

All Class I well operators must report the results of required monitoring and testing to the state or EPA UIC Director. Class I hazardous well operators must report quarterly on monitoring results and annually on the results of radioactive tracer surveys, casing pressure tests, ambient monitoring, and pressure fall-off tests. They must also report any changes to closure plans, including updates to plugging and abandonment cost estimates.

All Class I operators must report on the physical, chemical, and other relevant characteristics of injected fluids; monthly average, maximum, and minimum values for injection pressure, flow rate, volume, and annular pressure; and monitoring results of USDWs in the AoR.[26] MIT results, other required tests, and any well workovers must be reported in the next quarterly report following the tests or workovers.

Quarterly reports on Class I hazardous wells must also identify the maximum injection pressure for the quarter, any event that exceeds permitted annular or injection pressure, any event that triggers an alarm or shutdown from the continuous recording device, the total volume of fluid injected, any change in the annular fluid volume, results from the waste analysis program, and geochemical compatibility information.[27]

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[25] Warner, D. L. "Monitoring of Class I Injection Wells." In: *Deep Injection Disposal of Hazardous and Industrial Waste: Scientific and Engineering Aspects*. John A. Apps and Chin-Fu Tsang, eds. San Diego, California: Academic Press. 1996.

[26] 40 CFR 146.13 (c).

[27] 40 CFR 146.69.

In states where EPA administers the UIC program, the Regional Administrator may require operators to submit additional information, if needed to determine if a well poses a hazard to USDWs. Such information may include evidence of groundwater monitoring and periodic reports of such monitoring, periodic reports on analysis of injected fluids, and a description of the geologic strata through and into which injection is taking place.

In addition, all operators must notify the permitting authority of planned changes to the facility, changes that may result in noncompliance, progress in meeting the milestones of a compliance schedule, any loss of mechanical integrity or other indication of possible endangerment of a USDW (within 24 hours), and any noncompliance with permit conditions.

Summary of Reporting and Record Keeping Requirements	
Hazardous Wells	Nonhazardous Wells
• Report quarterly on injection and injected fluids and monitoring of USDWs in the AoR; results from the waste analysis program; and geochemical compatibility. • Report on internal MIT every year and external MIT every 5 years. • Report any changes to the facility, progress in meeting the milestones of a compliance schedule, loss of MI, or noncompliance with permit conditions.	• Report quarterly on injection and injected fluids and monitoring of USDWs in the AoR. • Report every 5 years on internal and external MITs. • Report any changes to the facility, progress in meeting the milestones of a compliance schedule, loss of MI, or noncompliance with permit conditions.

Closure Requirements

Upon closing their wells, operators must submit a plugging and abandonment report indicating that the well was plugged in accordance with the plugging and abandonment plan (submitted when the well was permitted). Plan requirements and subsequent closure reporting requirements are specified in greater detail for hazardous wells than for nonhazardous wells.

Class I hazardous well operators must also conduct pressure fall-off and mechanical integrity tests, and report the results in their closure reports. The well must be flushed with a non-reactive fluid. Each cement plug must be tagged and tested for seal and stability before the closure is completed.[28] In addition, Class I hazardous well operators are required to continue and complete outstanding clean-up actions, and continue groundwater monitoring until pressure in

[28] 40 CFR 146.71.

the injection zone decays to the point where no potential for influencing the USDW exists. They must also notify and provide appropriate information to local and state authorities regarding the well, its location, and its zone of influence at closure.[29]

Summary of Closure Requirements	
Hazardous Wells	Nonhazardous Wells
• Flush well with a non-reactive fluid; tag and test each cement plug. • Conduct pressure fall-off test and MIT. • Submit plugging and abandonment report. • Complete outstanding clean-up actions; continue groundwater monitoring until injection zone pressure can not influence USDW. • Inform authorities of the well, its location, and zone of influence.	• Flush well with a non-reactive fluid; tag and test each cement plug. • Submit plugging and abandonment report.

IV.B How EPA Administers the Class I UIC Program

Class I wells are regulated under the SDWA to ensure protection of USDWs. Class I hazardous wells also are regulated under RCRA and HSWA. They are subject to the ban on land disposal of certain wastes, unless owners/operators of these wells demonstrate via a no-migration petition that the wastewaters will not migrate from the injection zone for 10,000 years or as long as they remain hazardous.

EPA authorizes state agencies to regulate Class I wells, provided that the state meets requirements specified under section 1422 of the SDWA. States that receive primary regulatory and enforcement responsibility are referred to as primacy states. EPA regional offices administer the UIC program for tribes[30] and in states that do not have primacy authority, commonly referred to as direct implementation (DI) states.

[29] 40 CFR 146.72.

[30] There are no Class I wells on Indian lands.

Operators in primacy states submit data to the primacy agency, and the primacy agencies forward this information to the regions. Operators in DI states submit data directly to the EPA region. The regions forward appropriate information to EPA Headquarters.

EPA Headquarters' Management of the National Program

EPA Headquarters is responsible for performing a variety of rulemaking activities, as well as other analytical and oversight functions, for the UIC program. Headquarters UIC staff coordinate with the EPA Office of Solid Waste on LDR rulemaking efforts. In connection with these efforts, Headquarters staff conduct independent economic analyses and regulatory impact analyses (RIAs) of the potential costs and benefits of proposed rules.

EPA Headquarters uses information from the regions to respond to information requests and to perform analyses for EPA management, the Office of Management and Budget, Congress, and the public. In addition, Headquarters uses information submitted by primacy agencies via the UIC program's 7520 reporting forms to track, evaluate, and report on state performance. Headquarters establishes and tracks performance targets and measures for EPA regional programs. EPA Headquarters also assesses the effectiveness of existing regulatory requirements, using state and regional information to justify future program modifications.

Headquarters compiles and analyzes Class I well information on a national basis, through efforts such as the 1996 Class I UICWELLS database. This database contains detailed well-specific data, such as geology, waste characteristics, and injection volumes. Headquarters uses the database to analyze the potential impacts of proposed rules on the Class I community.

Regional Oversight of Primacy Programs

The regions develop operating budgets and program plans, allocate resources, track state-by-state performance, and respond to inquiries. The regions are responsible for reviewing and verifying information before forwarding it to EPA Headquarters.

EPA's regions oversee the primacy agencies using quarterly, semi-annual, and annual reports submitted by the states. The information is used to track state progress against commitments and to ensure that state programs can take timely and appropriate action in response to threats to public health from contaminated USDWs.

Regions use well-specific information to track state enforcement actions against facilities that are significant noncompliers—violators most likely to contaminate USDWs. Regions may initiate federal enforcement action jointly with a primacy state, at the request of the state, or where a state does not fulfill its enforcement responsibilities.

EPA's regions are also responsible for reviewing all no-migration petitions associated with Class I hazardous wells. Each no-migration petition must be submitted to the Regional Administrator.[31] In reviewing no-migration petitions, EPA expects to gain valuable experience and information which may affect future land disposal restrictions.

Regional staff work closely with well operators throughout the petition development process. Several technical staff members may review a single petition and may take a year or more to determine whether it should be approved. Each part of a petition is reviewed by a specialist. For example:

- An engineer or geologist reviews information about the construction, operation, maintenance, and compliance history of the well; local and regional geology and seismology; and the compatibility of the wastewater with the well materials and the injection and confining zone rock and fluids.
- A modeling expert evaluates the accuracy of the model's predictions compared to actual conditions at the site. The modeler has to verify that the model takes into account all significant processes that affect waste mobility and transformation, is sensitive to subsurface processes, and has been properly validated and calibrated.

The petition is subject to public notice and comment. EPA publishes a draft notice of its decision to approve or deny the petition, offers a public hearing, develops a fact sheet or statement of basis, and responds to all comments. Notice of the final decision on a petition is published in the *Federal Register*.

Direct Implementation of State Programs

In addition to their oversight responsibilities, EPA regional offices implement the UIC program on tribal lands and in states without primacy. In these DI states, EPA regional offices review permit applications to ensure that proposed wells are properly sited and designed. Following permit approval and well completion, the regions use monitoring and testing reports submitted by operators to determine if the well has mechanical integrity. EPA regions are also responsible for reviewing no-migration petitions for Class I hazardous wells in DI states.

DI programs also use information submitted by operators to focus efforts on injection wells that require enforcement action. Operators who have been out of compliance for at least two consecutive quarters are identified and targeted for enforcement action.

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[31] 40 CFR 268.6.

V. Risk Associated with Class I Wells

Early failures associated with Class I injection such as those at Hammermill Paper Company and Velsicol Chemical Company (described in section I.B), illustrated the potential threats of wastewater injection and the need for and importance of the UIC regulations.

The 1980 UIC regulations address many of these risks. Since passage of the regulations, EPA and other organizations have conducted numerous studies of hazardous and nonhazardous Class I wells which demonstrate that such failures are unlikely to occur. The following sections describe these studies. These reports are described in greater detail in the annotated bibliography at the end of this study report.

V.A Studies of the Effectiveness of the UIC Regulations

Early studies by EPA and other organizations looked at potential operational problems for Class I wells. Many of the failures documented in these studies were the result of historic practices that are no longer acceptable under the promulgated UIC regulations.

Underground Injection Practices Council and General Accounting Office Studies

In the mid-1980s, UIPC, presently the Ground Water Protection Council (GWPC), and the General Accounting Office (GAO) conducted studies which described past Class I well malfunctions in the United States and discussed how current Class I regulations would minimize the possibility of failures. In April 1986, UIPC published a study that provided comprehensive data on the operation and performance characteristics of Class I injection wells.[32] The study included case histories of Class I well sites or facilities with reported histories of operational problems. A 1987 GAO study focused on Class I failures resulting in aquifer contamination.[33] GAO reviewed the cause of each incident to determine whether regulations in place would have prevented it.

The UIPC study identified malfunctions at 26 facilities, involving 43 wells, suggesting an overall well malfunction rate of approximately 9 percent of the 500 Class I wells reported to exist at the time. Only six wells, or 2 percent of all Class I wells, experienced malfunctions resulting in leakage into a USDW. The 1987 GAO study reported only two cases of drinking

[32] Underground Injection Practices Council. *A Class I Injection Well Survey (Phase I Report): Survey of Selected Sites.* D19976.S1. Prepared by CH2M Hill, Gainesville, Florida. April 1986.

[33] U.S. General Accounting Office. *Hazardous Waste–-Controls Over Injection Well Disposal Operations*. 1987.

water contamination from Class I wells, one case of suspected contamination, and eight documented cases of non-drinking water aquifer contamination.[34]

At most of the facilities in the UIPC study where well malfunctions occurred and all of the cases in the GAO study, failing wells had been constructed and injection had commenced prior to the implementation of the 1980 UIC standards. Most of the malfunctions reported in the UIPC study were related to design, construction, or operating practices that are no longer allowed under UIC regulations. Examples of the various malfunction scenarios include the following:

Leaks in the injection well casing caused movement of wastewaters into a USDW at four facilities. The leaks were detected either through annular monitoring or separate monitoring wells. These leakages were attributed to defects in well construction that would not have been allowed under the 1980 UIC regulations.

Excessive injection pressure or hydraulic surges causing a blowout at the wellhead or surface piping, leading to contamination at the surface, was documented in the UIPC study. UIC requirements for siting wells to limit the need for excessive injection pressures and pressure monitoring requirements would have prevented such incidents.

The presence of improperly abandoned wells was cited as a factor in contamination at the surface in the UIPC study. Required AoR studies would have detected these pathways and, under UIC regulations, they would have been plugged prior to any allowed injection.

Leaking packer assemblies were the most likely cause of leakage into an unpermitted non-drinking water zone. This was the most commonly documented malfunction in the UIPC study, at 17 facilities involving 29 wells. Such leaks allow wastewater to come into contact with the protective well casing, causing corrosion. Under current UIC regulations, the packer design must meet EPA approval based on the chemical and physical characteristics of the injected fluids, as well as the rate, temperature, and volume of injected fluid.

Corrosion of the casing or tubing was suspected as the cause of leakage of injected fluids documented in the GAO study. In one case, corrosion caused the tubing to separate, resulting in a blowout and waste spillage at the surface. UIC requirements stipulate that the well casing be constructed of a corrosion-resistant material and that the wastewater be compatible with the well materials which come into contact with it.

[34] The incidents described in the GAO report may also be included in the UIPC study; at least the two incidents of drinking water contamination are described in both reports.

Injection directly through the casing, without packer and tubing, was the primary cause of two cases of drinking water contamination from Class I wells. This practice is not allowed under UIC regulations: current safety features include double casing and cementing to below the base of the drinking water zone.

All of the wells in the UIPC study that experienced serious malfunctions were removed from service and plugged, repaired, and returned to service, or repaired and converted to monitoring wells as part of ongoing injection operations or to monitor water quality in the USDW. Both studies reported that aquifer restoration was initiated at the facilities where a USDW or non-drinking water aquifer was contaminated. Remedial activities included installation of monitoring wells, groundwater recovery systems, and excavation of contaminated soils.

The OSWER Report

The EPA Office of Solid Waste and Emergency Response (OSWER) prepared a study which evaluated the relative risks posed by many waste management practices.[35] The study found that, based on acute and chronic health risks and other health risks (such as cancer risks), groundwater sources affected, welfare effects, and ecological risks, Class I hazardous wells are safer than virtually any other waste disposal practice.

EPA Analysis of Class I MI Failures

EPA analyzed trends of all nonhazardous and hazardous Class I MI failures, in selected states, from 1988 to 1991.[36] This report assessed the number of these Class I injection failures during the period, analyzed the causes of these MI failures, and identified EPA and state responses to them. EPA studied more than 500 Class I nonhazardous and hazardous wells in 14 states and identified the following:

- From 1988 to 1991, 130 cases of internal MI failures (leakage in the injection tubing that can result from corrosion or mechanical failure of the tubular materials) were reported. All of these internal MI failures were detected during well operation by the continuous annulus monitoring systems or by MITs. The wells were shut-in until they were repaired. Of these MI failures, 42 percent occurred in the tubing and 23 percent involved the long string casing.

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[35] U.S. EPA, Office of Solid Waste and Emergency Response. *OSWER Comparative Risk Project: Executive Summary and Overview*. EPA/540/1-89/003. November 1989.

[36] U.S. EPA, Office of Ground Water and Drinking Water, Underground Injection Control Branch. *Class I Well Failure Analysis: 1988-1991*. March 1993.

- One external MI failure (flow along the outside of the casing) occurred. It was detected by a routine external MIT and did not involve wastewater migration.

- Only four cases of significant nonhazardous wastewater migration were detected. Three of the cases were detected by monitoring wells. The fourth potential wastewater migration case was discovered when a Class I well was drilled into the same formation. None of these failures is known to have affected a USDW.

To provide as up-to-date information as possible for the Class I study, EPA performed a second analysis, summarizing mechanical integrity failures in Class I nonhazardous and hazardous wells between 1993 and 1998.[37] This was the most recent time period for which the Agency had complete information. EPA found that MI failures of all types dropped by half in every state, except Texas. MI failures for all Class I wells in Texas increased two-fold during the assessment's time period compared to the previous study period. In fact, a relatively high Class I well mechanical integrity failure rate of 65 percent was indicated. However, Texas' UIC primacy agency, the Texas Natural Resource Conservation Commission (TNRCC), reviewed that assessment and refutes these numbers. Based on a review of the draft report against its records, TNRCC cites a 37-percent failure rate for Class I wells in Texas from 1993 to 1998.

V.B Qualitative Studies of Class I Wells

Two studies were performed in anticipation of the 1988 updates to the UIC regulations to assess the risks associated with disposal of hazardous wastewater via Class I wells. They were conducted by GeoTrans, Inc., in two phases, and Industrial Economics, Inc. (IEc).

In 1987, GeoTrans, Inc. conducted a two-phase qualitative study of Class I injection.[38] Phase I assessed the effects of certain variables on the performance of the Texas Gulf Coast geologic setting in containing waste. The study produced findings about the relative impacts of certain failure scenarios, including the presence of an abandoned unplugged borehole, fractured deterioration of a grout seal, and the presence of fractures in the confining zone,[39] along with high rates of withdrawal from an aquifer above the confining unit.

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[37] ICF, Inc. *Class I Mechanical Integrity Failure Analysis: 1993-1998.* Prepared by ICF, Inc., Fairfax, Virginia, for U.S. Environmental Protection Agency, Office of Ground Water and Drinking Water, Underground Injection Control Program. September 1998.

[38] GeoTrans, Inc. *A Numerical Evaluation for Class I Injection Wells for Waste Confinement Performance, Final Report, Volumes I and II.* Prepared for U.S. Environmental Protection Agency, Office of Drinking Water, Underground Injection Control Program. September 30, 1987.

[39] Grout seal failure occurs when the seal is not sufficiently impermeable to prevent migration of wastewater to a USDW, or when the seal separates from the well casing or the borehole and loses integrity.

The Phase I study also modeled the extent of wastewater migration from the injection zone due to containment failure. It assessed the effect of the hydraulic conductivity of the potential failure pathway, the degree of containment loss, the injection fluid characteristics, and the relative location of the failure pathway to the injection well. The conclusions of the Phase I study include the following:

- Waste confinement increases in scenarios where abandoned unplugged boreholes are farthest from the injection zone.

- Under certain conditions, containment failure can result in migration of waste from the injection zone. When contamination of overlying strata does occur, waste migration appears to be localized to within a few hundred to a thousand feet from where the failure occurred.

- The mode of failure (e.g., grout seal failure, presence of an abandoned borehole, or fractures in the confining zone), is less significant than the degree of failure, the injection fluid characteristics, and the location of the failure pathway relative to the injection well.

- Pumpage in an overlying aquifer with failure pathways increases the amount of waste escaping from the injection zone. (It should be noted that, if a USDW were directly over a proposed injection zone, Class I regulations would not allow the well to be constructed; this makes the addition of the pumping scenario to the model overly conservative.)

The Phase II study by GeoTrans, Inc. focused on two of the failure scenarios studied in Phase I—grout seal failure and the presence of an unplugged abandoned borehole—and three ranges in the degree of failure for four hydrogeologic settings (East Gulf Coast, Great Lakes, Kansas, and Texas). Some of the conclusions reached in the Phase II study were:

- To ensure waste confinement, the confining zone should be much less permeable than the injection zone (by one-thousand fold). Where there is less contrast in permeability, significant amounts of wastewater may migrate into the overlying zone.

- Models should provide sufficient hydrogeological detail to account for rock layers between the injection zone and the USDW that could attenuate some of the wastewater that migrates upward through a failure pathway. Using simplified zones for injection, confinement, and USDW in models may cause overestimation of the potential extent of contamination in USDWs.

- The additional stress on the systems related to pumpage in the USDW significantly reduced waste containment in all settings.

Using the data from the GeoTrans modeling, IEc estimated the magnitude of human health risks which might occur if underground injection of hazardous wastewaters results in contamination of USDWs.[40] IEc assessed the difference in risk among the four geologic settings modeled by GeoTrans. Risk between the best and the worst setting may vary by over 20 orders of magnitude depending on the type of failure. The study also estimated relative risks associated with an abandoned, unplugged borehole and a grout seal failure along with the impact of withdrawing water from the USDW.

V.C Quantitative Studies of Risks Due to Phase III Wastes

In 1995, in support of EPA's Phase III LDR rulemaking (see section I.B), the EPA Office of Ground Water and Drinking Water (OGWDW) prepared a draft Benefits Analysis (as part of the Regulatory Impact Analysis [RIA] of the proposed Phase III LDR rule) to estimate the risks associated with injection of Phase III wastes into Class I hazardous wells. The Chemical Manufacturers Association (CMA), now the American Chemistry Council (ACC), submitted comments on the Benefits Analysis in 1995, after which EPA revised the RIA. In 1996, EPA performed an analysis in support of the *de minimis* requirements that the underlying hazardous constituent concentrations must be less than 10 times the universal treatment standard (UTS).

EPA OGWDW Draft Phase III LDR RIA

In 1995, OGWDW performed a Benefits Analysis as part of the RIA of the proposed Phase III LDR rule. In the RIA, EPA modified the approach taken in the 1987 IEc study to estimate human health risks from five Phase III waste constituents (benzene, carbon tetrachloride, chloroform, phenol, and toluene).[41] EPA estimated health risks, including cancer risks and hazard indices,[42] for each of the four geologic settings and two malfunction scenarios (grout seal failure and abandoned, unplugged borehole). The study also assessed the effects of varying drinking water well pumping rates. The results showed:

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[40] Industrial Economics, Inc. *Risk Analyses for Underground Injection of Hazardous Wastes.* May 1987.

[41] U.S. EPA, Office of Ground Water and Drinking Water. *Draft Regulatory Impact Analysis of Proposed Hazardous Waste Disposal Restrictions for Class I Injection of Phase III Wastes: Benefits Analysis.* 1995.

[42] A hazard index is used to compare the relative risk posed by contaminants. A hazard index of greater than one indicates an increased risk of non-carcinogenic health effects.

- Only two of the estimated cancer risks for both malfunction scenarios slightly exceed the one-in-ten-thousand to one-in-one-million risk range generally used by EPA to regulate exposure to carcinogens.[43] These were the cancer risks from exposure to benzene and carbon tetrachloride, assuming an abandoned borehole scenario in the East Gulf Coast region at the highest drinking water well pumping rate.

- All but one of the hazard indices for both malfunction scenarios are less than EPA's level of concern for a hazard index of 1.55 (i.e., greater than the concern level of 1). The exception is for exposure to carbon tetrachloride in the East Gulf Coast setting with an abandoned borehole and the highest drinking water well pumping rate.

Comments by the Chemical Manufacturers Association on the Phase III LDR RIA

CMA submitted a critique of the Benefits Analysis in the Phase III RIA as part of its comments on the proposed Phase III LDR rule.[44] CMA claimed the analysis was overly conservative, given that Class I regulations have made the occurrence of these failure scenarios highly unlikely. CMA expressed concerns about the assumptions used, the placement of receptors, and the modeling of the East Gulf Coast hydrogeologic setting. CMA also indicated in its critique that the benefits analysis should have taken into account the probability of the failure scenarios actually occurring, given Class I operational safeguards, and should have weighed the risks of injecting Phase III wastes against the risks of handling, storing, and transporting them.

CMA also evaluated the qualitative risk assessment. Its critique emphasized that there have not been any instances of USDW contamination at a facility in compliance with the current UIC program regulations, and the malfunctions cited in the EPA study involved facilities that had not yet been required to comply with the UIC program requirements. CMA further asserted that underground injection of hazardous waste is particularly low risk compared to other waste management practices,[45] and the risks of handling, transporting, and treating segregated Phase III wastes might actually be greater than the risks of injecting the waste.

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[43] U.S. EPA, Office of Solid Waste and Emergency Response. *Role of the Baseline Risk Assessment in Superfund Remedy Selection Decisions*. OSWER Directive 9355.0-30. 1991.

[44] *Comments on Benefits Assessment of EPA's Draft Regulatory Impact Analysis*. Prepared by Woodward-Clyde Consultants for Chemical Manufacturers Association UIC Management Task Group. May 1995.

[45] U.S. EPA, Office of Solid Waste and Emergency Response. *OSWER Comparative Risk Project: Executive Summary and Overview*. EPA/540/1-89/003. November 1989.

EPA OGWDW Final RIA

The revised Phase III RIA[46] addressed several of the concerns raised in the CMA critique of the Phase III LDR Benefits Analysis. Specifically, waste receptors in the base of the USDW were included in the analysis, and limitations on the results of the analysis were discussed. Although a lack of data precluded a quantitative assessment of the probability of the failure scenarios actually occurring, incident occurrences were discussed further. The conclusions regarding human health risks did not change.

Evaluation of Risks from Exceedance of the UTS

To provide a quantifiable assessment in support of the *de minimis* requirements in the proposed Phase III rule, EPA analyzed the effects of varying the criteria that underlying hazardous constituent concentrations must be less than 10 times UTS.[47] Specifically, it outlined how increasing permissible levels to 50 times UTS changes the estimated potential health risks for several contaminants detected in the wastewaters of facilities affected by the Phase III LDR rule. The analysis estimated cancer and noncancer risks based on the well failure scenario and geologic setting that are associated with the greatest risk as depicted in the Benefits Analysis of the Phase III LDR RIA. In this analysis, EPA again used the five Phase III waste constituents (benzene, carbon tetrachloride, chloroform, phenol, and toluene) that were evaluated in the Phase III LDR RIA and Benefit Analysis.

Results of the analysis showed that, in general, carcinogenic risks were within the range generally used by EPA to regulate exposure to carcinogens, and noncancer risks were less than the hazard index of 1. The analysis concluded that a standard which would be more reflective of the potential for health hazards could be satisfied by defining the *de minimis* criterion as a value between 10 times and 50 times the UTS.

Using the same methodology, EPA conducted a brief analysis of the Hazardous Waste Identification Rule exit levels for the five chemicals examined. For benzene, carbon tetrachloride, and chloroform, the HWIR exit level concentrations were well below the UTS. Since the risk analysis presented above showed acceptable risk levels for these three chemicals at concentrations higher than the HWIR exit levels, no significant risk would be associated with the HWIR exit levels. For toluene and phenol, however, the HWIR exit levels were significantly

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[46] U.S. EPA, Office of Ground Water and Drinking Water. *Final Draft: Regulatory Impact Analysis of Proposed Hazardous Waste Disposal Restrictions for Class I Injection of Phase III Wastes: Benefits Analysis*. 1995.

[47] U.S. EPA, Office of Ground Water and Drinking Water. *Evaluation of Risks from Exceedance of the Universal Wastewater Treatment Standards (UTS), Including Addendum on HWIR Concentrations*. February 1996.

higher than 50 times the UTS. Neither chemical analyzed yielded a hazard index equal to or greater than 1, indicating an acceptable level of risk.

V.D Other Studies of Risk Due to Class I Wells

More recently, GeoTrans conducted additional modeling of MI failure scenarios using then current data on Class I wastewaters. In 1998, CMA quantitatively estimated the risk of waste containment loss from a Class I well based on probabilities that sequences of events would occur and result in a loss of containment.

Revisions to GeoTrans' Modeling Assumptions

At EPA's request, in response to CMA's 1995 comments on the Benefits Analysis and using more recent data on the constituents of Class I wastewaters, GeoTrans revised certain assumptions in its 1987 modeling of failure scenarios.[48] In this study, additional modeling focused on the scenario of an abandoned unplugged borehole 500 feet from the Class I well and a high drinking water well pumping rate. In the models, the differences in permeability between the injection zone and the layer just above the injection zone were increased by four orders of magnitude (i.e., by 10,000 times).

Results from the analysis showed that the effect of the abandoned borehole overwhelms the transport directly through the confining zone—with increasing permeability ratios, greater amounts of fluid are transported upward through the borehole and into the USDW. In effect, the reduced conductivity "squeezes" more of the waste fluids up the path of least resistance (the borehole). This is consistent with the conclusions drawn in the 1987 study.

This increase in concentration, however, occurs only between the base case and the revised scenarios. Comparison of the individual results for the revised scenarios shows that the concentrations decrease as the permeability ratio increases. This could imply that the "squeezing" effect does not hold true after a certain permeability contrast has been achieved, or that possibly some small amount of leakage occurs through the confining zone. Thus, greater permeability contrasts lead to lower contamination concentrations in the USDW. These potential causes may be the subject of further research.

Human health risks were calculated using the results of the revised GeoTrans analysis. (Appendix B to this report presents the complete revised human health risks analysis.) Recent data from EPA's UICWELLS database were used to determine 90th-percentile concentrations for benzene, carbon tetrachloride, and arsenic. The cancer risks for each chemical, based on

[48] *Revisions to GeoTrans' Modeling Assumptions, Analysis of New Data From 1996 Class I UICWELLS Database.* September 1996.

exposures to concentrations estimated at a receptor 500 feet from the injection well in an aquifer below the USDW at higher permeability ratios, exceed the risk range generally used by EPA to regulate exposures to carcinogens.[49] Likewise, at the same receptor location, the hazard indices estimated for each chemical are greater than EPA's level of concern for a hazard index greater than 1. All other cancer risk and hazard index estimates are within regulatory levels.

These risk levels should, however, be assessed in the context of the low probability of this failure scenario actually occurring given Class I AoR requirements. Although no quantitative method to assess this probability currently exists, the small number of such failures after promulgation of the existing UIC regulations, indicates that the probability is likely very low.

A number of detailed human health risk analyses were conducted using actual Class I waste constituent data to determine the potential for cancer and noncancer risks associated with ingesting water from a USDW contaminated by a Class I well. The results showed that cancer and noncancer risks exceed the acceptable risk range for three chemicals at one receptor located adjacent to an abandoned unplugged borehole, 573 feet from the injection well, in an aquifer below the USDW. This assumes an abandoned borehole is located 500 feet from the injection well, and a drinking water well located 1,000 feet from the injection well is pumping 720,000 gallons per day from an overlying aquifer. Under current UIC regulations requiring AoR studies, however, it is unlikely that an abandoned borehole would go undetected. Also, given the small number of documented USDW contamination incidents (described in section V.A), the probability of this scenario actually occurring is likely very low.

Probabilistic Risk Assessment of Class I Hazardous Wells

In 1998, Rish et al. quantitatively estimated the risk of waste containment loss as a result of various sets of events associated with Class I hazardous wells.[50] Through a series of "event trees," the study estimated the probability that an initiating event will occur and be undiscovered, followed by subsequent events that could ultimately result in a release of injected fluids to a USDW.

The study assumed that, given the redundant safety systems in a typical Class I well, loss of containment requires a string of improbable events to occur in sequence. For example, a leak develops in the packer, followed by a drop in annulus pressure that is undetected due to a

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[49] U.S. EPA, Office of Solid Waste and Emergency Response. *Role of the Baseline Risk Assessment in Superfund Remedy Selection Decisions*. OSWER Directive 9355.0-30. 1991.

[50] Rish, W.A., T. Ijaz, and T.F. Long. *A Probabilistic Risk Assessment of Class I Hazardous Waste Injection Wells*. Draft. 1998.

simultaneous malfunction of the pressure monitoring system, followed by a leak in the long string casing between the surface casing and the upper confining layer, resulting in a loss of waste isolation.

The Rish study concluded that Class I hazardous injection wells which meet EPA's minimum design and operating requirements (i.e., a completed no-migration study, two confining zones between the injection zone and the lowermost USDW, completed long string and surface casings, and redundant safety systems) pose risks that are well below acceptable levels. According to the study, the probability of containment loss resulting from each of the scenarios examined ranges from one-in-one-million to one-in-ten-quadrillion. The risks for each are ranked as follows (from most probable to least probable): cement microannulus leak, inadvertent extraction from the injection zone, major injection tube failure, major packer failure, breach of the confining zone(s), leak in the packer, and leak in the injection tubing.

This low risk is attributed to the use of engineered systems and geologic knowledge to provide multiple barriers to the release of wastewater to USDWs. And although this risk analysis was primarily concerned with Class I hazardous wells, many of the well design and construction requirements pertain to Class I nonhazardous wells also. Therefore, the findings of a relative low risk in operation of the wells investigated in the Rish study can be extrapolated to the typical Class I well which may be managing only decharacterized wastewaters.

VI. Conclusions

EPA's UIC requirements and current operational practices for all Class I wells reflect years of experience and insight into what makes Class I wells safe and what practices are unacceptable. From the early failures of Class I wells, EPA learned that migration of injected wastewater can result from failure of injection wells due to faulty design, construction, operating practices, or the presence of pathways for migration near the injection zone.

Recognizing this, EPA passed its UIC regulations for Class I nonhazardous and hazardous wells in 1980 based on the idea that injection into properly constructed and operated wells is a safe means to dispose of wastewater. EPA's geologic siting, well engineering, and operating requirements for Class I wells offer multiple safeguards against failure of the well or migration of injected fluids.

Because the presence of an unplugged abandoned borehole can be a significant potential contributing factor to migration of injected fluids from the injection zone, EPA requires operators to identify and address all improperly abandoned wells in the AoR. Several states that account for the majority of all Class I wells require an AoR that is even larger than that required by federal regulations. These unplugged wells, if found, must be properly addressed before UIC permitting authorities will allow operators to begin injection.

In addition to the AoR requirement, Class I wells are sited to minimize the potential for waste migration. Pre-construction studies by operators must demonstrate that the rock formations which make up the injection and confining zones and the local geologic structure are amenable to safe injection and confinement of wastewaters. Wells are constructed using well materials that are suitable to the injection of wastewaters at the intended pressure, rate, and volume.

Inspections and well testing, along with passive monitoring systems such as continuous annulus monitoring systems, can detect malfunctions before wastewaters could escape the injection system. Periodic MITs are an additional means of ensuring the integrity of the well components. An internal or external MI failure does not imply failure of the injection well or loss of wastewater confinement. Rather, they indicate that one of the several protective elements may have malfunctioned.

The probability of Class I well failures, both nonhazardous and hazardous, has been demonstrated to be low. Many early Class I failures were a result of historic practices that are no longer permissible under the UIC regulations. Class I wells have redundant safety systems and several protective layers; an injection well would fail only when multiple systems fail in sequence without detection. In the unlikely event that a well would fail, the geology of the injection and confining zones serves as a final safety net against movement of wastewaters to USDWs. Injection well operators invest millions of dollars in the permitting, construction, and operation of wells, and even in the absence of UIC regulations would carefully monitor the integrity of the injection operation to safeguard their investments.

Indeed, failures of Class I wells are rare. Most failures of MI are internal failures, detected by continuous annulus monitoring systems or MITs, and the wells are shut-in until they are repaired. EPA's study of more than 500 Class I nonhazardous and hazardous wells showed that loss of MI contributed to only 4 cases of significant wastewater migration (none of which affected a drinking water source) over several decades of operation. Even as injection wells are entering "middle age," their MI remains intact. This can be attributed to the rigorous requirements for monitoring and for ensuring that the well materials are compatible with the wastewater injected.

The 1988 UIC regulations implementing the HSWA offer additional protection by requiring operators of Class I hazardous wells to complete a no-migration petition to demonstrate that the hazardous constituents of the wastewater will not migrate from the injection zone for 10,000 years, or as long as the wastewater remains hazardous. Although operators are not required to place decharacterized wastes in wells subject to no migration requirements, the fact that these wastes are being injected into Class I hazardous wells offers additional protection by this practice.

From an assessment of information collected on Class I wells, both nonhazardous and hazardous, EPA believes that a substantial volume of decharacterized wastes are still being disposed via Class I hazardous wells, particularly where the facility may not segregate waste streams. Thus, public health and the environment is being afforded an additional level of protection by this injection practice, because the additional controls on hazardous wells are in place. No migration petitions account for all volumes of waste injected into a Class I hazardous well to ascertain the size, shape, and directional drift of the waste plume.

In addition, states with a proportionally large number of the national total for Class I injection wells have stricter regulatory requirements than the minimum federal standards for their Class I nonhazardous wells. As such, a substantial number of Class I nonhazardous wells managing decharacterized wastes are extremely protective. The EPA has no reason but to conclude that existing Class I UIC regulatory controls are strong, adequately protective, and provide an extremely low-risk option in managing the wastewaters of concern.

VII. Annotated Bibliography of Class I Documents

The sections below provide an annotated bibliography of documents related to Class I injection wells. The bibliography is organized by type of document as follows: general information on Class I injection; descriptions of computer modeling; studies of mechanical integrity testing; program histories, overviews, and evaluations; Class I research; risk analyses; and technical and instructional documents.

General Information on Class I Injection

The American Association of Petroleum Geologists. "Underground Waste Management and Environmental Implications." Memoir 18 in T.D. Cook, ed., *Proceedings of the Symposium on Underground Waste Management and Environmental Implications* Houston, Texas, December 6-9, 1971. AAPG. 1972.

> The United States Geological Survey and The American Association of Petroleum Geologists undertook joint sponsorship of the Symposium on Underground Waste Management and Environmental Implications. Their goal was to document the facts, clearly and objectively review the state of the art, and highlight segments of the underground waste disposal problems that need further study. The organizing committees arranged a program which touched on all aspects of underground waste management and its environmental implications. They called upon a panel of distinguished authors and practitioners to discuss various segments of the problem. Their data are presented in this document.

The American Association of Petroleum Geologists. "Underground Waste Management and Environmental Implications." Jules Braunstein, ed. *Papers Presented at the Second International Symposium on Underground Waste Management and Artificial Recharge* New Orleans, Louisiana, September 26-30, 1973. Vol. 1 and Vol. 2, AAPG. 1973.

> The two volumes in this publication represent the third in a continuing series of AAPG publications devoted to the subject of underground waste management. They were preceded by *Memoir* 10, *Subsurface Disposal in Geologic Basins*, and *Memoir* 18, the proceedings of the First Symposium on Underground Waste Management and Environmental Implications.

Brown, Michael. "The Lower Depths: Underground Injection of Hazardous Wastes." *The Amicus Journal.* Winter 1986.

> The premise of this article is that deep injection of industrial waste has become extensive in America and a way for corporations to rid themselves of toxic residues without encountering rigid governmental restrictions and the public clamor associated with the more visible landfills. During the previous two decades (especially during the period in which the Clean Water Act was implemented), use of such wells had grown to the point where more hazardous liquids are injected deep underground than are poured into metal drums and buried in standard dumpsites. At the same time that the Chemical Manufacturers Association describes deep well injection as "a technically sound and costly practice," a small but growing band of critics contends that, quite to the contrary, it is both cheap and dangerous. Several cases of groundwater and air pollution resulting from injection wells are provided. The author asserts that problems with UIC programs include insufficient regulation and noncompliance with existing regulations. The author also claims that some of the weaknesses of the UIC program are its failure to set testing requirements to prevent adverse interactions between waste and formation; the lack of requirements for financial responsibility after well abandonment; lack of monitoring requirements; lack of requirements for post-closure care; and infrequent mechanical integrity testing.

Carter, L.M.H., ed. *Energy and the Environment—Application of Geosciences to Decision-Making*. U.S. Geological Survey Circular 1108. February 13-16, 1995.

> Sessions of the Tenth V.E. McKelvey Forum on Mineral and Energy Resources included an introduction to energy and the environment, availability and quality of energy resources, environmental effects of natural energy occurrence, and environmental effects of energy extraction and utilization. This document contains the program and a list of short papers from the event.

Chemical Manufacturers Association. *Class I Underground Injection Wells: Responsible Management of Chemical Wastes* (Pamphlet). 1994.

> This pamphlet highlights many of the successful efforts by Chemical Manufacturers Association members to minimize wastes sent to deep injection wells.

Chemical Manufacturers Association. *Deep Well Injection: An Option for Responsible Management of Chemical Wastes* (Pamphlet). 1994.

> The suitability of deep well injection as a disposal method depends upon the local geology and hydrology and the nature and volume of wastes. This pamphlet by the Chemical Manufacturers Association provides an introduction to deep well injection of chemical wastes.

Clark, James E. “Environmental Scoring Without Risk Assessment.” Presented at CLEAN TEXAS 2000 - Environmental Trade Fair, Underground Injection Control Workshop, Austin, Texas. April 14, 1994.

> Many environmental ranking systems continue to rely heavily on the U.S. EPA Toxic Release Inventory (TRI) regarding releases of toxic chemicals to the environment. The author believes that the current system of TRI reporting does not accurately measure exposure or risk to human health and the environment and can overstate the risks associated with underground injection.

E.I. DuPont de Nemours & Co., DuPont Deepwell Training Committee. *An Introduction to Deepwell Disposal.* Injection Well Operator Training Series, Vol. 1. Beaumont, Texas: Tele-Con Productions (Videocassette). 1989.

E.I. DuPont de Nemours & Co., DuPont Deepwell Training Committee. *Well Operations and Diagnostic Procedures.* Injection Well Operator Training Series, Vol. 2. Beaumont, Texas: Tele-Con Productions (Videocassette). 1989.

Ground Water Protection Council. *Injection Well Bibliography*. Third Edition. Oklahoma City, Oklahoma: Ground Water Protection Council. August 1995.

> This is the most comprehensive bibliography published to date on injection wells in the United States. It is an update of the editions published by the Underground Injection Practices Council in 1989 and 1993. The project was designed by the Ground Water Protection Council as a primary reference tool for persons interested in the operation, construction, and regulation of various types of injection wells. The bibliography is divided into sections based upon well classification and associated topics for easier and

more accurate searching. The bibliography includes four sections on Class I injection wells: "General," "Hazardous Waste Wells," "Non-Hazardous, Industrial Wells," and "Non-Hazardous, Municipal Wells."

Hickey, John J., and John Vecchioli. "Subsurface Injection of Liquid Waste with Emphasis on Injection Practices in Florida." U.S. Geological Survey Water-Supply Paper 2281. 1984.

Subsurface injection of waste is not well understood by many state and local governmental officials and environmentally concerned citizens who make decisions about waste disposal. This report serves as an elementary guide to subsurface injection and presents subsurface injection practices in Florida as an example of how one state is managing injection.

Lehr, Jay H. "Underground Injection: A Positive Advocate." *Proceedings of the International Symposium on Subsurface Injection of Liquid Waste.* New Orleans, Louisiana, March 3-5, 1986. Dublin, Ohio: National Water Well Association. 1986.

EPA has focused most of its public attention on the more prevalent brine reinjection wells known as Class II wells. Concurrently EPA oversees *in situ* mining wells (Class III), outlaws the disposal of hazardous wastes into or above potable aquifers (Class IV), and intends to offer general guidelines for all other injection wells from salt-water intrusion barrier wells to geothermal energy wells (Class V). Since the passage of SDWA, the least attention was focused on wells disposing of hazardous waste below and separated from current or potential underground sources of drinking water (Class I).

Moffett, Tola B., Philip E. LaMoreaux, Janet Y. Smith, and M. Ben Dismukes. *Management of Hazardous Wastes by Deep-Well Disposal*. Open File Report No. 11. Tuscaloosa, Alabama: University of Alabama, Environmental Institute for Waste Management Studies. 1987.

This report provides an assessment of the deep-well injection of hazardous waste for technically trained audiences and the general public. Chapter 2, "Relevant Issues," describes the complex factors that affect deep-well injection. Chapters 3 through 8 provide basic information concerning the history of deep-well injection, its methodology, and its current status. These chapters also provide a basis for determining benefits and risks of deep-well injection and for analyzing its potential role in hazardous waste management.

National Water Well Association. *Proceedings of the International Symposium on Subsurface Injection of Liquid Waste.* New Orleans, Louisiana, March 3-5, 1986. Dublin, Ohio: National Water Well Association. 1986.

> The International Symposium on Subsurface Injection of Liquid Wastes was held in New Orleans, Louisiana, March 3-5, 1986. Government officials, industry representatives, consulting engineers, and geologists, researchers, and other interested persons met to learn about and discuss state-of-the-art techniques employed and variables to consider in the operation of underground injection facilities. The conference papers addressed a wide variety of topics including a point/counterpoint on the practice of underground injection, well construction and testing methods, case studies on the operation of selected facilities, and a discussion of the fate and transport of injected wastes. This conference provided a forum for all who attended to communicate and share experiences about the practice of subsurface disposal and to learn about the implications of future regulation in this area.

Russian-American Center for Contaminant Transport Studies. *Summary Report (1993-1994).* 1994.

> This report summarizes the activities of the Russian-American Center for Contaminant Transport Studies at the Lawrence Berkeley National Laboratory in 1993-1994. It presents the publications and workshops sponsored by the Center, including the International Symposium on Scientific and Engineering Aspects of Deep Injection Disposal of Hazardous and Industrial Waste (May 10-13, 1994). Co-sponsored by EPA's Office of Ground Water and Drinking Water and the Department of Energy's Office of Environmental Management, the symposium provided an avenue to compare experiences and ideas for improving deep well injection technology.

Smith, R. E. EPA Mission Research in Support of Hazardous Waste Injection 1986-1994. In: *Deep Injection Disposal of Hazardous and Industrial Waste: Scientific and Engineering Aspects.* John A. Apps and Chin-Fu Tsang, eds. San Diego, California: Academic Press. 1996. p. 9-24.

> The central focus of the UIC Class I research program has been to determine under what conditions (if any) injection of hazardous wastes is protective of human health and the environment. Geological and hydrogeological research helped EPA set minimum siting criteria for Class I wells and determine the appropriateness of specific areas for injection. Geophysical research has helped delineate underground reservoirs, find abandoned wells for Area of Review studies, and determine whether injection could contribute to earthquake risk. Geochemical research has provided some additional information on transformation of injected waste. Several studies have suggested new methods for well siting, testing, and monitoring. Computer models have been required since the 1988

Land Ban Regulations. A new area of study in modeling is diffusion, which can cause minor upward vertical movement of injected wastes.

Strycker, Arden, and A. Gene Collins. *State-of-the-Art Report: Injection of Hazardous Wastes Into Deep Wells*. Prepared by National Institute for Petroleum and Energy Research for U.S. Department of Energy and U.S. Environmental Protection Agency, Robert S. Kerr Environmental Research Laboratory. December 15, 1986.

A survey of the literature shows that some information is available on nearly all of the potential chemical and biological transformation processes of hazardous wastes. This survey also indicates that additional research is needed in all areas of abiotic and biotic waste interactions before definitive explanations can be given on their long-term fate.

Thornton, Joe. *A Shot in the Dark: Underground Injection of Hazardous Waste.* A Greenpeace Report. July 1990.

Deep well disposal of hazardous wastes has contaminated groundwater resources, caused earthquakes, damaged geological formations, and contaminated soils and surface water near wellheads. Because of loopholes in federal laws governing hazardous waste disposal, deep well injection is the cheapest and one of the most poorly regulated of all disposal methods.

Underground Injection Practices Council. *Injection Wells: An Introduction to Their Use, Operation, and Regulation.* Undated.

This document is an outreach brochure designed to disseminate general information about all classes of underground injection wells (including Class I).

Underground Injection Practices Council. *An Introduction to the Underground Injection Control Program.* May 1990.

This manual is written to inform interested persons about the basic concepts, elements, and procedures of the UIC program. Its purpose is to present a comprehensive overview of the UIC program so those working with a single program element will have an appreciation of the whole program and so elected officials and administrators will be able to understand the operation and needs of a successful UIC program. This manual has been written from the standpoint of experience gained operating and administering state regulatory programs.

U.S. EPA, Office of Water. *Class I Injection Wells and Your Drinking Water.* EPA 813-F-94-002. July 1994.

This document is an EPA outreach brochure designed to disseminate general information about Class I underground injection wells.

U.S. EPA, Office of Water. *Underground Injection Wells and Your Drinking Water.* EPA 813-F-94-001. July 1994.

This document is an EPA outreach brochure designed to disseminate general information about all classes of underground injection wells (including Class I wells).

Computer Modeling

Javandel, Iraj, Chin Fu Tsang, and Paul A. Witherspoon. *Hydrologic Detection of Abandoned Wells*. Prepared by Lawrence Berkeley Laboratory for U.S. Environmental Protection Agency, Office of Drinking Water. June 1986.

Thorough characterization of injection zones and confining beds is essential to ensuring that no pathways exist for movement of injected wastes to USDWs. This paper presents an analytical model for detecting improperly abandoned wells. The analytic solution calculates the amount of leakage from an abandoned well and the corresponding drawdown at monitoring wells. This paper also proposes a method for detecting deep abandoned wells in the area of influence of proposed deep injection wells in a multiple aquifer system.

Kazmann, Raphael G. "Deep Well Injection: Models, Reality, and How to Do It Right." *Ground Water.* November/December 1988.

Deep well disposal, when properly done, is the safest method that can be devised for removing hazardous wastes from the biosphere. The critical point is the wellhead where injection takes place. The fate of the waste should be of no concern, if the geology has been interpreted correctly and the other mechanical criteria that have been established are met. The article asserts that mathematical modeling does not improve the safety of the procedure and that, in the interest of saving time and money, EPA should abandon the requirement that mathematical models be prepared as part of the application for a permit for deep well disposal of hazardous wastes. The safety of the procedure depends on the ability and integrity of the hydrogeologist who interprets the field data and the engineer who designs and tests the injection well.

LaMoreaux, P. E. *Synopsis of Use of Mathematical Models to Evaluate Sites for Injection Wells for Disposal of Hazardous Wastes.* Preliminary Draft. Environmental Institute for Waste Management Studies. December 1986.

> Mathematical models are representations of physical systems or processes. Models, both flow and geochemical, range from simple to complicated. There are three methods of simulating injection of wastewater into reservoirs: analytical, semi-analytical, and numerical.

Larkin, R. G., J. E. Clark, and P. W. Papadeas. “Modeling the Effect of Injectate-Density Changes on Disposal Well Plumes.” In: *Deep Injection Disposal of Hazardous and Industrial Waste: Scientific and Engineering Aspects.* John A. Apps and Chin-Fu Tsang, eds. San Diego, California: Academic Press. 1996. p. 381-402.

> This paper compares the waste plumes generated by a model using two different calculations for injectate density. Models of such plumes are required in some no-migration petitions. Injectate that is of lower density than the native fluid in the injection zone can cause the plume to float upward, while injectate with densities higher than those of native fluids can cause the plume to sink. One run of the model was performed using the average of densities recorded over time at an actual well. Another run was performed using varying daily densities at the same well. In addition, equivalent runs were done using randomly generated density data. No significant difference in the plume extent existed between runs using an average and runs using fluctuating daily data.

Miller, C., T.A. Fischer II, J.E. Clark, W.M. Porter, C.H. Hales, and J.R. Tilton. “Flow and Containment of Injected Wastes.” *Ground Water Monitoring Review.* Summer 1986.

> This article examines several analytical models for predicting waste movement and pressure increases within the injection zone and describing upward permeation of wastes through confining layers. Models attempted to account for density differences between the waste and native formation brine and permeability variation within the injection zone. Initial results indicate that faults and fractures are not likely to provide conductive pathways for contaminant migration in Gulf Coast settings, and that site-specific evaluations are required to assess the impact of abandoned wells.

Milly, P.C.D. *Obstacles Associated with Transport Modeling of Hazardous Waste Injected Underground.* 1987.

> Mathematical modeling is one of the few alternatives available for assessing the risk of future USDW contamination resulting from subsurface waste injection; alternatives are extensive monitoring or comprehensive prohibitions of injection. This report describes

some of the more serious problems associated with using models to predict waste transport. The discussion is general and not limited to any particular mathematical model; most remarks apply to most of the models currently in use.

Morganwalp, David W., and Robert E. Smith. *Modeling of Representative Injection Sites*. 1987.

There are three main objectives to this study. The first is to find key parameters that control the transport of hazardous waste at representative injection well sites. The second is to investigate the role of molecular diffusion in hazardous waste injection well settings. The third objective is to show by example that hazardous waste injection can be modeled. The objectives were achieved by modeling idealized representations of actual hazardous waste injection wells.

Papadeas, P. W. "Field Testing for Model Confirmation: Case Histories from Du Pont." In: *Deep Injection Disposal of Hazardous and Industrial Waste: Scientific and Engineering Aspects.* John A. Apps and Chin-Fu Tsang, eds. San Diego, California: Academic Press. 1996. p. 325-348.

As part of hazardous and nonhazardous waste injection at Class I injection wells, detailed, site-specific models are employed to predict and track waste injectate over time. Flow and containment of this injected waste in the subsurface can be demonstrated to regulators with a reasonable degree of certainty exclusively through the use of modeling techniques; however, only direct field testing can corroborate the model results. Case histories covering over 40 years of injection well operations corroborate the findings of models and active disposal systems.

Thornhill, J.T., T.E. Short, and L. Silka. "Application of the Area of Review Concept." *Ground Water.* Vol. 20, No. 1. January/February 1982.

Analytical equations can be used to calculate pressure buildup in injection zones. In areas of review characterized by numerous injection wells, care must be taken to account for the effect of every injection well on pressure buildup to prevent the migration of fluids to USDWs.

Mechanical Integrity Testing

The Cadmus Group, Inc. *External Mechanical Integrity Log Interpretations for Class I Wells in Texas (DRAFT).* Prepared for U.S. Environmental Protection Agency, Region 6, Underground Injection Control Section. September 30, 1993.

> This report presents a summary and analysis of the geophysical log interpretations performed for Class I hazardous waste (HW) disposal wells in Texas. This task was part of a larger Cadmus study of Class I HW file reviews undertaken for EPA Region 6, as part of the oversight efforts required for primacy states under the UIC Program. The report explains the technology, including radioactive tracer tests and cement bond logs, used to assess mechanical integrity for 61 Class I wells. Analysis of the data indicate that most radioactive tracer surveys were not conducted according to Texas Natural Resources Conservation Commission guidelines, 29 percent of the wells had no cement bond logs (CBLs) on file, and most wells that did have logs showed insufficient cement casing (even though their permit applications state that cement extends to the surface). Of the wells that did have CBLs, many had logs so poorly calibrated that interpretation could not be considered reliable. Recommendations included minimum standards for cement bond logs, performance standards for cementing Class I hazardous wells, use of oxygen activation logs instead of radioactive tracer tests in some cases, and supplemental training of MI reviewers at primacy agencies.

Engineering Enterprises, Inc. *Analysis of Mechanical Integrity Tests and Permit File Reviews.* Prepared for U.S. Environmental Protection Agency, Office of Drinking Water, Groundwater Protection Branch. September 1986.

> This report analyzes the mechanical integrity testing programs for Direct Implementation states. It discusses the applicability and effectiveness of various types of mechanical integrity tests and comments on significant variances in failure rates. The report evaluates the adequacy of file review procedures and provides recommendations for standardizing reporting forms, for follow-up actions for MIT failures and call-in procedures, and for file reviews of well operations.

Geraghty & Miller, Inc. *Mechanical Integrity Testing of Injection Wells.* Prepared for U.S. Environmental Protection Agency, Office of Drinking Water. April 30, 1980.

> The various logging techniques used in determining mechanical integrity are widely employed and were developed for this purpose. They are an indirect measurement and are indicators of a condition. They measure something electronically: temperature, sound velocity, noise levels, etc. Thus, data interpretation is subjective and depends on the skills and experience of the operator, in contrast to a pressure test, which is a more direct,

readily observable indicator of a condition. But surveys such as noise, temperature, and tracer logs can be substituted for pressure testing. While the pressure tests yield more positive results, it may be more economical for the operator to substitute the appropriate log or logs. The evidence will be less direct, but the burden of proof should be on the operator to demonstrate conclusively that the well possesses the required integrity.

Jarrell, Malcolm D. "Integrity Testing of Class I Hazardous Injection Wells—Related Experience in the Great Lakes Region." *Proceedings of the International Symposium on Subsurface Injection of Liquid Waste.* New Orleans, Louisiana, March 3-5, 1986. Dublin, Ohio: National Water Well Association. 1986.

This paper discusses mechanical integrity testing of Class I hazardous waste disposal wells in EPA Region 5. It addresses test procedure development, implementation, and interpretation. The test procedures are based on site-specific well construction, operation, and geological considerations. Testing methods include the radioactive tracer survey and annular pressure testing. The interpretation of test results are discussed as related to U.S. EPA's criteria for acceptance. The principles applied could prove helpful in establishing regional standards for mechanical integrity testing.

Whiteside, Robert F., and Stuart F. Raef. "Mechanical Integrity of Class I Injection Wells." *Proceedings of the International Symposium on Subsurface Injection of Liquid Waste.* (New Orleans, Louisiana, March 3-5, 1986). Dublin, Ohio: National Water Well Association. 1986.

This paper reviews the siting, construction, and testing of Class I disposal wells and how these are designed to ensure mechanical integrity. Periodic mechanical integrity testing is discussed, including pressure testing and logging, as are the advantages and limitations of each technique. Advantages and disadvantages of packer-annulus versus packerless well completions are discussed as they pertain to annulus monitoring.

Program Histories, Overviews, and Evaluations

Brower, Ross D., Ivan G. Krapac, Bruce R. Hensel, Adrian P. Visocky, Gary R. Peyton, John Stephen Nealon, and Mark Guthrie. *Evaluation of Current Underground Injection of Industrial Waste in Illinois.* Final Draft Report. Savoy, Illinois: Illinois Department of Energy and Natural Resources, Hazardous Waste Research and Information Center. March 1986.

The objectives of this assessment were to determine whether underground injection is an appropriate method of waste disposal in Illinois and to provide recommendations to the Legislature, Legislative Council, the Governor's Office, and state agencies concerning this disposal practice. The final report presents the results of the study mandated by legislation. The following topics are addressed in the report: (1) The current state

regulations and regulatory practices of the Illinois Class I UIC program; (2) An historical evaluation of the operation and maintenance of underground injection facilities in Illinois, including a review of the types of wastes and potential problems associated with underground waste disposal; (3) A review of the Class I UIC programs in other states and comparison with the program in Illinois, including current issues and trends in deep well injection; (4) A summary of geologic information in Illinois to identify areas and geologic formations that are being used and might be targeted for future injection; (5) An identification of alternative waste disposal management options, along with treatment requirements, treatment technologies, associated costs for selected waste management options, and potential environmental impacts; and (6) Conclusions and recommendations. The authors conclude that deep well injection is a viable means of disposal when carried out within the requirements of the UIC regulations. The regulations are sufficient, although updates are needed for waste sampling protocol and chemical analysis of samples in order to keep up with technological advances. Additions recommended for Illinois' UIC program include analysis of the injection waste, which should be required at the time of permitting and annually thereafter. Pretreatment of injection waste to remove hazardous components could increase operating costs 3 to 40 times, depending on the industry, and could have more serious environmental impacts than injection without treatment. More research is needed on interaction between wastes, pore water, and formations. A monitoring strategy should be developed.

The Cadmus Group, Inc. Responses to questions 2, 5c, and 9b of Congressman John D. Dingell's letter to William K. Reilly, dated October 22, 1992, regarding disposal of hazardous wastes, deep injection, and underground wells at 42 U.S.C. section 6924 (F) - (G). Prepared for U.S. Environmental Protection Agency, Office of Ground Water and Drinking Water, Underground Injection Control Branch. January 29, 1993 (for responses to 2 and 5c) and February 24, 1993 (for response 9b).

Questions 2, 5c, and 9b of Congressman Dingell's letter request a list of wells for which EPA has granted no-migration petitions, the education and background of staff who review no-migration petitions, and reviews of compliance with groundwater monitoring requirements associated with injection wells. This information is provided in the response document.

Chemical Manufacturers Association, Underground Injection Control Program. *Operational Status of Class I HW Wells: 1984-1991.* Washington, DC: Bryan, Cave, McPheeters & McRoberts. February 1991.

This study was conducted to determine the impact of the Hazardous and Solid Waste Amendments of 1984 on Class I hazardous waste injection well practices. The data includes only those facilities that were in existence prior to 1984. The conclusions are based on available documentation, including EPA's 1985 *Report to Congress on the Injection of Hazardous Waste*, EPA's February 1988 Federal Underground Injection Control Reporting System Class I wells printout, and individual facility reports.

Davis, Ken E., and T. Lawrence Hineline. "Two Decades of Successful Hazardous Waste Disposal Well Operation—A Compilation of Case Histories." *Proceedings of the International Symposium on Subsurface Injection of Liquid Waste.* New Orleans, Louisiana, March 3-5, 1986. Dublin, Ohio: National Water Well Association. 1986.

The monitoring systems and mechanical integrity programs required by the federal and state UIC programs have an excellent record of detecting problem areas prior to any deleterious effects on the environment. Most alleged MI failures are due merely to the improper operation of monitoring equipment and do not result in any environmental hazard. This article presents case histories on how operation problems were identified and successfully eliminated, how monitoring systems identified potential problems, and how wells were repaired.

Dingell, John D., Chairman, U.S. House of Representatives, Subcommittee on Oversight and Investigations of the Committee on Energy and Commerce. Letter to William K. Reilly, Administrator, U.S. Environmental Protection Agency, regarding disposal of hazardous wastes, deep injection, and underground wells at 42 U.S.C. section 6924 (F) - (G). October 22, 1992.

Citing public concern about EPA's implementation of the HSWA Amendments, Congressman Dingell requested information on injection wells, including no-migration petitions, Class I well failures, inspection requirements, and other information.

Elsevier Science Inc. "RCRA Land Disposal Restrictions: A Guide to Compliance—1996 Edition." *The Hazardous Waste Consultant.* June/July 1996.

The most recent revisions to the Land Disposal Restrictions program were promulgated in the Phase III LDR rule in early April 1996. The primary focus of this regulation is implementation of H.R. 2036, the Land Disposal Program Flexibility Act. All of the rules issued under Phases I, II, and III are discussed in this guide.

Gordon, Wendy, and Jane Bloom. "Deeper Problems: Limits to Underground Injection as a Hazardous Waste Disposal Method." New York: Natural Resources Defense Council, Inc. 1986.

The injection of hazardous waste into subsurface rock formations is the predominant form of liquid hazardous waste disposal in the United States and one of the least understood. Despite the considerable reliance on underground injection for disposing of hazardous wastes, neither the effective injection of fluids nor their safe containment can presently be ensured. This article analyzes the practice of underground injection as a hazardous waste disposal method and evaluates the limits to its use and the degree of protection against groundwater contamination current injection methods can ensure. It identifies specific research needs necessary to determine the technical and environmental constraints associated with underground injection and its potential for ensuring complete containment of waste. Also examined is the adequacy of the UIC program in preventing groundwater contamination and other environmental damage due to migration of hazardous wastes. The article recommends specific regulatory changes that could result in more protective underground injection operations.

ICF, Inc. *Class I Mechanical Integrity Failure Analysis: 1993-1998.* Prepared by ICF, Inc., Fairfax, Virginia, for U.S. Environmental Protection Agency, Office of Ground Water and Drinking Water, Underground Injection Control Program. September 1998.

This report summarizes mechanical integrity failures in Class I wells between 1993 and 1998, including the number of Class I injection failures during the period, the causes of these MI failures, and EPA and state responses to them. It is a follow up to a similar study of the period from 1988 to 1991. EPA found that between the last study and this one, MI failures of all types dropped by half in every state, except Texas, where MI failures increased two-fold. (The results of the study are described in greater detail in Section V.A.)

Michigan Department of Natural Resources. *Deep Well Injection of Hazardous Waste In Michigan.* May 1986.

The State of Michigan convened an advisory committee to determine whether deep well injection in Michigan should be banned or allowed to continue under existing or revised regulations. The committee concluded that deep well injection should be allowed to continue, provided that the state's regulatory program is improved. Key recommendations included specifying construction, closure, and mechanical integrity testing requirements; banning the injection of highly toxic, persistent halogenated organics; requiring shallow groundwater monitoring; requiring regular reassessments of alternative technologies; and improving the compliance and enforcement program.

Reeder, Louis R., James H. Cobbs, John W. Field, Jr., William D. Finley, Steven C. Vokurka, and Bernard N. Rolfe. *Review and Assessment of Deep-Well Injection of Hazardous Waste (Volumes I-IV).* Prepared by Louis R. Reeder and Associates for U.S. Environmental Protection Agency, Office of Research and Development, Municipal Environmental Research Laboratory. June 1977.

> Geologic and engineering data are generally available to locate, design, and operate a deep injection well. In contrast, little information exists on salaquifer chemistry as well as waste interactions with the receiving salaquifer. Problems occur when there is a failure to use available geologic information and proven engineering practices in design and completion. For more effective oversight of deep well injection, standardization of state regulations is necessary.

Temple, Barker & Sloane, Inc. "Findings on Class I Hazardous Wells Affected by the Land Ban Rules." Memorandum from Annette Hulse, Elaine Haemisegger, Marc Blaustein, Laurie Remmers, and Hollie Maheney (TBS) to John Atecheson, Dave Morganwalp, and Mario Salazar, U.S. Environmental Protection Agency. December 15, 1987.

> This report summarizes the findings of a study on (1) wells affected by the land ban rules, (2) available alternative commercial treatment, and (3) available transportation capacity (truck and rail) to move the banned wastes from the current point of disposal to the point of alternative treatment. The report concludes that, in the short-term after the land ban would take effect, there would likely be a shortage of transport capacity given the great increase in liquid hazardous waste to be transported. The report predicts that, after 2 years, the combination of reduced volumes of wastes to be transported and increased transportation capacity should allow for safe movement of banned wastes.

Texas Department of Water Resources. *Underground Injection Operations in Texas: A Classification and Assessment of Underground Injection Activities*. Compiled by Ben Knape. Report 291. Texas Department of Water Resources, Austin, Texas. December 1984.

> Underground injection operations in Texas are regulated by the Texas Department of Water Resources (succeeded by the Texas Natural Resource Conservation Commission) and the Railroad Commission of Texas. This report presents the history of regulatory program development for underground injection operations in Texas. It describes the construction features, operating practices, nature and volume of injected fluids, relative pollution potentials, legal and jurisdictional considerations, and regulatory recommendations for the various types of injection wells that exist in the state.

Underground Injection Practices Council. *A Class I Injection Well Survey (Phase I Report): Survey of Selected Sites*. D19976.S1. Prepared by CH2M Hill, Gainesville, Florida. April 1986.

> This two-phase study provides a comprehensive data base and an objective summary of the performance and operation of Class I injection wells. Phase I of study consisted of a survey of the operational history of 45 Class I well sites representing 106 individual wells. The selection of these 45 sites was based upon published reports and input from UIC Program directors that identified injection well facilities with some history of or alleged operation problems. This report provides a factual summary of the events surrounding alleged operational problems at 45 Class I injection well facilities. (The results of the study are described in greater detail in Section V.A.)

Underground Injection Practices Council. *A Class I Injection Well Survey (Phase II Report): Survey of Operations*. December 1987.

> In this nationwide study of Class I injection wells, files were reviewed and information collected on 539 operational, previously operational, or planned wells. Phase II of the study consisted of a survey of approximately 250 Class I injection well sites. Phase II included development of a comprehensive data base for each of these sites and an assessment of the performance characteristics of Class I injection wells. Ninety-nine of these wells were eliminated from the data base because they could not be classified as Class I wells by the type of waste injected, they were never constructed, or were under construction when the study was conducted. Construction, operation, and permit data for the remaining 440 wells as of January 1, 1985, were collected and reviewed to evaluate the suitability and reliability of these wells as a waste disposal method. The primary sources of information on Class I wells were the state or federal agencies responsible for permitting the Class I wells in each state. The study concludes that Class I wells are a viable method for disposal of wastewaters, where suitable hydrogeologic conditions exist.

Underground Injection Practices Council. *Class I Injection Well Survey*. Prepared by Golder Associates, Inc., Houston, Texas. April 1990 (updated from April 1986).

> This nationwide survey of Class I injection wells was conducted by Golder Associates to evaluate the changes in geographic distribution and usage patterns and to identify the major concerns of Class I injection operators. The collection of data for this survey occurred from January 1 to March 31, 1990. As concluded in the previous Class I Injection Well Survey (UIPC, 1987), this type of injection, as presently regulated, is a cost-effective yet environmentally sound method of liquid waste disposal when suitable hydrogeologic conditions exist.

U.S. EPA. *Land Disposal Restrictions: Court Decision on Characteristic Hazardous Wastes.* Briefing for Administrator Carol Browner. March 1993.

> This decisional briefing provides an overview of the RCRA Land Disposal Restrictions Program, discusses the Third Third Rule, and highlights key aspects of the DC Circuit Court's 1992 opinion on characteristic wastes and aspects of the Court's decision that EPA must address.

U.S. EPA, Office of Drinking Water. *Report to Congress on Injection of Hazardous Waste.* EPA 570/9-85-003. May 1985 (Second Printing, July 1985).

> This report was prepared to meet the requirement of section 701 of the Hazardous and Solid Waste Amendments of 1984. The report summarizes the collected raw data and provides general information about disposal of waste by underground injection wells. The report also covers aspects of engineering, hydrogeology, waste characteristics, and regulatory controls.

U.S. EPA, Office of Drinking Water. *Site Visit Report; (Facilities Visited as Part of the Data Gathering Effort for the Preparation of the Report to Congress on the Injection of Hazardous Waste).* May 1985.

> This document represents working papers used in preparation of the final *Report to Congress on the Injection of Hazardous Waste.* It is a compilation of field reports on the geology, well design and operation, and regulatory controls based on visits to 20 facilities representing various hydrogeologic, regulatory, and other circumstances.

U.S. EPA, Office of Ground Water and Drinking Water. *Underground Injection Control Program: Information Collection Request*. Prepared by the Cadmus Group, Inc. June 1998.

> This document estimates the burden and cost to operators, states, and EPA associated with implementing the UIC requirements. It outlines required activities associated with siting, constructing, operating, and closing Class I hazardous and nonhazardous injection wells based on the federal requirements at 40 CFR 146 and estimates cost associated with all required activities, including no-migration petitions.

U.S. EPA, Office of Ground Water and Drinking Water. *Analysis of the Effects of EPA Restrictions on the Deep Injection of Hazardous Waste.* EPA 570/9-91-031. October 1991.

> This report describes how EPA regulations, including the no-migration petition requirement, prevent Class I hazardous wells from endangering USDWs. It also documents changes in the Class I hazardous well population and Class I hazardous waste

management practices that have occurred since the regulations were promulgated. The report concludes that Class I hazardous wells are subject to strict technical requirements and are rigorously evaluated to ensure that they do not endanger USDWs.

U.S. EPA, Office of Ground Water and Drinking Water, Underground Injection Control Branch. *Class I Well Failure Analysis: 1988-1991*. Prepared in response to Question 4 in Congressman John D. Dingell's letter to William K. Reilly, dated October 22, 1992, regarding disposal of hazardous wastes, deep injection, and underground wells at 42 U.S.C. section 6924 (F) - (G). March 5, 1993.

This study focuses on the records of over 500 Class I wells in 14 states for the period January 1988 to January 1993. Findings include 130 internal mechanical integrity (MI) failures, 1 external MI failure, and 4 cases of significant waste migration. None of the failures is known to have affected a USDW. The 130 internal MI failures were detected during operation by the continuous annulus monitoring system, and the wells were automatically shut-in until operators could make repairs. The single external MI failure did not involve waste migration from the injection zone or flow into a USDW, and was detected by routine periodic external MIT. Three of the 4 cases of nonhazardous waste migration occurred in areas of Florida known to have small-scale natural fracturing and were detected by deep monitoring wells installed for that purpose. The mechanism of migration of the other case (Aristech, Ironton OH) is unclear, but is believed to be small-scale natural fracturing. The need for deep monitoring wells at every Class I facility is precluded by geologic conditions at most sites, but the option is available to directors if local conditions warrant their use. (The results of the study are described in greater detail in Section V.A.)

U.S. EPA, Office of Water Supply. *The Report to Congress. Waste Disposal Practices and Their Effects on Ground Water*. January 1977.

This report to Congress examines the impact of waste disposal practices, including injection, on groundwater quality in the United States. It discusses the severity of contamination, sources of contaminants, and the regions of the nation where contamination is most prevalent. The report recommended additional legislation for groundwater protection. It also encouraged data collection on potential sources of contamination and more careful siting of new land disposal facilities.

U.S. General Accounting Office. *Hazardous Waste---Controls Over Injection Well Disposal Operations.* Report to the Chairman, Environment, Energy, and Natural Resources Subcommittee, Committee on Government Operations, House of Representatives. GAO/RCED-87-170. August 1987.

At the request of the Chairman of the Environment, Energy, and Natural Resources Subcommittee, House Committee on Government Operations, GAO assessed the controls that monitor the operations of underground injection wells. It evaluated whether and to what extent there is evidence that hazardous waste from underground wells has contaminated underground sources of drinking water. GAO also assessed EPA and state oversight of underground injection of hazardous waste and determined what program changes are expected from an upcoming ban on the underground injection of hazardous waste. (The results of the study are described in greater detail in Section V.A.)

U.S. General Accounting Office. *Information on EPA's Underground Injection Control Program.* GAO/RCED-95-21. Report to The Honorable John D. Dingell, Chairman, Subcommittee on Oversight and Investigations, Committee on Energy and Commerce, House of Representatives. December 5, 1994.

This report reviews certain aspects of EPA's program governing deep-well injection. Specifically, these include (1) results of EPA's efforts to implement the 1984 amendments to ban underground injection of hazardous wastes, (2) accuracy of EPA's inspection and enforcement data to ensure reliable program oversight, and (3) implementation of recommendations to improve the UIC program made in earlier reports. The report concludes that EPA has either implemented or is in the process of implementing most of the recommendations contained in GAO's prior two reports, including strengthening its oversight of each region's underground injection control program. EPA is currently reviewing proposed changes to the oil and gas waste injection well program. One of the proposed changes would require all well operators to search for and plug any improperly plugged wells in the immediate vicinity of their wells, as GAO recommended.

Van Voorhees, Robert F., Kenneth M. Kastner, and Barton D. Day. *New RCRA Land Disposal Restrictions Will Radically Change Regulation of Characteristic Hazardous Waste.* Prepared by Bryan Cave. 1994.

This report is an update on the status of the RCRA LDR rules imposed by EPA in response to the "Third Third" court decision. The report also summarizes the key changes that occurred to the LDR program and EPA's rulemaking schedule.

Visocky, Adrian P., Gary R. Peyton, and John S. Nealon. "Study of Current Underground Injection Control Regulations and Practices in Illinois." *Proceedings of the International Symposium on Subsurface Injection of Liquid Waste.* New Orleans, Louisiana, March 3-5, 1986. Dublin, Ohio: National Water Well Association. 1986.

> The regulatory structure for Class I injection wells is generally adequate in concept and scope to ensure containment of injected wastes and to safeguard underground sources of drinking water in Illinois. There is a need to update and strengthen selected portions of the regulatory practices in the areas of waste sampling protocol, chemical analysis of collected waste samples, and evaluation of well testing and monitoring data.

Class I Research

Collins, A. Gene and M.E. Crocker. *Laboratory Protocol for Determining Fate of Waste Disposed in Deep Wells: Project Summary.* EPA/600/S8-88/008. Ada, Oklahoma: U.S. Environmental Protection Agency, Robert S. Kerr Environmental Research Laboratory. April 1988.

> The objective of this research investigation was to develop a laboratory protocol for use in determining degradation, interaction, and fate of organic wastes disposed of in deep subsurface reservoirs via disposal wells. Knowledge of the ultimate fate of such wastes is important because provisions of the Resource Conservation and Recovery Act (RCRA) require that by August 1988, EPA must show that the disposal of specified wastes by deep-well injection is safe to human health and the environment, or the practice must be stopped. The National Institute for Petroleum and Energy Research (NIPER) developed this protocol primarily by transferring some of its expertise and knowledge of laboratory protocol relevant to improved recovery of petroleum; for example, (1) core analysis, (2) brine analysis, (3) oil analysis, (4) dynamic fluid flow systems, which simulate subsurface reservoir conditions, and (5) appropriately trained personnel. This study was designed to investigate the adsorption properties of a specific reservoir rock which is representative of porous sedimentary geologic formations used as repositories for hazardous organic wastes. Phenol is the principal hazardous waste product that has been injected into the Frio formation; therefore, a decision was made to use phenol and sedimentary rock from the Frio formation for a series of laboratory experiments to demonstrate the protocol. The developed protocol can be used to evaluate mobility, adsorption, and degradation of an organic hazardous waste under simulated subsurface reservoir conditions.

Goolsby, Donald A. *Geochemical Effects and Movement of Injected Industrial Waste in a Limestone Aquifer*. April 1972.

This paper presents a case history and the hydraulic and geochemical effects of an industrial injection well system near Pensacola, Florida. Geochemical effects of the injection, which were first detected at a monitoring well 10 months after injection commenced, included increases in calcium ion concentration, total alkalinity, and nitrogen and methane gas generation. Tests made in 1968 indicated that rapid denitrification and neutralization of the waste occurred near the wells.

Grula, M.M., and E.A. Grula. *Feasibility of Microbial Decomposition of Organic Wastes Under Conditions Existing in Deep Wells.* Final Report. U.S. Bureau of Mines. December 31, 1975.

The objective of this work was to determine the feasibility of inoculation of underground injected wastes with bacteria which would decompose toxic substances underground through metabolic processes. If such a technique could be developed, the toxicity of the injected wastes could eventually be neutralized and thus eliminate a possible, although remote, hazard that would result if the injected wastes found a conducting path to the surface at some future date. Several new aspects of microbe growth under conditions of elevated temperature and pressure were discovered. However, the general conclusion drawn from this work is that biodegradation of organic compounds will be very limited, or entirely absent, under the conditions existing in deep geologic formations.

Hickey, John J., and William E. Wilson. *Results of Deep-Well Injection Testing at Mulberry, Florida.* USGS/WRI 81-75. PB82-193004. Tallahassee, Florida: U.S. Geological Survey, Water Resources Division. February 1982.

At the Kaiser Aluminum and Chemical Corporation plant, Mulberry, Florida, high-chloride, acidic liquid wastes are injected into a dolomite section at depths below about 4,000 feet. Sonar caliper logs made in April 1976 revealed a solution chamber that is about 100 feet in height and has a maximum diameter of 23 feet in the injection zone. Results from two injection tests in 1972 were inconclusive because of complex conditions and the lack of an observation well that was open to the injection zone. In 1975, a satellite monitor well was drilled 2,291 feet from the injection well and open to the injection zone. In April 1975 and September 1976, a series of three injection tests were performed. Based on an evaluation of the factors that affect hydraulic response, water-level data suitable for interpretation of hydraulic characteristics of the injection zone were identified to occur from 200 to 1,000 minutes during the test. Test results indicate that leakage through confining beds is occurring. It appears that the overlying beds are probably relatively impermeable and significantly retard the vertical movement of neutralized waste effluent.

Horvath, Edward. *Interactions of Aquifer Flora and Industrial Waste in a Model Deep Well Disposal System.* Ph.D. Thesis, Department of Microbiology, North Carolina State University at Raleigh. 1977.

> A model system was developed to study the biological compatibility of aqueous industrial waste and subterranean disposal zones for injected waste. The model design incorporated devices for anaerobic, aseptic compositing of effluent samples (for chemical and biological analysis); collection of gases generated in the model elements; isolation of model elements against downstream contamination; and imposition of a normally distributed waste concentration profile in the feed stream. The model demonstrated that degradation of waste constituents was dependent on the addition of inorganic nutrients, even in diluted wastes. The model was also used to study the mutual effects of formaldehyde-free waste and aquifer flora. In effluent samples, formic acid in the waste was completely degraded in 2 months; this degradation is related to reduction of sulfate and nitrate in aquifer flora.

Jafvert, Chad T. and N. Lee Wolfe. *Degradation of Selected Halogenated Ethanes in Anoxic Sediment-Water Systems.* Undated.

> This paper presents the results of a study on degradation of selected halogenated ethanes in anoxic sediment-water suspensions. This study was undertaken to investigate factors that influence the rates of reductive transformations of halogenated hydrocarbons in environmental systems. The study examined both environmental variables and inherent chemical properties of substituted compounds. *Eh* measurements indicated reduced environmental conditions. Hexachloroethane, 1,1,2,2-tetrachloroethane, 1,2-diiodoethane and 1,2-dibromoethane degraded within minutes to days; 1,2-dichloroethane remained in the systems for at least 35 days (the length of the experiment).

Johnston, Orville C., and Ben K. Knape. *Pressure Effects of the Static Mud Column in Abandoned Wells*. LP86-06. Texas Water Commission, Austin, Texas. September 1986.

> This study evaluated historical drilling practices and the safety of injection operations as they relate to possible inter-formational fluid movement through abandoned boreholes, gel strength of wellbore muds, and the effects of geologic and geographic variation on natural borehole closure. It was based on literature and file research and interviews with knowledgeable staff. The study found that wells plugged with mud only resist vertical fluid movement to some extent, that abandoned uncased wells may remain stable for up to decades, mud gel strengths increase with time and temperature, and some abandoned uncased wells close on themselves due to unstable geology.

Kreitler, Charles W. “Hydrogeology of Sedimentary Basins as it Relates to Deep-Well Injection of Chemical Wastes.” Preprint of a paper presented at the International Symposium on Subsurface Injection of Liquid Waste. New Orleans, Louisiana. March 3-5, 1986.

> This paper describes and compares the hydrogeology of three sedimentary basins in Texas (the Gulf of Mexico, East Texas, and Palo Duro basins). Sedimentary basin hydrogeology is important to hazardous waste injection because regional hydrogeology controls the fate, transport, and confinement of chemical wastes injected into deep saline sections of sedimentary basins. Factors that control and describe basin hydrogeology include geologic history, flow mechanisms, potential energy distributions, permeability, the occurrence of faults and fractures, and the origin and age of saline waters.

Leenheer, R.L. Malcolm and W.R. White. *Physical, Chemical, and Biological Aspects of Subsurface Organic Waste Injection Near Wilmington, North Carolina*. U.S. Geological Survey Professional Paper 987. 1976.

> This is a case study of injection of an industrial organic waste into a sand, gravel, and limestone aquifer near Wilmington, North Carolina. Field and laboratory data pertaining to the physical, chemical, and biological effects of waste injection at the site are also presented. The report discusses a conceptual model of the various stages of injectate reactivity and its subsurface movement. Problems with injection well pressure build-up and migration of wastes into shallower aquifers are attributed to reactions between certain organic wastes and aquifer components.

Schwarzenbach, Rene P., and Walter Giger. *Behavior and Fate of Halogenated Hydrocarbons in Ground Water.* Undated.

> Groundwater contamination by halogenated hydrocarbons has been reported on numerous occasions, and these compounds present human health concerns. This paper summarizes the results of laboratory and field studies on the behavior and fate of halogenated hydrocarbons in ground water and during groundwater infiltration. For example, many halogenated hydrocarbons are very mobile and are quite resistant to chemical transformations. Little is known about biotransformation, however. The paper focuses on sorption behavior and mobility of halogenated hydrocarbons in aquifers. The chemical and biological transformations of individual chemicals are discussed as well.

Scrivner, N.C., K.E. Bennett, R.A. Pease, A. Kopatsis, S.J. Sanders, D.M. Clark, and M. Rafal. "Chemical Fate of Injected Wastes." *Proceedings of the International Symposium on Subsurface Injection of Liquid Waste.* New Orleans, Louisiana, March 3-5, 1986. Dublin, Ohio: National Water Well Association. 1986.

> The chemical fate of wastes put into disposal wells can be determined using standard chemical engineering techniques. The concentration of hazardous constituents is typically reduced by reactions within the waste itself or by reactions with the injection zone material, thus reducing any potential impact on the environment. Such reactions include neutralization, hydrolysis, ion exchange, adsorption, precipitation, co-precipitation, and microbial degradation. Extensive research was done to quantify these phenomena, so they could be used in a predictive model.

Vecchioli, John, D.J. McKenzie, C.A. Pascale, and W.E. Wilson. *Active Waste-Injection Systems in Florida, 1976.* Open-File Report 79-1296. U.S. Department of the Interior, Geological Survey. 1979.

> By the end of 1976, seven systems were injecting liquid wastes into Florida's subsurface environment at a combined average rate of 15 million gallons per day. This report presents information for each of these systems on the kind and amount of waste injected and type of pre-treatment, construction characteristics of the injection and monitor wells, type of test and monitoring data available, and briefly discusses any operational problems experienced.

Walter, Bill. "Remediation of Ground-Water Contamination Resulting From the Failure of a Class I Injection Well: A Case History." *Proceedings of the International Symposium on Subsurface Injection of Liquid Waste.* New Orleans, Louisiana, March 3-5, 1986. Dublin, Ohio: National Water Well Association. 1986.

> The purpose of this paper is to describe the sequence of events leading to the contamination of a USDW and the ongoing cleanup process at an oil refinery industrial waste disposal well in the New Orleans, Louisiana area. The case history is unique in that the chronology covers a period of time which includes both pre- and post-regulatory compliance with respect to permitting, monitoring, reporting, inspection and testing of injection wells. Contaminated ground water near the injection zone has not been shown to pose a hazard to any water wells in the area. Furthermore, future ground water contamination being caused by the injection method used is unlikely because injection wells currently permitted in Louisiana are equipped with injection tubing and continuous monitoring of the annular space.

Risk Analyses

Chemical Manufacturers Association UIC Management Task Group. *Comments on Benefits Assessment of EPA's Draft Regulatory Impact Analysis*. Prepared by Woodward-Clyde Consultants. May 1995.

> This critique of the Benefits Analysis in the Phase III RIA evaluated the qualitative risk assessment in the RIA. It emphasized that there have not been any instances of USDW contamination at a facility in compliance with the current UIC program regulations, and the malfunctions cited in the RIA involved facilities that had not yet been required to comply with the UIC program requirements. The comments assert that injection of hazardous waste is particularly low risk compared to other waste management practices, and the risks of handling, transporting, and treating segregated Phase III wastes might actually be greater than the risks of injecting the waste. (The results of the study are described in greater detail in Section V.C.)

GeoTrans, Inc. *A Numerical Evaluation for Class I Injection Wells for Waste Confinement Performance, Final Report, Volumes I and II.* Prepared for U.S. Environmental Protection Agency, Office of Drinking Water, Underground Injection Control Program. September 30, 1987.

> The objective of this study was to evaluate the hydrogeologic response of injection well systems to potential migration pathways in order to assess their impact on waste containment performance. The scope of work assumed that these pathways may exist, allowing waste to migrate from the injection interval into the containment and/or other hydrogeologic strata in the vicinity of injection wells. The study relied on numerical models of groundwater flow and chemical waste transport. Among the findings were the following: under certain conditions, failure can result in escape of significant waste volumes from the injection zone within a localized area; confinement performance increases with distance between the injection well and the failure pathway; and the effect of pumpage on overlying strata increases the volume of waste escaping in the presence of a failure pathway. (The results of the study are described in greater detail in Section V.B.)

Industrial Economics, Inc. *Risk Analyses for Underground Injection of Hazardous Wastes*. Prepared for U.S. EPA, Office of Drinking Water. May 1987.

> This report estimates the magnitude of human health risks posed if underground injection of hazardous wastes resulted in contamination of USDWs. Risk estimates are presented for four geologic settings (East Gulf Coast, Great Lakes, Texas, and Kansas) and various failure modes and barrier thickness between the injection zone and the USDW. The risk

analysis concludes that risk varies substantially (over 20 orders of magnitude) among the geologic settings studied. Also, the risks associated with an abandoned, unplugged borehole are significantly greater than those associated with grout seal failure. Lastly, the report concludes that estimated health risks rise significantly when water is withdrawn from a USDW in the abandoned borehole failure scenario. (The results of the study are described in greater detail in Section V.B.)

Rish, W.A., T. Ijaz, and T.F. Long. *A Probabilistic Risk Assessment of Class I Hazardous Waste Injection Wells*. Draft. 1998.

This study quantitatively estimates the risk of waste containment loss as a result of various sets of events associated with Class I hazardous wells. Through a series of "event trees," the study estimated the probability that an initiating event will occur and be undiscovered, followed by subsequent events that could ultimately result in a release of injected fluids to a USDW. It concluded that Class I hazardous injection wells which meet EPA's minimum design and operating requirements (i.e., a completed no-migration study, two confining zones between the injection zone and the lowermost USDW, completed long string and surface casings, and redundant safety systems) pose risks that are well below acceptable levels. (The results of the risk assessment are described in greater detail in Section V.D.)

U.S. EPA, Office of Ground Water and Drinking Water. *Final Draft: Regulatory Impact Analysis of Proposed Hazardous Waste Disposal Restrictions for Class I Injection of Phase III Wastes: Benefits Analysis*. 1995.

This Benefits Analysis of the proposed Phase III LDR rule estimated human health risks from five Phase III waste constituents (benzene, carbon tetrachloride, chloroform, phenol, and toluene). EPA estimated health risks, including cancer risks and hazard indices, for four geologic settings and two malfunction scenarios (grout seal failure and abandoned, unplugged borehole) at varying drinking water well pumping rates. The results showed that only two of the estimated cancer risks for both malfunction scenarios slightly exceed the risk range generally used by EPA to regulate exposure to carcinogens. The analysis also showed that all but one of the hazard indices for both malfunction scenarios are less than EPA's level of concern for a hazard index of 1.55. (The results of the benefits analysis are described in greater detail in Section V.C.)

U.S. EPA, Office of Ground Water and Drinking Water. *Evaluation of Risks from Exceedance of the Universal Wastewater Treatment Standards (UTS), Including Addendum on HWIR Concentrations.* February 1996.

> To support the *de minimis* requirements in the proposed Phase III rule, EPA analyzed the effects of varying the criteria that underlying hazardous constituent concentrations must be less than 10 times UTS. Results of the analysis showed that, in general, carcinogenic risks were within the range generally used by EPA to regulate exposure to carcinogens, and noncancer risks were less than the hazard index of 1. The analysis concluded that a standard which would be more reflective of the potential for health hazards could be satisfied by defining the *de minimis* criterion as a value between 10 times and 50 times the UTS. (The results of the risk evaluation are described in greater detail in Section V.C.)

U.S. EPA, Office of Solid Waste and Remedial Response. *OSWER Comparative Risk Project: Executive Summary and Overview*. EPA/540/1-89/003. November 1989.

> In this study, several workgroups explored the comparative risks posed by various waste management practices regulated by or under OSWER purview. The study determined that injection wells generally posed medium or low risk for the types of effects examined. The workgroups found Class I hazardous wells to be of comparatively low risk for non-acute heath effects. Injection wells were ranked medium in terms of risk for acute health effects, medium-low for ecological effects, and of low risk for welfare effects. (The results of the study are described in greater detail in Section V.A.)

Ward, D.S., D.R. Buss, T.D. Wadsworth, J. Rosenblum, and S.T. Shaw. *Numerical Simulation for Waste Injection in Deep Wells: Phase 1 — Potential Failure Scenarios, Texas Gulf Coast.* Prepared by Engineering Enterprises, Inc. Prepared for U.S. Environmental Protection Agency, Office of Drinking Water. Herndon, Virginia: GeoTrans, Inc. January 1986.

> This report presents the results of the first phase of a three-part study on well failures. The purpose of Phase 1 was to assess the effect of undetected characteristics (the presence of an abandoned unplugged borehole, fractured discontinuities in the confining zone, failure of a grout seal, and high rates of ground water withdrawal in the aquifer above the confining layer) on the hydrologic performance of an injection zone. Preliminary results include the following findings: under certain conditions, failure can result in escape of significant waste volumes from the injection zone; potential contaminations can vary from waste concentrations that are below detection levels to nearly the same as that of the injectate; and potential contamination occurs within a localized area. These results will be used to formulate recommendations in later phases of the study.

Ward, D.S., T.D. Wadsworth, D.R. Buss, and J.W. Mercer. "Analysis of Potential Failure Mechanisms Pertaining to Hazardous Waste Injection in the Texas Gulf Coast Region." *International Symposium on Subsurface Injection of Liquid Wastes* New Orleans, Louisiana. March 3-5, 1986.

> Three failure scenarios are presented and simulated to assess the effect of undetected characteristics of the Texas Gulf Coast hydrologic system in containing waste. The scenarios are failure of a grout seal, the presence of an abandoned unplugged borehole, and fractured discontinuities in the confining zone. A three-dimensional, finite-difference model is used to simulate these three failure scenarios. Results from the simulations are presented as time series plots of concentrations for various locations in the injection zone and the USDW. These simulations assist in determining the degree of safety inherent in hazardous waste injection.

Ward, David S., David R. Buss, David W. Morganwalp, and Terry D. Wadsworth. "Waste Confinement Performance of Deep Injection Wells." Proceedings from *Solving Ground Water Problems With Models.* Denver, Colorado. February 10-12, 1987.

> A numerical flow and transport model is used to simulate the potential migration of waste over the operational life of an injection well and to evaluate the hydraulic response to hypothetical undetected pathways in the confining formations. Three potential pathways are considered in this analysis: annular grout seal deterioration (cement between casing and formation); presence of an unplugged, abandoned borehole; and plane of fractures or conductive faults in the confining unit. The study includes findings on the impact of migration pathways in four hydrogeologic settings studied (East Gulf Coast, Great Lakes, Texas, and Kansas), and the waste confinement potential within each setting.

Technical and Instructional Documents

Apps, John A., and Chin-Fu Tsang, eds. *Deep Injection Disposal of Hazardous and Industrial Waste: Scientific and Engineering Aspects.* San Diego, California: Academic Press. 1996.

> This book is divided into eight sections that address the major subject areas pertinent to deep injection disposal. The first section concerns some topics from the regulatory perspective. It is followed by an introductory section covering the general aspects of deep-well injection disposal. The focus of this section is on principles and criteria affecting the optimal siting and operation of disposal wells. Section III includes papers on the engineering aspects of well design and emplacement. Following in Section IV is a collection of papers dealing with the important issues of well testing and model development. Section V addresses some of the attendant problems of well performance monitoring. Section VI, consisting of 10 chapters, addresses various aspects of the

chemical processes affecting the fate of the waste in the subsurface environment. Consideration is given here to reactions, such as acid neutralization, between the waste and the geologic medium and to reactions that take place within the wastewater itself, leading to the destruction of hazardous organic compounds. All aspects of this subject are covered, including experimentation, field observation, theoretical modeling, and prediction. Section VII provides a unique perspective on the philosophy and implementation of radioactive waste disposal practices in the former Soviet Union. Section VIII brings together four chapters that discuss novel technologies concerned with the disposal of hazardous waste slurries by deep well injection.

Booz, Allen and Hamilton, Inc. *Development of Procedures and Costs for Proper Abandonment and Plugging of Injection Wells.* Prepared by Booz, Allen and Hamilton Inc. under the direction of Geraghty & Miller, Inc. for U.S. Environmental Protection Agency, Office of Drinking Water. April 30, 1980.

This report summarizes the data analysis and findings on proper abandonment and plugging. The objective was to assist EPA in resolving issues raised in public comments on the proposed abandonment regulations and in completing the rule making. Five major topic areas are discussed: (1) procedures for proper abandonment; (2) feasibility of aquifer restoration; (3) abandonment costs; (4) financial responsibility; and (5) timing of abandonment. Based on the public comments, literature review, and interviews, several recommendations were made. The authors recommended retaining the proposed mud weight equalization requirement for the well preparation phase of abandonment. On the issue of aquifer restoration, they recommended that EPA issue guidance for restoration and allow states to adopt requirements if desired; they concluded it was not feasible to restore all degraded aquifers to baseline levels. The data indicate that costs of new abandonment regulation will be low, since most states already require proper abandonment. The authors suggest that EPA not require immediate abandonment but determine a reasonable deadline beyond which wells must be properly abandoned or put back into operation.

Clark, J. E., P. W. Papadeas, D. K. Sparks, and R. R. McGowen. "Gulf Coast Borehole Closure Test Well: Orangefield, Texas." In: *Proceeding of the Underground Injection Practices Council, 1991 Winter and Summer Meetings.* Point Clear, Alabama, February 24-27, 1991 and Reno, Nevada. July 28-31, 1991.

This paper describes a borehole closure protocol for a Gulf Coast site near Orangefield, Texas, developed by Du Pont. The procedures, based largely upon recommendations provided by EPA Region 6, created a test to demonstrate that, under a worst case scenario, any artificial penetration will seal naturally. The test successfully demonstrated natural sealing. Within 1 week of setting the screen, tubing, and pressure transducers in the borehole, testing confirmed the absence of upward movement of fluid from the test sand. The absence of upward movement is documented by a Schlumberger Water Flow Log and the absence of pressure response on the upper transducer located outside the tubing and inside the casing. Testing was conducted in accordance with specified procedures, with pressure testing conducted at even higher pressures to allow an added margin of confidence. The borehole closure test provides a significant additional margin of confidence that there will be no migration of hazardous constituents from the injection zone for as long as the waste remains hazardous.

Creech, John R. "Class I Injection Well Design Considerations." *Proceedings of the International Symposium on Subsurface Injection of Liquid Waste.* New Orleans, Louisiana, March 3-5, 1986. Dublin, Ohio: National Water Well Association. 1986.

No single material is available that is universally resistant to all types of waste fluids. It is important to match well materials to the injection stream for each injection well application. For some wastes, the ferrous and nonferrous metals or Portland cements commonly used in deep well construction may not offer the desired corrosion resistance. This paper discusses two materials, fiber-reinforced thermoset plastics (FRP) and epoxy resin cement, which have been particularly useful in solving these corrosion resistance problems. The report concludes that when proper materials are used to minimize corrosion, less maintenance and repairs are required and well operations are more reliable.

Davis, Ken E. *Factors Affecting the Area of Review for Hazardous Waste Disposal Wells.* 1986.

This paper presents a method for calculating the area of review for hazardous waste wells. It focuses on artificial pathways such as abandoned test holes or oil and gas wells. These pathways are sealed with cement plugs and drilling mud; the mud provides resistance to upward flow. Flow in an improperly abandoned well bore is initiated when the pressure in an injection zone exceeds the sum of the static mud pressure and the mud gel strength pressure. If the sum of these values is not exceeded, no potential for USDW contamination exists. This paper presents a simplified approach for calculating the area affected by the injection pressures.

Engineering Enterprises, Inc. *Assessment of Treatment Technologies Available to Attain Acceptable Levels for Hazardous Waste in Deep Injection Wells.* Prepared for U.S. Environmental Protection Agency, Underground Injection Control Branch. October 1987.

The potential for restrictions on land-disposal of hazardous waste into deep injection wells under the Hazardous and Solid Waste Amendments of 1984 stimulated the need to evaluate the ability of treatment technologies to reduce the likelihood of migration of hazardous waste constituents from the injection zone. Physical/chemical and biological (both above ground and *in situ*) pre-treatment technologies were assessed with respect to their potential applicability in minimizing the mobility of injected hazardous constituents via adsorption, precipitation, or transformation. The study shows that pretreatment applications to minimize the mobility of contaminants in the injection zone could pose operational problems for deep well injection systems. The extent to which specific contaminants may be removed is unknown and may be complicated by interference with nonhazardous components of the wastestream and by varying composition and concentrations of many wastestreams. One important consideration is that many pretreatment technologies result in the generation of sludge residue, requiring further treatment or disposal.

Geraghty & Miller, Inc. *Technical Manual: Injection Well Abandonment.* Final. Prepared for U.S. Environmental Protection Agency, Office of Drinking Water. 1983.

The purpose of this document is to provide technical guidance to assist the regulator in reviewing proposed well abandonment plans. Emphasizing that proper abandonment consists of more than cement plug placement, the document discusses all aspects of well abandonment. Many procedures and materials are available for well abandonment; their selection is influenced by a number of factors and depends on the specifics of the situation. Frequently, there is no single best method. The approach taken in this document is to identify and discuss the considerations needed to plug and abandon wells of Classes I, II, or III. This approach will enable the regulator to make decisions regarding a specific abandonment plan. In this document, four major chapters follow the introduction in Chapter 1. Chapter 2 considers injection well construction, general considerations important to abandonment, and special Class III abandonment considerations. Chapter 3 discusses the preparation of the well prior to plugging. Procedures for plugging are covered in Chapter 4. Chapter 5 concludes the report with an analysis of abandonment costs.

Geraghty & Miller, Inc., and Booz, Allen & Hamilton, Inc. *Injection Well Construction Practices and Technology*. Prepared for U.S. Environmental Protection Agency, Office of Drinking Water. October 1982.

This document describes construction practices and technologies related to Class I, Class II, and selected Class III and Class V injection wells as defined by EPA. Topics covered include siting, drilling, completion, equipment and materials, corrosion control, well evaluation/logging, and formation testing. This document is not intended to be a comprehensive “how-to” treatment of injection well construction; rather, it is a reference that describes the different aspects of design and construction of injection wells.

Kazmann, Raphael G. "A Closer Look at Deep Well Disposal of Wastes." *Ground Water*. May/June 1981.

> This discussion is directed to conditions in the area away from the injection well: within the quarter-mile to half-mile radius required by the EPA and the various state agencies. The wells and abandoned test holes in this area are seen as potential pathways for the movement of dangerous aqueous wastes from the storage aquifer to the biosphere. The concern here is primarily with conditions in the Gulf Coast area, where the underlying formations are either unconsolidated or semiconsolidated.

Keckler, K. P. "BP Chemicals Lima No-Migration Petition Demonstration Based on Stratigraphic Test-Well and Site-Specific Data." In: *Deep Injection Disposal of Hazardous and Industrial Waste: Scientific and Engineering Aspects.* John A. Apps and Chin-Fu Tsang, eds. San Diego, California: Academic Press. 1996. p. 287-314.

> To demonstrate containment of injected wastewater and to calibrate a site-specific reservoir model, BP Chemicals drilled a stratigraphic test well at a Lima, Ohio, facility where it has injected wastewater from acrylonitrile production since 1968. This paper presents the results of the extensive geologic testing and transport modeling. Sampling from the waste plume at a test well approximately 1,700 feet from the nearest injection well indicated significant degradation of most of the nitriles in the injected waste. In addition, BP developed an extensive database which included core mechanical properties; *in situ* stress test, transient pressure test, and minifrac test data; and a summary of the facility's 20-year operating history.

Ken E. Davis Associates. *Annulus Pressure Monitoring Systems for Class I Wells.* Prepared by Ken E. Davis Associates, Houston, Texas, for U.S. Environmental Protection Agency, Office of Drinking Water. October 1986.

> This report presents specific information concerning equipment and procedures currently in use or available for detecting leakage from the annulus between the injection tubing and the protection casing in injection wells. In current operating practice, this annulus space is filled with nonhazardous, nonreactive fluid and maintained at a predetermined pressure. The annulus pressure is monitored because a leak will result in a change in the annulus pressure. However, the minimum rate of leakage or the amount of leakage that can be detected by pressure-monitoring systems is not known. In addition, information is also needed on alternative means of detecting leaks in disposal wells. This report is therefore not confined to reporting on equipment and systems in use, but also on systems

that have the potential for such use. This report includes a review and inventory of equipment that is, has, or could be used to detect leaks into or out of the annulus space in injection wells. In addition, the review compares the leak detection capability of wells completed with packers, seal assemblies, and fluid seals.

Mankin, Charles J., Tola B. Moffett, and Laura E. Whitaker. *Evaluation of Certain Crucial Issues Regarding the Use of Hazardous Waste Injection Wells*. Prepared by the University of Alabama Environmental Institute for Waste Management Studies for U.S. Environmental Protection Agency, Office of Drinking Water. August 1988.

This report contains an evaluation of specific methodologies for siting, testing, and monitoring of Class I injection wells. The evaluation of potential locations for hazardous waste injection wells is a site-specific process which is analogous to that performed in the siting of oil and gas wells. Seismic surveys and pressure testing, both of which are used in the petroleum industry, are recommended. Regional studies and standard well logs are considered insufficient. Hydrogeologic models of the site should be developed and updated through the drilling and testing of the injection well. Recommendations for the monitoring and testing of industrial waste injection wells are discussed.

SMC Martin, Inc., and The Underground Injection Control Quality Assurance Workgroup. *Technical Assistance Document: Corrosion, Its Detection and Control in Injection Wells*. Prepared for U.S. Environmental Protection Agency, Office of Drinking Water. August 1987.

This report summarizes available information on the occurrence, detection, and control of corrosion in injection wells. Corrosion of the metallic materials and degradation of nonmetallic materials are possible causes of leaks in injection wells. General corrosion, the uniform or near-uniform thinning of metal, may be addressed by building a corrosion allowance into the design thickness of the well casing. Localized corrosion, such as pitting and cracking, is problematic because it can lead to premature failure of the well.

Tsang, C. F. "Some Hydrologic Factors Affecting the Safety of Deep Injection Disposal of Liquid Wastes." In: *Deep Injection Disposal of Hazardous and Industrial Waste: Scientific and Engineering Aspects.* John A. Apps and Chin-Fu Tsang, eds. San Diego, California: Academic Press. 1996. p. 35-45.

Factors such as the presence of faults, formation fracturing pressures, and hydrology as they relate to monitoring systems are important considerations in the planning of deep injection wells. This paper reviews three phenomena that could affect estimates of waste plume movement within the injection zone. They are formation heterogeneity; sloping of the injection zone, which can cause a plume to flow by gravity; and fractures that can form in the injection zone if the injection pressure is too high. The paper concludes that the issues presented should be considered in determining optimal designs for monitoring deep well injection.

U.S. EPA, Office of Drinking Water, State Programs Division. *Technical Assistance Document: The Application and Calibration of Pressure Instruments, Flowmeters, and Flow Control Devices as Applied to Injection Wells.* EPA 570/9-87-003. September 1987.

This report discusses the various devices that are used to measure the pressures and the flow rates of injection wells, particularly those instruments used by regulatory agencies and operators for assessing well operations. This report introduces the basic concepts of flow and pressure metering in injection wells to EPA regional office staffers, state regulators, and the regulated community.

U.S. EPA, Office of Ground Water and Drinking Water, and U.S. Department of Energy, Environmental Management, Office of Technology Development. *Scientific and Engineering Aspects of Deep Injection Disposal of Hazardous and Industrial Wastes: An International Symposium*. Lawrence Berkeley Laboratory, Berkeley, California. May 10-13, 1994.

This document contains abstracts of papers presented at an international symposium on the scientific and engineering aspects of the deep injection of hazardous and industrial wastes. The symposium covered general aspects of deep well injection, engineering aspects of well emplacement, well testing, monitoring, and model development.

U.S. EPA, Office of Research and Development. *Assessing the Geochemical Fate of Deep-Well-Injected Hazardous Waste: A Reference Guide*. EPA/625/6-89/025a. June 1990.

This reference guide presents state-of-the-art information on the geochemical fate of injected wastes to address issues related to no-migration petitions and determination of the compatibility of injected wastes with the injection zone formation. The seven chapters in the guide provide an overview of injection practices in the United States, processes affecting the geochemical fate of wastes, environmental factors affecting geochemical processes, geochemical characteristics of hazardous wastes, methods and models for predicting the geochemical fate of injected wastes, field sampling and laboratory procedures, and case studies of deep-well injection of hazardous wastes.

Warner, D. L. "Monitoring of Class I Injection Wells." In: *Deep Injection Disposal of Hazardous and Industrial Waste: Scientific and Engineering Aspects.* John A. Apps and Chin-Fu Tsang, eds. San Diego, California: Academic Press. 1996. p. 421-431.

Class I injection wells have historically been monitored by observing well operating parameters and by testing and logging to verify the mechanical integrity of the well.

Engineering and geologic reasoning support such limited monitoring as the most appropriate, since most possible vertical pathways for escape of fluids from the injection zone are concentrated in or immediately around the injection well. Such pathways can be detected or inferred by monitoring and testing of the injection well. This paper discusses ways to determine the necessity of monitoring wells, and how wells should be selected and positioned.

Warner, Don L., and Jay H. Lehr. *An Introduction to the Technology of Subsurface Wastewater Injection*. Prepared for U.S. Environmental Protection Agency, Office of Research and Development, Robert S. Kerr Environmental Research Laboratory. December 1977.

This report provides an introduction to the proper siting, construction, testing, operation, and abandonment of injection wells. Prior to construction, the local geologic and hydrologic setting must be determined to assess compatibility with injected wastes. If necessary, the waste may be treated to ensure physical, biological, and chemical compatibility with the injection zone. Once the well begins operation, it should be monitored for changes in injection conditions which may lead to system failure. (Reprinted as: Warner, Don L, and Jay H. Lehr. *Subsurface Wastewater Injection: The Technology of Injecting Wastewater into Deep Wells for Disposal.* Berkeley, California: Premier Press. 1981.)

Whiteside, R. F., T. P. Roth, and J. R. Creech. "Applications of Corrosion-Resistant Materials and Cement in the Design and Construction of Class I Injection Wells." In: *Deep Injection Disposal of Hazardous and Industrial Waste: Scientific and Engineering Aspects.* John A. Apps and Chin-Fu Tsang, eds. San Diego, California: Academic Press. 1996. p. 145-164.

Although numerous alternative candidate materials have been available, the typical problems encountered with corrosion-resistant injection well designs prior to the mid to late 1970s were due mainly to the inherent difficulties in adapting various alloy metals, fiberglass, elastomers, resins, plastics, etc., from surface to subsurface applications. Refinements over the past 15 to 20 years in the fabrication and machining of these materials and well designs have dramatically improved the integration of specialized corrosion-resistant materials into the design of Class I wells. This article describes these materials and how they are tested by manufacturers.

APPENDIX A

Land Disposal Program Flexibility Act of 1996

Public Law 104-119, March 26, 1996

PUBLIC LAW 104–119—MAR. 26, 1996

LAND DISPOSAL PROGRAM FLEXIBILITY ACT OF 1996

Public Law 104–119
104th Congress

An Act

Mar. 26, 1996
[H.R. 2036]

To amend the Solid Waste Disposal Act to make certain adjustments in the land disposal program to provide needed flexibility, and for other purposes.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

Land Disposal Program Flexibility Act of 1996.
Environmental protection.
42 USC 6901 note.

SECTION 1. SHORT TITLE.

This Act may be cited as the "Land Disposal Program Flexibility Act of 1996".

SEC. 2. LAND DISPOSAL RESTRICTIONS.

42 USC 6924.

Section 3004(g) of the Solid Waste Disposal Act is amended by adding after paragraph (6) the following:

"(7) Solid waste identified as hazardous based solely on one or more characteristics shall not be subject to this subsection, any prohibitions under subsection (d), (e), or (f), or any requirement promulgated under subsection (m) (other than any applicable specific methods of treatment, as provided in paragraph (8)) if the waste—

"(A) is treated in a treatment system that subsequently discharges to waters of the United States pursuant to a permit issued under section 402 of the Federal Water Pollution Control Act (commonly known as the "Clean Water Act") (33 U.S.C. 1342), treated for the purposes of the pretreatment requirements of section 307 of the Clean Water Act (33 U.S.C. 1317), or treated in a zero discharge system that, prior to any permanent land disposal, engages in treatment that is equivalent to treatment required under section 402 of the Clean Water Act (33 U.S.C. 1342) for discharges to waters of the United States, as determined by the Administrator; and

"(B) no longer exhibits a hazardous characteristic prior to management in any land-based solid waste management unit.

"(8) Solid waste that otherwise qualifies under paragraph (7) shall nevertheless be required to meet any applicable specific methods of treatment specified for such waste by the Administrator under subsection (m), including those specified in the rule promulgated by the Administrator June 1, 1990, prior to management in a land-based unit as part of a treatment system specified in paragraph (7)(A). No solid waste may qualify under paragraph (7) that would generate toxic gases, vapors, or fumes due to the presence of cyanide when exposed to pH conditions between 2.0 and 12.5.

"(9) Solid waste identified as hazardous based on one or more characteristics alone shall not be subject to this subsection, any prohibitions under subsection (d), (e), or (f), or any requirement promulgated under subsection (m) if the waste no longer exhibits a hazardous characteristic at the point of injection in any Class I injection well permitted under section 1422 of title XIV of the Public Health Service Act (42 U.S.C. 300h–1).

"(10) Not later than five years after the date of enactment of this paragraph, the Administrator shall complete a study of hazardous waste managed pursuant to paragraph (7) or (9) to characterize the risks to human health or the environment associated with such management. In conducting this study, the Administrator shall evaluate the extent to which risks are adequately addressed under existing State or Federal programs and whether unaddressed risks could be better addressed under such laws or programs. Upon receipt of additional information or upon completion of such study and as necessary to protect human health and the environment, the Administrator may impose additional requirements under existing Federal laws, including subsection (m)(1), or rely on other State or Federal programs or authorities to address such risks. In promulgating any treatment standards pursuant to subsection (m)(1) under the previous sentence, the Administrator shall take into account the extent to which treatment is occurring in land-based units as part of a treatment system specified in paragraph (7)(A).

"(11) Nothing in paragraph (7) or (9) shall be interpreted or applied to restrict any inspection or enforcement authority under the provisions of this Act.".

SEC. 3. GROUND WATER MONITORING.

(a) AMENDMENT OF SOLID WASTE DISPOSAL ACT.—Section 4010(c) of the Solid Waste Disposal Act (42 U.S.C. 6949a(c)) is amended as follows:

(1) By striking "CRITERIA.—Not later" and inserting the following: "CRITERIA.—

"(1) IN GENERAL.—Not later".

(2) By adding at the end the following new paragraphs:

"(2) ADDITIONAL REVISIONS.—Subject to paragraph (3), the requirements of the criteria described in paragraph (1) relating to ground water monitoring shall not apply to an owner or operator of a new municipal solid waste landfill unit, an existing municipal solid waste landfill unit, or a lateral expansion of a municipal solid waste landfill unit, that disposes of less than 20 tons of municipal solid waste daily, based on an annual average, if—

"(A) there is no evidence of ground water contamination from the municipal solid waste landfill unit or expansion; and

"(B) the municipal solid waste landfill unit or expansion serves—

"(i) a community that experiences an annual interruption of at least 3 consecutive months of surface transportation that prevents access to a regional waste management facility; or "(ii) a community that has no practicable waste management alternative and the landfill unit is located in an area that annually receives less than or equal to 25 inches of precipitation.

"(3) PROTECTION OF GROUND WATER RESOURCES.—

"(A) MONITORING REQUIREMENT.—A State may require ground water monitoring of a solid waste landfill unit that would otherwise be exempt under paragraph (2) if necessary to protect ground water resources and ensure compliance with a State ground water protection plan, where applicable.

"(B) METHODS.—If a State requires ground water monitoring of a solid waste landfill unit under subparagraph (A), the State may allow the use of a method other than the use of ground water monitoring wells to detect a release of contamination from the unit.

"(C) CORRECTIVE ACTION.—If a State finds a release from a solid waste landfill unit, the State shall require corrective action as appropriate.

"(4) NO-MIGRATION EXEMPTION.—

"(A) IN GENERAL.—Ground water monitoring requirements may be suspended by the Director of an approved State for a landfill operator if the operator demonstrates that there is no potential for migration of hazardous constituents from the unit to the uppermost aquifer during the active life of the unit and the post-closure care period.

"(B) CERTIFICATION.—A demonstration under subparagraph (A) shall be certified by a qualified ground-water scientist and approved by the Director of an approved State.

"(C) GUIDANCE.—Not later than 6 months after the date of enactment of this paragraph, the Administrator shall issue a guidance document to facilitate small community use of the no migration exemption under this paragraph.

"(5) ALASKA NATIVE VILLAGES.—Upon certification by the Governor of the State of Alaska that application of the requirements described in paragraph (1) to a solid waste landfill unit of a Native village (as defined in section 3 of the Alaska Native Claims Settlement Act (16 U.S.C. 1602)) or unit that is located in or near a small, remote Alaska village would be infeasible, or would not be cost-effective, or is otherwise inappropriate because of the remote location of the unit, the State may exempt the unit from some or all of those requirements. This paragraph shall apply only to solid waste landfill units that dispose of less than 20 tons of municipal solid waste daily, based on an annual average.

"(6) FURTHER REVISIONS OF GUIDELINES AND CRITERIA.—Recognizing the unique circumstances of small communities, the Administrator shall, not later than two years after enactment of this provision promulgate revisions to the guidelines and criteria promulgated under this subtitle to provide additional flexibility to approved States to allow landfills that receive 20 tons or less of municipal solid waste per day, based on an annual average, to use alternative frequencies of daily cover application, frequencies of methane gas monitoring, infiltration layers for final cover, and means for demonstrating financial assurance: *Provided,* That such alternative requirements take into account climatic and hydrogeologic conditions and are protective of human health and environment.”.

(b) REINSTATEMENT OF REGULATORY EXEMPTION.—It is the intent of section 4010(c)(2) of the Solid Waste Disposal Act, as added by subsection (a), to immediately reinstate subpart E of part 258 of title 40, Code of Federal Regulations, as added by the final rule published at 56 Federal Register 50798 on October 9, 1991. 42 USC 6949a note.

SEC. 4. TECHNICAL CORRECTIONS TO SOLID WASTE DISPOSAL ACT.

The Solid Waste Disposal Act is amended as follows:

(1) In section 3001(d)(5) by striking “under section 3001” and inserting “under this section”. 42 USC 6921.

(2) By inserting a semicolon at the end of section 3004(q)(1)(C). 42 USC 6924.

(3) In section 3004(g), by striking “subparagraph (A) through (C)” in paragraph (5) and inserting “subparagraphs (A) through (C)”.

(4) In section 3004(r)(2)(C), by striking “pertroleum-derived” and inserting “petroleum-derived”.

(5) In section 3004(r)(3) by inserting after “Standard” the word “Industrial”.

(6) In section 3005(a), by striking “polycholorinated” and inserting “polychlorinated”. 42 USC 6925.

(7) In section 3005(e)(1), by inserting a comma at the end of subparagraph (C).

(8) In section 4007(a), by striking “4003” in paragraphs (1) and (2)(A) and inserting “4003(a)”. 42 USC 6947.

Approved March 26, 1996.

LEGISLATIVE HISTORY—H.R. 2036:

HOUSE REPORTS: No. 104–454 (Comm. on Commerce).
CONGRESSIONAL RECORD, Vol. 142 (1996):
Jan. 30, 31, considered and passed House.
Feb. 20, considered and passed Senate, amended.
Mar. 7, House concurred in Senate amendments.
WEEKLY COMPILATION OF PRESIDENTIAL DOCUMENTS, Vol. 32 (1996):
Mar. 26, Presidential statement.

○

APPENDIX B

Supplemental Risk Analysis in Support of The Class I UIC Regulatory Impact/Benefits Analysis For Phase III Wastes:

Examination of Risks Associated With East Gulf Coast/Abandoned Borehole Scenario And Variations in Permeability Ratio Between The Injection Zone And The Confining Layer

Supplemental Risk Analysis in Support of The Class I UIC Regulatory Impact/Benefits Analysis For Phase III Wastes:

Examination of Risks Associated With East Gulf Coast/Abandoned Borehole Scenario And Variations in Permeability Ratio Between The Injection Zone And The Confining Layer

Introduction

This study further explores the results of the quantitative risk analysis conducted in the benefits assessment for the Class I well injection of Phase III wastes described in the revised Phase III RIA.[1] In that analysis, EPA estimated health risks associated with five Phase III waste constituents under two malfunction scenarios (grout seal failure and abandoned unplugged borehole) in four geologic settings. The study also assessed the effects of varying drinking water well pumping rates. The analysis showed that the only cases of elevated cancer and non-cancer risks estimated were associated with exposure to benzene or carbon tetrachloride via migration of injected Class I waste through an abandoned borehole into a USDW, with a drinking water well pumping from an overlying aquifer at a rate of 720,000 gallons per day (gpd). The slightly elevated risks were observed only when the above scenarios was assumed to be located in a hydrogeologic situation comparable to the East Gulf Coast.

In the GeoTrans[2] study, the model of the East Gulf Coast hydrogeology was designed to examine the effect of highly permeable confining zones. Specifically, GeoTrans set the ratio of the hydraulic conductivity between adjacent formations to be less than 100:1. That is, the injection zone was less than 100 times more permeable than the confining layer.

The purpose of this analysis is to supplement the GeoTrans[3] original risk assessment of the above scenario by assuming five different permeability ratios of 1:1,000; 1:10,000; 1:100,000; 1:1,000,000; and, 1:10,000,000. GeoTrans varied the permeability ratio by reducing the hydraulic conductivity of the lowest hydrogeologic zone (aquitard 6) just above the injection zone.

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[1] U.S. EPA, Office of Ground Water and Drinking Water. *Draft Regulatory Impact Analysis of Proposed Hazardous Waste Disposal Restrictions for Class I Injection of Phase III Wastes: Benefits Analysis.* 1995.

[2] GeoTrans, Inc. *Numerical Simulations of Deep Injection Wells in Support of EPA's UIC, Office of Ground Water and Drinking Water.* August 21, 1995.

[3] GeoTrans, Inc. *Numerical Simulations of Deep Injection Wells in Support of EPA's UIC, Office of Ground Water and Drinking Water.* September 17, 1996.

Other aquifer and aquitard properties from the former analysis were unchanged in this analysis. Specifically:

- The same hydrogeologic scenario is used: the East Gulf Coast hydrogeology, with an abandoned borehole, and a high rate of pumping from the overlying aquifer.

- The same quantitative risk methodology as described previously and based on the Industrial Economics, Inc. (IEc) methodology is used.[4] The current version of SWIFT/486 was used to model these scenarios.

- The chemicals of concern for this risk assessment were selected via a procedure consistent with that in the original risk analysis. Carbon tetrachloride and benzene, two organic contaminants reported in Class I facilities, were selected as the chemicals of concern. (The present risk analysis also includes arsenic, an inorganic contaminant reported in Class I facilities.)

- The present analysis also uses the methods described in the previous studies to determine the normalized injectate concentrations, to provide a range of concentrations achieved, and to examine the ultimate effect on the risk estimates at different locations relative to the injection well and USDW.

To assess the cancer and non-cancer risks from exposure to each of these three contaminants, EPA used the 90th percentile concentration data for each contaminant as reported in the Class I facility-specific data from OGWDW's 1996 Class I UICWELLS database. The waste stream concentrations ("initial concentrations") of Phase III contaminants were obtained from recent information provided by Class I facilities on concentrations of contaminants in their waste streams.

The following section describes the normalized injectate concentrations modeled by GeoTrans[5] assuming the variations in permeability ratio as noted above and assuming three different receptors. Concentrations at these receptors are upper-bound estimates.

Quantitative Risk Assessment

EPA used the results of GeoTrans' fate and transport modeling of drinking water contamination from a nearby unplugged borehole to estimate the concentrations of certain Phase III contaminants at three selected receptor locations within or below the USDW. The three receptors are located: 500 feet from the injection well in an aquifer below the USDW (receptor

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[4] Industrial Economics, Inc. *Risk Analyses for Underground Injection of Hazardous Wastes.* May 1987.

[5] GeoTrans, Inc. 1996.

B2); 500 feet from the injection well in the USDW (receptor A2); and approximately 2,000 feet from the injection well in the USDW (receptor A4).

The concentrations at each receptor were used to estimate the risk to human health from the hypothetical occurrence of these failures. Exhibits 1 and 2 present the normalized injectate concentrations at the designated receptors assuming permeability ratios of 1:1,000 and 1:10,000,000, respectively.

Exhibit 1

Normalized Injectate Concentrations in the USDW Based on East Gulf Coast Hydrogeology/Abandoned Borehole Failure Scenario With Pumping at 720,000 GPD and 1:1,000 Permeability Ratio [1]

Geographic Location	Abandoned Unplugged Borehole: Concentration (mg/L) 500 feet away from the injection well in the USDW plus a well pumping drinking water at 720,000 gpd (and time of occurrence in years) [2]	Abandoned Unplugged Borehole: Concentration (mg/L) 500 feet away from the injection well in an aquifer below the USDW plus a well pumping drinking water at 720,000 gpd (and time of occurrence in years) [3]	Abandoned Unplugged Borehole: Concentration (mg/L) 2,000 feet away from the injection well in the USDW plus a well pumping drinking water at 720,000 gpd (and time of occurrence in years) [4]
East Gulf Coast	2.52E-04 (22.2 years)	3.34E-02 (22.2 years)	4.83E-10 (22.2 years)

[1] Source: GeoTrans, Inc. September 13, 1996. *Numerical Simulation of Deep Injection Wells in Support of EPA's UIC, Office of Ground Water and Drinking Water.*

[2] The concentration noted is based on the concentration at receptor A2, located 500 feet away from the injection well in the USDW.

[3] The concentration noted is based on the concentration at receptor B2, located adjacent to an abandoned unplugged borehole that is 573 feet away from the injection well in an aquifer below the USDW.

[4] The concentration noted is based on the concentration at receptor A4, located 2,000 feet away from the injection well in the USDW.

Exhibit 2
Normalized Injectate Concentrations in the USDW
Based on East Gulf Coast Hydrogeology/Abandoned Borehole Failure Scenario
With Pumping at 720,000 GPD and 1:10,000,000 Permeability Ratio [1]

Geographic Location	Abandoned Unplugged Borehole: Concentration (mg/L) 500 feet away from the injection well in the USDW plus a well pumping drinking water at 720,000 gpd (and time of occurrence in years) [2]	Abandoned Unplugged Borehole: Concentration (mg/L) 500 feet away from the injection well in an aquifer below the USDW plus a well pumping drinking water at 720,000 gpd (and time of occurrence in years) [3]	Abandoned Unplugged Borehole: Concentration (mg/L) 2,000 feet away from the injection well in the USDW plus a well pumping drinking water at 720,000 gpd (and time of occurrence in years) [4]
East Gulf Coast	1.68E-04 (22.2 years)	2.10E-02 (22.2 years)	3.06E-10 (22.2 years)

[1] Source: GeoTrans, Inc. September 13, 1996. *Numerical Simulation of Deep Injection Wells in Support of EPA's UIC, Office of Ground Water and Drinking Water.*

[2] The concentration noted is based on the concentration at receptor A2, located 500 feet away from the injection well in the USDW.

[3] The concentration noted is based on the concentration at receptor B2, located adjacent to an abandoned unplugged borehole that is 573 feet away from the injection well in an aquifer below the USDW.

[4] The concentration noted is based on the concentration at receptor A4, located 2,000 feet away from the injection well in the USDW.

Exhibit 3 presents toxicity factors and concentration data for benzene, carbon tetrachloride, and arsenic. Information presented includes the Cancer Slope Factor, Reference Dose, and initial concentrations for each contaminant.

Exhibit 3

Toxicity and Concentration Data for Hazardous Phase III Contaminants

	Benzene	Carbon Tetrachloride	Arsenic
Chemical Abstract Services (CAS) Number	71-43-2	56-23-5	7440-38-2
Cancer Slope Factor* $(mg/kg/day)^{-1}$	2.9×10^{-2}	1.3×10^{-1}	1.5×10^{0}
Reference Dose (RfD)** (mg/kg/day)	NA	7×10^{-4}	3.4×10^{-4}
Initial Concentration*** (mg/L)	47	2.23	2.6

* Source: U.S. EPA. January 11, 1995. Integrated Risk Information System (IRIS). Arsenic CSF is from IRIS. 1993.

** Source: U.S. EPA. January 11, 1995. IRIS. Arsenic RfD is from IRIS. 1993.

*** Based on the 90th percentile concentration from USEPA OGWDW. 1996. UICWELLS database.

NA = Not Available

Methodology for Estimating Health Risks

The risk to human health was estimated separately for benzene, carbon tetrachloride, and arsenic. The risk calculations were based on several assumptions about the average individual. These include an average body weight of 70 kilograms and the ingestion of 2 liters of contaminated water per day. The calculations also assumed that the affected person's body retains 100 percent of the contaminants in the water.

The calculation of carcinogenic risk was based on the Cancer Slope Factor (CSF) developed for individual carcinogens by EPA's Carcinogen Assessment Group. The Cancer Slope Factor, an upper-bound estimate of the probability of an individual developing cancer as a result of a lifetime of exposure to a particular level of a potential carcinogen, is calculated as follows:

- The actual chemical concentration in the drinking water, expressed as milligrams per liter, is calculated by multiplying the unit concentration from the dispersion modeling by the contaminant concentration in the waste stream.

- Using the above assumptions about consumption of drinking water, the concentration figure is converted to a dose expressed in milligrams of contaminant consumed per kilogram of body weight per day (mg/kg/day).

- The dose is multiplied by the cancer unit risk factor, resulting in an upper-bound estimate of the increased likelihood of developing cancer. The CSFs for benzene, carbon tetrachloride, and arsenic are presented in Exhibit 3.

To calculate noncarcinogenic health effects, the chronic daily intake (CDI), in mg/kg/day, of each contaminant is estimated. The CDI is based on a 70-year lifetime exposure. The CDI is then compared to the toxicity factor for non-cancer effects, known as the Reference Dose (RfD). The RfD is an estimate of a daily exposure level for the human population, including sensitive subpopulations, that is likely to be without an appreciable risk of adverse effects during a lifetime of exposure. The RfD represents EPA's preferred toxicity value for evaluating non-cancer effects.[6] Exhibit 3 presents the RfD for carbon tetrachloride and arsenic. Benzene does not have an RfD.

The ratio of the CDI to the RfD represents the hazard index, which is used to compare the relative risk posed by contaminants. A hazard index of greater than one indicates an increased risk of non-carcinogenic health effects.

Results of Applying Methodologies

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[6] U.S. EPA. *Risk Assessment Guidance for Superfund. Volume I. Human Health Evaluation Manual*. EPA/540/1-89/002. 1989.

Exhibit 4 summarizes the cancer risks and hazard indices for each chemical of concern given the malfunction scenario and assuming 1:1,000 and 1:10,000,000 permeability conductivity ratios. Exhibits 5 to 8 present specific input parameters used in the calculations of cancer risks and hazard indices for benzene, carbon tetrachloride, and arsenic under the scenario of concern. The quantitative risk assessment for the East Gulf Coast/abandoned borehole scenario shows the following results:

- Cancer risks at receptors in the USDW are lower than those from the aquifer below the USDW. The cancer risks were higher for the 1:1,000 permeability ratio than for the 1:10,000,000 permeability ratio.

    - The risk assessment shows that cancer risks are the lowest at the receptor 2,000 feet from the well for either permeability ratio. These risks are extremely low: on the order of four- to 120-in-one-trillion.

    - Cancer risks are higher at the receptor located 500 feet from the injection well in the aquifer below the USDW. These cancer risks range from on the order of 1.4-in-one-million to 1.8-in-one-hundred-thousand.

    - The cancer risks associated with exposures to concentrations estimated at receptor B2, 500 feet from the injection well in an aquifer below the USDW, consistently exceed the one-in-ten-thousand to one-in-one-million risk range generally used by EPA to regulate exposures to carcinogens.[7] All other cancer risk estimates are within regulatory levels.

- The hazard indices for each contaminant were lowest at the receptor 2,000 feet from the well, higher at the receptor 500 feet from the well, and the highest in the aquifer below the USDW. For both carbon tetrachloride and arsenic, hazard indices were higher for the 1:1,000 permeability ratio than for the 1:10,000,000 permeability ratio.

- Similar to the results for the cancer risk estimates, all of the hazard indices estimated at the receptor in the aquifer below the USDW at both permeability ratios are greater than EPA's level of concern for a hazard index of greater than 1. All other hazard index estimates are within regulatory levels.

Thus, the cancer risks and hazard indices in all cases are higher assuming the permeability ratio of 1:1,000 versus 1:10,000,000. The cancer and non-cancer risks associated with exposure to contaminant concentrations at receptor B2, 500 feet from the injection well in an aquifer below the USDW are, in all cases, above the level recommended by EPA as being acceptable for human health exposures.

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[7] U.S. EPA. Office of Solid Waste and Emergency Response. *Role of the Baseline Risk Assessment in Superfund Remedy Selection Decisions.* OSWER Directive 9355.0-30. 1991.

It should be noted that, given the existing UIC regulations, a failure scenario such as that described in this analysis occurring is highly unlikely. Current regulations require that an area of review (AoR) surrounding injection wells be identified, and abandoned boreholes within this area be located. Therefore, a borehole within 500 feet of the well would be identified and properly plugged before any injection would be permitted.

Exhibit 4

Cancer Risks and Hazard Indices for Contaminants of Concern Based on East Gulf Coast/Abandoned Borehole Scenario With Pumping at 720,000 GPD and 1:1,000 and 1:10,000,000 Permeability Ratio [1]

Chemical/ Receptor Location	Cancer Risk/1:1,000 Permeability Ratio	Hazard Index/ 1:1,000 Permeability Ratio	Cancer Risk/ 1:10,000,000 Permeability Ratio	Hazard Index/ 1:10,000,000 Permeability Ratio
Benzene:				
- 500 feet from well in base of USDW plus pumping	9.82E-06	NA	6.55E-06	NA
- 500 feet from well in aquifer below USDW plus pumping	1.30E-03	NA	8.19E-04	NA
- 2,000 feet from well in base of USDW plus pumping	1.88E-11	NA	1.19E -11	NA
Carbon Tetrachloride:				
- 500 feet from well in base of USDW plus pumping	2.09E-06	2.30E-02	1.39E-06	1.53E-02
- 500 feet from well in aquifer below USDW plus pumping	2.77E-04	3.04E+00	1.74E-04	1.91E+00
- 2,000 feet from well in base of USDW plus pumping	4.00E-12	4.40E-08	2.54E-12	2.79E-08
Arsenic:				
- 500 feet from well in base of USDW plus pumping	2.81E-05	6.25E-02	1.87E-05	4.16E-02
- 500 feet from well in aquifer below USDW plus pumping	3.73E-03	8.28E+00	2.34E-03	5.21E+00
- 2,000 feet from well in base of USDW plus pumping	5.39E-11	1.20E-07	3.41E-11	7.58E-08

Exhibit 5

CANCER RISKS ASSOCIATED WITH BENZENE, CARBON TETRACHLORIDE, AND ARSENIC ASSUMING EAST GULF COAST WITH AN ABANDONED BOREHOLE SCENARIO AND WITH PUMPING AT 720,000 GPD AND A PERMEABILITY RATIO OF 1:1,000 BETWEEN THE INJECTION ZONE AND THE CONFINING LAYER

Chemical/ Receptor Location	Initial Constituent Concentrations (mg/l) [1]	Normalized Injectate Concentrations (mg/l) [2]	Drinking Water Concentration (mg/l)	Ingestion Conversion Factor (l/kg/day) [3]	Unit Dose (mg/kg/day)	Cancer Slope Factor $(mg/kg/day)^{-1}$ [4]	Individual Cancer Risk
Benzene:							
- 500 feet from well in base of USDW plus pumping [5, 6]	47.00	2.250E-04	1.18E-02	0.0286	3.39E-04	2.90E-02	9.82E-06
- 500 feet from well in aquifer below USDW plus pumping [7]	47.00	3.340E-02	1.57E+00	0.0286	4.49E-02	2.90E-02	1.30E-03
- 2,000 feet from well in base of USDW plus pumping [8]	47.00	4.830E-10	2.27E-08	0.0286	6.49E-10	2.90E-02	1.88E-11
Carbon Tetrachloride:							
- 500 feet from well in base of USDW plus pumping [5, 6]	2.23	2.250E-04	5.62E-04	0.0286	1.61E-05	1.30E-01	2.09E-06
- 500 feet from well in aquifer below USDW plus pumping [7]	2.23	3.340E-02	7.45E-02	0.0286	2.13E-03	1.30E-01	2.77E-04
- 2,000 feet from well in base of USDW plus pumping [8]	2.23	4.830E-10	1.08E-09	0.0286	3.08E-11	1.30E-01	4.00E-12
Arsenic:							
- 500 feet from well in base of USDW plus pumping [5, 6]	2.60	2.250E-04	6.55E-04	0.0286	1.87E-05	1.50E+00	2.81E-05
- 500 feet from well in aquifer below USDW plus pumping [7]	2.60	3.340E-02	8.68E-02	0.0286	2.48E-03	1.50E+00	3.73E-03
- 2,000 feet from well in base of USDW plus pumping [8]	2.60	4.830E-10	1.26E-09	0.0286	3.59E-11	1.50E+00	5.39E-11

[1] Concentration set at 90th percentile concentration reported from hazardous and nonhazardous Class I facilities.

[2] Based on information provided in GeoTrans, Inc., September 13, 1996 report titled “ Numerical Simulation of Deep Injection Wells in Support of UIC OGWDW.”

[3] IEC, Inc., 1987.

[4] IRIS. January 11, 1995.

[5] Assume pumping rate of 720,000 gallons per day.

[6] The concentration measured at receptor A2 located in the base of the USDW as modeled in GeoTrans, Inc., 1995.

[7] The concentration measured at receptor B2 located in an aquifer below the USDW as modeled in GeoTrans, Inc., 1995.

[8] The concentration measured at receptor A4 located in the base of the USDW as modeled in GeoTrans, Inc., 1995.

Exhibit 6

CANCER RISKS ASSOCIATED WITH BENZENE, CARBON TETRACHLORIDE, AND ARSENIC ASSUMING EAST GULF COAST WITH AN ABANDONED BOREHOLE SCENARIO AND WITH PUMPING AT 720,000 GPD AND A PERMEABILITY RATIO OF 1:10,000,000 BETWEEN THE INJECTION ZONE AND THE CONFINING LAYER

Chemical/ Receptor Location	Initial Constituent Concentrations (mg/l) [1]	Normalized Injectate Concentrations (mg/l) [2]	Drinking Water Concentration (mg/l)	Ingestion Conversion Factor (l/kg/day) [3]	Unit Dose (mg/kg/day)	Cancer Slope Factor $(mg/kg/day)^{-1}$ [4]	Individual Cancer Risk
Benzene:							
- 500 feet from well in base of USDW plus pumping [5, 6]	47.00	1.680E-04	7.90E-03	0.0286	2.26E-04	2.90E-02	6.55E-06
- 500 feet from well in aquifer below USDW plus pumping [7]	47.00	2.100E-02	9.87E-01	0.0286	2.82E-02	2.90E-02	8.19E-04
- 2,000 feet from well in base of USDW plus pumping [8]	47.00	3.060E-10	1.44E-08	0.0286	4.11E-10	2.90E-02	1.19E-11
Carbon Tetrachloride:							
- 500 feet from well in base of USDW plus pumping [5, 6]	2.23	1.680E-04	3.75E-04	0.0286	1.07E-05	1.30E-01	1.39E-06
- 500 feet from well in aquifer below USDW plus pumping [7]	2.23	2.100E-02	4.68E-02	0.0286	1.34E-03	1.30E-01	1.74E-04
- 2,000 feet from well in base of USDW plus pumping [8]	2.23	3.060E-10	6.82E-10	0.0286	1.95E-11	1.30E-01	2.54E-12
Arsenic:							
- 500 feet from well in base of USDW plus pumping [5, 6]	2.60	1.680E-04	4.37E-04	0.0286	1.25E-05	1.50E+00	1.87E-05
- 500 feet from well in aquifer below USDW plus pumping [7]	2.60	2.100E-02	5.46E-02	0.0286	1.56E-03	1.50E+00	2.34E-03
- 2,000 feet from well in base of USDW plus pumping [8]	2.60	3.060E-10	7.96E-10	0.0286	2.28E-11	1.50E+00	3.41E-11

[1] Concentration set at 90th percentile concentration reported from hazardous and nonhazardous Class I facilities.

[2] Based on information provided in GeoTrans, Inc., September 13, 1996 report titled " Numerical Simulation of Deep Injection Wells in Support of UIC OGWDW."

[3] IEC, Inc., 1987.

[4] IRIS. January 11, 1995.

[5] Assume pumping rate of 720,000 gallons per day.

[6] The concentration measured at receptor A2 located in the base of the USDW as modeled in GeoTrans, Inc., 1995.

[7] The concentration measured at receptor B2 located in an aquifer below the USDW as modeled in GeoTrans, Inc., 1995.

[8] The concentration measured at receptor A4 located in the base of the USDW as modeled in GeoTrans, Inc., 1995.

Exhibit 7

HAZARD INDEX – CARBON TETRACHLORIDE AND ARSENIC ASSUMING EAST GULF COAST WITH AN ABANDONED BOREHOLE SCENARIO AND WITH PUMPING AT 720,000 GPD AND A PERMEABILITY RATIO OF 1:1,000 BETWEEN THE INJECTION ZONE AND THE CONFINING LAYER

Chemical/ Receptor Location	Initial Constituent Concentrations (mg/l) [1]	Normalized Injectate Concentrations (mg/l) [2]	Drinking Water Concentration (mg/l)	Ingestion Conversion Factor (l/kg/day)[3]	Unit Dose (mg/kg/day)	Reference Dose (RfD) (mg/kg/day) [4]	Hazard Index
Carbon Tetrachloride:							
- 500 feet from well in base of USDW plus pumping [5, 6]	2.23	2.520E-04	5.62E-04	0.0286	1.61E-05	7.00E-04	2.30E-02
- 500 feet from well in aquifer below USDW plus pumping [7]	2.23	3.340E-02	7.45E-02	0.0286	2.13E-03	7.00E-04	3.04E+00
- 2,000 feet from well in base of USDW plus pumping [8]	2.23	4.830E-10	1.08E-09	0.0286	3.08E-11	7.00E-04	4.40E-08
Arsenic:							
- 500 feet from well in base of USDW plus pumping [5, 6]	2.60	2.520E-04	6.55E-04	0.0286	1.87E-05	3.00E-04	6.25E-02
- 500 feet from well in aquifer below USDW plus pumping [7]	2.60	3.340E-02	8.68E-02	0.0286	2.48E-03	3.00E-04	8.28E+00
- 2,000 feet from well in base of USDW plus pumping [8]	2.60	4.830E-10	1.26E-09	0.0286	3.59E-11	3.00E-04	1.20E-07

[1] Concentration set at 90th percentile concentration reported from hazardous and nonhazardous Class I facilities.

[2] Based on information provided in GeoTrans, Inc., September 13, 1996 report titled " Numerical Simulation of Deep Injection Wells in Support of UIC OGWDW."

[3] IEC, Inc., 1987.

[4] IRIS. January 11, 1995.

[5] Assume pumping rate of 720,000 gallons per day.

[6] The concentration measured at receptor A2 located in the base of the USDW as modeled in GeoTrans, Inc., 1995.

[7] The concentration measured at receptor B2 located in an aquifer below the USDW as modeled in GeoTrans, Inc., 1995.

[8] The concentration measured at receptor A4 located in the base of the USDW as modeled in GeoTrans, Inc., 1995.

Exhibit 8

HAZARD INDEX – CARBON TETRACHLORIDE AND ARSENIC
ASSUMING EAST GULF COAST WITH AN ABANDONED BOREHOLE SCENARIO AND WITH PUMPING AT 720,000 GPD AND A PERMEABILITY RATIO OF 1:10,000,000 BETWEEN THE INJECTION ZONE AND THE CONFINING LAYER

Chemical/ Receptor Location	Initial Constituent Concentrations (mg/l) [1]	Normalized Injectate Concentrations (mg/l) [2]	Drinking Water Concentration (mg/l)	Ingestion Conversion Factor (l/kg/day)[3]	Unit Dose (mg/kg/day)	Reference Dose (RfD) (mg/kg/day) [4]	Hazard Index
Carbon Tetrachloride:							
- 500 feet from well in base of USDW plus pumping [5, 6]	2.23	1.680E-04	3.75E-04	0.0286	1.07E-05	7.00E-04	1.53E-02
- 500 feet from well in aquifer below USDW plus pumping [7]	2.23	2.100E-02	4.68E-02	0.0286	1.34E-03	7.00E-04	1.91E+00
- 2,000 feet from well in base of USDW plus pumping [8]	2.23	3.060E-10	6.82E-10	0.0286	1.95E-11	7.00E-04	2.79E-08
Arsenic:							
- 500 feet from well in base of USDW plus pumping [5, 6]	2.60	1.680E-04	4.37E-04	0.0286	1.25E-05	3.00E-04	4.16E-02
- 500 feet from well in aquifer below USDW plus pumping [7]	2.60	2.100E-02	5.46E-02	0.0286	1.56E-03	3.00E-04	5.21E+00
- 2,000 feet from well in base of USDW plus pumping [8]	2.60	3.060E-10	7.96E-10	0.0286	2.28E-11	3.00E-04	7.58E-08

[1] Concentration set at 90th percentile concentration reported from hazardous and nonhazardous Class I facilities.

[2] Based on information provided in GeoTrans, Inc., September 13, 1996 report titled " Numerical Simulation of Deep Injection Wells in Support of UIC OGWDW."

[3] IEC, Inc., 1987.

[4] IRIS. January 11, 1995.

[5] Assume pumping rate of 720,000 gallons per day.

[6] The concentration measured at receptor A2 located in the base of the USDW as modeled in GeoTrans, Inc., 1995.

[7] The concentration measured at receptor B2 located in an aquifer below the USDW as modeled in GeoTrans, Inc., 1995.

[8] The concentration measured at receptor A4 located in the base of the USDW as modeled in GeoTrans, Inc., 1995.