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State and National Energy and Environmental Risk Analysis Systems for Underground Injection Control

FINAL REPORT

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Prepared by:

ICF Resources Incorporated

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STATE AND NATIONAL ENERGY AND ENVIRONMENTAL RISK ANALYSIS SYSTEMS FOR UNDERGROUND INJECTION CONTROL

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Program Manager:	Michael L. Godec
Principal Investigator:	Glenda E. Smith
Technical Project Officer:	Brent W. Smith U.S. Department of Energy Metairie Site Office
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Abstract

The purpose of this effort is to develop and demonstrate the concept of a national Energy and Environmental Risk Analysis System that could support DOE policy analysis and decision-making. That effort also includes the development and demonstration of a methodology for assessing the risks of groundwater contamination from underground injection operations.

EERAS is designed to enhance DOE's analytical capabilities by working with DOE's existing resource analysis models for oil and gas. The full development of EERAS was not planned as part of this effort. The design and structure for the system were developed, along with interfaces that facilitate data input to DOE's other analytical tools. The development of the database for EERAS was demonstrated with the input of data related to underground injection control, which also supported the risk assessment being performed. The utility of EERAS has been demonstrated by this effort and its continued development is recommended.

Since the *absolute* risk of groundwater contamination due to underground injection is quite low, the risk assessment methodology focuses on the *relative* risk of groundwater contamination. The purpose of this methodology is to provide DOE with an enhanced understanding of the relative risks posed nationwide as input to DOE decision-making and resource allocation. Given data problems encountered, a broad assessment of all oil reservoirs in DOE's resource database was not possible. The methodology was demonstrated using a sample of 39 reservoirs in 15 states. While data difficulties introduce substantial uncertainties, the results found are consistent with expectations and with prior analyses. Therefore the methodology for performing assessments appears to be sound. Recommendations on steps that can be taken to resolve uncertainties or obtain improved data are included in the report.

Executive Summary

A. Background

Oil and gas exploration and production (E&P) activities result in large volumes of produced brine that must be managed and disposed. Over 90% of this produced brine is currently reinjected into underground formations through Class II injection wells (Wakim, 1987). Two-thirds of this brine is reinjected to producing formations for pressure maintenance and enhanced recovery operations. The remainder is injected in saltwater formations below the base of the deepest potentially usable drinking water aquifers.

Class II wells include three categories: (1) type II-D for brine disposal; (2) type II-R for waterflood injection; and (3) type II-H for storage of hydrocarbons. Class II injection operations can potentially contaminate underground sources of drinking water (USDWs) in two ways: (1) the casing can leak and allow produced water to enter a USDW; or (2) the pressure differential within the reservoir system can allow produced fluids to flow from the injection zone to a USDW via inadequately or improperly plugged wells. In the first case, the construction type of the well and the regular testing of its mechanical integrity can prevent contamination or detect the potential threat early. In the second case, an analysis of the potential for waste fluids flow and the presence of conduits can be performed to ensure protection of USDWs.

In 1980, EPA promulgated regulations for Underground Injection Control (UIC) programs under the Safe Drinking Water Act (SDWA), which establishes minimum requirements to protect underground sources of drinking water (USDWs) from endangerment by subsurface emplacement of fluids. The UIC program established standards for the construction and operation of Class II injection wells, and provided states with primary enforcement authority for the program. In 1988, EPA initiated a Mid-Course Evaluation (MCE) of its Class II injection program. The MCE identified several areas that warranted additional investigation to assure that groundwater was being adequately protected.

In December 1990, EPA assembled a Federal Advisory Committee (FAC) to assist with the development of an acceptable framework for new regulations to address the issues raised during the MCE. The Advisory Committee included representatives of oil companies, the

American Petroleum Institute (API), the Independent Petroleum Association of America (IPAA), environmental groups, four primacy states, the U.S. Department of Energy (DOE), and the U.S. Department of Interior (DOI).

In January 1992, the FAC recommended changes to the Class II UIC program. EPA has indicated that it plans to follow the recommendations of the FAC in developing the proposed rules that govern the construction standards, mechanical integrity testing, and area-of-review requirements for Class II injection wells. Issuance of these regulations has been delayed and it is unclear when new requirements for injection wells are likely to be issued.

B. Objectives

This effort originally included two primary tasks (development of state and national systems respectively) and a technology transfer element. The state system was planned to assist states with data management related to underground injection control (UIC). However, during 1993, a change was received to the Statement of Work which discontinued work on this task. This change was made to avoid duplication of other ongoing efforts being sponsored by industry. Prior to discontinuation, the concept for a protocol that would assess the relative risk of groundwater contamination due to UIC activities in various areas of a state was developed (Godec, Smith, and Lang, 1993). A risk assessment protocol similar to that designed could be used to assist states in allocating scarce resources and potentially could form the analytical basis of a state variance program. The work performed on this task prior to its termination has been documented and submitted and has not been included in this final report.

This report focuses on the second task — the development of a national Energy and Environmental Risk Analysis System (EERAS). EERAS is designed to enhance DOE's analytical capabilities. The full development of EERAS was not planned under this contract. This effort was designed to demonstrate the concept of EERAS using UIC-related data.

As part of its mission, DOE regularly has need to comment on environmental issues and how they may affect domestic production of oil and gas. DOE provides information to the regulatory development process on both the economic impacts of proposed changes and the need for regulations that can address site-specific risks. At the state level, DOE has also been supporting the development of risk-based data management systems that will facilitate the incorporation of risk into decision-making.

To date, most of DOE's economic impact assessments have considered only national- or regional-average data. While the site-specific nature of risks and the benefit of regulating only the real risks posed are intuitive, DOE has lacked the capability to demonstrate these differences and benefits. EERAS is designed to improve DOE's capabilities in this area, by providing data at a more disaggregate level that can be used in economic impact assessments. Further by comparing the results of a disaggregate level assessment with one performed using national-level data, it may be possible to demonstrate the benefits that could be captured by substituting flexible, site-based regulations for blanket, national-level standards.

While its primary near-term use will be for economic impact assessments, the information compiled in EERAS can also be applied in risk assessments and cost-benefit analyses. The application of EERAS for performing an assessment of the relative risks of groundwater contamination from underground injection control is discussed in Section III of this report. As data on industry effluents and emissions is collected and added to EERAS (see section on future development options below), the system can also support cost-benefit analyses. The costs of a future requirement can be assessed as currently performed for an economic impact assessment. Then the benefits of installing a new control technology can be assessed in terms of reduced emissions or effluent. These can then be combined in a cost-effectiveness calculation — for example, cost per ton of pollutant removed. As the focus on use of cost-benefit assessments increases, EERAS will be a valuable tool to support DOE decision-making.

C. Energy and Environmental Risk Analysis System (EERAS)

The database and interfaces of EERAS have been designed to be compatible with DOE's Tertiary Oil Recovery Information System (TORIS) and Gas Systems Analysis Model (GSAM). This will allow environmental data from EERAS to be used in assessments of future oil and gas recovery potential, typically in evaluating the economic impact of potential changes in environmental regulations. EERAS is designed to bring together data at several different levels of aggregation in a single assessment to provide the best possible approximation of site-specific differences.

EERAS has a locational translation file serves as a "gatekeeper" to match reservoir data in TORIS and GSAM with data aggregated at other locational levels (such as county, basin, or state). Because of the differing characterization of reservoirs in TORIS and GSAM, a separate locational file exists for each model, but these files are consistently structured. The database has been developed in a modular format, with separate modules for data on surface conditions, subsurface conditions, wastes, waste management, compliance costs, technology performance, and so forth. Available data relevant to assessments of underground injection control operations has been input to the EERAS database. The EERAS database has been developed in FoxPro for DOS, which was selected after a careful examination of current state-of-the-art database systems.

The database module provides relevant data for estimating compliance costs, determining which fields/reservoirs could be affected by an environmental regulation, selecting appropriate technologies, and so forth. To estimate the incremental costs of compliance with a regulation being analyzed, data at the appropriate levels of aggregation can be transferred from the database to a spreadsheet model. [Development of this spreadsheet model was not part of this effort, but the approach is consistent with that typically used in performing economic impact assessments for DOE.] Once incremental environmental compliance costs or similar required data have been developed, an interface system that is part of EERAS provides an output file that becomes an input to a run of TORIS or GSAM. This interface translates the data to a reservoir-specific cost input file for TORIS or GSAM.

EERAS holds substantial potential to assist DOE in its mission. It can provide valuable input to the regulatory development process, through economic impact, risk, and cost-benefit assessments. EERAS can also support DOE's environmental research program planning, by helping to estimate the benefits of DOE activities in various areas.

To reach this potential, the EERAS database must be expanded to broadly cover environmental issues related to the production of oil and gas. In addition to UIC-related analyses, the data must be available to support analysis of air, water, and production waste issues. Much of the data required to support the traditional economic impact assessment in these other areas is available, having been collected during prior assessments for DOE. However, much of this data is at a fairly aggregate level and assessments could be improved through the collection of more disaggregate-level data. Performing risk and cost-benefit assessments will require the inclusion of data that has not traditionally been collected for economic impact assessments. This includes factors that affect or measure risks posed, along with the volume of effluents, emissions, or other contaminants of concern associated with industry operations. It will also require data on the performance of environmental technologies in reducing these pollutants. The effort involved in identifying, collecting, and applying these data will be substantial.

During the period of performance for this effort, DOE's Morgantown Energy Technology Center (with funding from the Metairie Site Office) also began the development of an environmental module to the Gas Systems Analysis Model (GSAM). Since ICF Resources is also the contractor for that effort, we were able to develop that module so that it builds on the development of EERAS under this effort. The basic structure developed for EERAS has been used for the GSAM environmental module. Since much of the environmental data related to oil and gas production is equally applicable to both oil and gas, a common database is a reasonable approach. The EERAS database developed for this effort will be combined with the database developed for the GSAM environmental module, thereby avoiding any duplication of effort using government funds. The continued development of the GSAM environmental module can serve the same purpose as continued development of EERAS. Since the database and analytical structure will be equally applicable to TORIS- and GSAM-based analyses, this effort should serve to further the development of the EERAS concept to it full potential in supporting DOE policy analysis and decision-making.

D. Assessment of Groundwater Contamination Risks

Underground injection of fluids has the potential to contaminate aquifers that are, or could be, used as sources of drinking water. However, documented cases of contamination due to underground are very few in number, and most of these cases are attributable to operating practices that were in violation of existing state and federal regulations governing underground injection. Thus, in absolute terms, the risk of groundwater contamination from Class II injection operations in quite low.

Given the low *absolute* risk of contamination, it is more appropriate to focus on the *relative* risk for groundwater contamination between areas. Even an older producing area with numerous inadequately plugged abandoned wells and highly corrosive subsurface conditions is unlikely to have an occurrence of groundwater contamination due to injection. But the relative risk of such an area compared with an area discovered and developed after 1984 may be considerably higher. To lower the risk of groundwater contamination occurring, it may be appropriate to focus limited resources on the area with the higher relative risk potential.

The potential pending revisions to the Class II UIC program based on the Federal Advisory Committee recommendations includes a provision allowing states to establish variance programs from areas-of-review requirements for low risk injection wells. A methodology for evaluating variance eligibility has been developed by the Underground Injection Practices Research Foundation (UIPRF) and industry, under a grant from DOE (UIPRF, 1994). This methodology is highly effective for evaluating wells in a specific area, but is rather data intensive, making it impractical for a national assessment.

DOE has made major investments in supporting state UIC programs, including the development and implementation of risk-based data management systems. As DOE moves into an environment where it is more crucial to understand the potential benefits associated with its research investments, the need for a broad national assessment of relative risk of contamination was determined to be helpful in decision-making. The purpose of this assessment was not to focus efforts solely in those areas with the highest relative risk, but rather to understand the problems faced in specific geographic areas (dealing with high risk areas, justifying variances for numerous low risk areas, etc.) as a basis for determining appropriate federal action.

This project was designed to develop a methodology for such an assessment and demonstrate this methodology with an assessment of relative risks for the oil reservoirs in DOE's TORIS database. While a broad national assessment was planned, data problems (explained below) have prohibited a meaningful assessment of all oil reservoirs nationwide. Rather, this methodology has been demonstrated with a sampling of 39 reservoirs from across the nation. The approach developed is a useful assessment tool, if data difficulties can be overcome.

Several previous assessments of the risk of groundwater contamination from Class II injection have been performed (Michie, 1988, 1989, 1991; ICF Incorporated, 1990; Warner and

McConnell, 1990; Dunn-Norman, et al., 1995). The intention of this effort was to build on these prior efforts, using the most appropriate data and approaches for a broad national assessment. Some of the prior assessments focused on a single potential pathway for contaminants to reach a USDW, such as a casing failure or an abandoned well serving a conduit. To provide a comprehensive risk assessment, the methodology developed considers these alternative pathways for contamination in a single assessment.

All assessments agree that the single most important factor affecting whether groundwater contamination could occur is the presence or absence of groundwater. In certain producing areas, there are no principle aquifers that could be used as a source of drinking water. In Alaska, the presence of permafrost conditions prohibit the use of groundwater. Logically, if no groundwater sources exist to be contaminated, then the risk of contamination is zero.

The second most important factor affecting the risk of groundwater contamination is the distance between the injection zone and the lowermost drinking water aquifer and whether sufficient pressure exists for contaminants to overcome the forces of gravity and travel that distance. If the subsurface pressure is insufficient to force injected fluids to travel the required distance (assuming that a pathway is available), then risks are minimal, unless injection operations or other factors subsequently raise the pressure to a level that could pose concern. Even if pressure were sufficient and a pathway for contaminants to migrate through existed, the probability is high that the fluids would migrate to one of the formations between the reservoir and the USDW, given pressure differentials, permeability, and other factors. This would lower or eliminate the potential for contamination of the USDW. However, for the purposes of this assessment, the presence of intervening formations has not been considered. It has been assumed that if the pressure is sufficient to cover the required distance, then the risk of contamination exists.

If the pressure is sufficient to force fluids the required distance, then the likelihood of a pathway for contaminants to travel through must be assessed. Two categories of wells must be considered: 1) current production and injection wells, and 2) abandoned wells and wells that are currently idle. Based on field experience, prior risk assessments, and other relevant literature, the key factors affecting the potential for a pathway for contaminants to exist have been summarized as follows:

- Current production/injection wells
  - Quality of the cement job, which affects whether a small annulus or channel may exist behind pipe
  - Corrosion potential, which affects the likelihood of tubing or casing failures due to corrosive influences
  - Use of construction practices that include short surface casing strings, which could mean that surface casing does not cover the lowermost aquifer, removing a layer of protection
  - Use of unconventional injection well construction practices (such as tubingless or packerless construction), which can also remove one or more layers of protection for groundwater.

- Abandoned and idle wells
  - Density of abandoned wells, which determines the number of potential conduits
  - Density of idle wells, which also determines the number of potential conduits
  - Historic plugging/construction practices, which affects the potential for abandoned or idle wells to serve as conduits.

To combine these diverse factors in a single assessment of *relative* risk, risk points are assigned to each key factor, using a scale of one (low) to five (high), based on the potential for contamination to occur. These risk points can be summed and used as a basis for comparing the relative risk of contamination across areas. A consistent scale of one to five was used for all factors to avoid introducing bias based on differing scales. The methodology developed weights all of the above factors equally, since data upon which to determine more appropriate relative weights is not available. While it may be possible to postulate that historic construction and plugging practices is more important than the density of idle or abandoned wells, no basis for determining whether it is one and one-half, two, or more times as important exists. Since the focus of this analysis is on *relative* risk, and substantial uncertainty is associated with some of the data used (as described below), a uniform weighting of the key factors provides a reasonable basis for an assessment.

Substantial data problems were encountered in attempting to apply this methodology on a national scale. When assessing the potential risks associated with an individual well, data are available: from well logs to provide specifics on the location of aquifers relative to the injection zone; from completion records, to determine well construction; from operational data, to calculate injection zone pressures; from cement bond logs, to assess the quality of the cement job; etc. Performing a national assessment still requires information for each of these key risk factors, but the data are much less readily available. For certain aspects, data are not available and surrogates must be used. Moreover, the quality of the data that are available is often uncertain.

The risks associated with underground injection operations are very site specific. Any time a national, or aggregate-level, assessment is being performed, certain simplifying assumptions are required due to the infeasibility of a well-by-well assessment for a large area. The methodology developed to perform a nationwide assessment of the relative risks of groundwater contamination follows these principles. Reasonable data or surrogates that could be used to represent key risk factors have been identified. Some of these data, or their application, have substantial uncertainty associated with them. Nonetheless, using available data, the relative risks associated with selected reservoirs throughout the country have been assessed, and the results are consistent with what would be expected.

A total of 39 reservoirs from the TORIS database were assessed. For ten of the reservoirs assessed, even original reservoir pressure would be insufficient to force contaminants upwards to the aquifer. For these ten reservoirs, risk is minimal and no further assessment is required. Using an estimate of current reservoir pressure, only seven of the 39 reservoirs evaluated are likely to have pressure sufficient to result in a migration of injected fluids to groundwater aquifers. The reservoirs with the highest number of risk points were found in the Appalachian basin, where the large number of abandoned wells and numerous wells drilled prior to current construction and plugging practices would imply that risks may be higher relative to other areas. The next highest risk points were found in the Permian basin, which is a highly corrosive environment with substantial ongoing enhanced recovery operations. This finding is consistent with a previous risk assessment performed by Michie (1988).

The results of this analysis tend to support the validity of the methodology developed. If data difficulties can be overcome, this methodology can be used to perform a national risk assessment that would provide DOE with additional data for planning its research investments.

I. Introduction

A. Background

Oil and gas exploration and production (E&P) activities result in large volumes of produced brine that must be managed and disposed. Over 90% of this produced brine is currently reinjected into underground formations through Class II injection wells (Wakim, 1987). Two-thirds of this brine is reinjected to producing formations for pressure maintenance and enhanced recovery operations. The remainder is injected in saltwater formations below the base of the deepest potentially usable drinking water aquifers.

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In 1980, EPA promulgated regulations for Underground Injection Control (UIC) programs under the Safe Drinking Water Act (SDWA), which establishes minimum requirements to protect underground sources of drinking water (USDWs) from endangerment by subsurface emplacement of fluids. The UIC program established standards for the construction and operation of Class II injection wells, and provided states with primary enforcement authority for the program. In 1988, EPA initiated a Mid-Course Evaluation (MCE) of its Class II injection program. The MCE identified several areas that warranted additional investigation to assure that groundwater was being adequately protected.

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American Petroleum Institute (API), the Independent Petroleum Association of America (IPAA), environmental groups, four primacy states, the U.S. Department of Energy (DOE), and the U.S. Department of Interior (DOI).

In January 1992, the FAC recommended changes to the Class II UIC program. EPA has indicated that it plans to follow the recommendations of the FAC in developing the proposed rules that govern the construction standards, mechanical integrity testing, and area-of-review requirements for Class II injection wells. The following is a brief description of FAC's recommendations:

- Construction Standards. The committee recommended that all new Class II injection wells (newly-drilled or newly-converted) have 3 layers of protection: (1) surface casing set and cemented to protect USDWs of 3,000 mg/l total dissolved solids (TDS) or less; (2) long string casing extending from the surface through the injection zone, completely or partially cemented; and (3) tubing set on a packer.

- Mechanical Integrity Testing. The mechanical integrity of a well must be tested periodically to detect the potential for leaks. The current Mechanical Integrity Testing (MIT) frequency requirement for Class II injection wells is once every five years, regardless of their construction features. The Federal Advisory Committee recommended that a well with three layers of protection and surface casing set to protect 3,000 mg/l TDS USDWs be tested once every 5 years; if the well has a short surface casing, then it must undergo testing once every 3 years. Furthermore, an unconventional well (i.e., with two layers of protection) must be tested once every 3 years; if the well also has a short surface casing, the testing frequency must be increased to annually.

- Area of Review Requirements and Corrective Action. To prevent potential contamination of USDWs, the operator of an injection well must study an area around the well to review the plugging and construction records of wells in the area to check for the presence of a conduit that could potentially serve as a pathway for injected fluids to flow from the injection zone to the USDW. In most states, this "Area of Review" (AOR) is specified to be a 1/4-mile radius around the injection well. If any wells within the AOR study could potentially pose a threat to USDWs, corrective measures must be undertaken by the operator to eliminate the threat of contamination. These measures may range from limiting the injection pressure to repairing or plugging the wells.

  Current UIC regulations subject all injection wells permitted since May 1982 to conduct an AOR study, while wells constructed prior to 1982, which were originally permitted by rule, are exempted. The Federal Advisory Committee recommended that an AOR study be conducted within five years for all Class II injection wells, followed by necessary corrective action (CA) unless the well: (1) has already been the subject of an AOR study; (2) was overlapped by an AOR study conducted for an adjacent well; or (3) is granted a variance (based on low risk of USDW contamination) by the UIC Director for the state.

EPA's proposed regulatory changes based on the FAC recommendations were originally expected in 1993. These changes are the subject of some controversy within EPA, and thus it is unclear when they will be issued. There has been some discussion of issuing the changes as guidance to state programs implementing federal UIC requirements, rather than as regulations. The status of these changes, including when and how they will be issued, is highly uncertain.

B. Objectives/Scope

This effort originally included two primary tasks (development of state and national systems respectively) and a technology transfer element. The state system was planned to assist states with data management related to underground injection control (UIC). However, during 1993, a change was received to the Statement of Work which discontinued work on this task. This change was made to avoid duplication of other ongoing efforts being sponsored by industry. Prior to discontinuation, the concept for a protocol that would assess the relative risk of groundwater contamination due to UIC activities in various areas of a state was developed (Godec, Smith, and Lang, 1993). A risk assessment protocol similar to that designed could be used to assist states in allocating scarce resources and potentially could form the analytical basis of a state variance program. The work performed on this task prior to its termination has been documented and submitted and has not been included in this final report.

This report focuses on the second task — the development of a national Energy and Environmental Risk Analysis System (EERAS). EERAS is designed to enhance DOE's analytical capabilities. The full development of EERAS was not planned under this contract. This effort was designed to demonstrate the concept of EERAS using UIC-related data.

As part of its mission, DOE regularly has need to comment on environmental issues and how they may affect domestic production of oil and gas. DOE provides information to the regulatory development process on both the economic impacts of proposed changes and the need for regulations that can address site-specific risks. At the state level, DOE has also been supporting the development of risk-based data management systems that will facilitate the incorporation of risk into decision-making.

To date, most of DOE's economic impact assessments have considered only national- or regional-average data. While the site-specific nature of risks and the benefit of regulating only the real risks posed are intuitive, DOE has lacked the capability to demonstrate these differences and benefits. EERAS is designed to improve DOE's capabilities in this area, by providing data at a more disaggregate level that can be used in economic impact assessments. Further by comparing the results of a disaggregate level assessment with one performed using national-level data, it may be possible to demonstrate the benefits that could be captured by substituting flexible, site-based regulations for blanket, national-level standards.

While its primary near-term use will be for economic impact assessments, the information compiled in EERAS can also be applied in risk assessments and cost-benefit analyses. The application of EERAS for performing an assessment of the relative risks of groundwater contamination from underground injection control is discussed in Section III of this report. As data on industry effluents and emissions is collected and added to EERAS (see section on future development options below), the system can also support cost-benefit analyses. The costs of a future requirement can be assessed as currently performed for an economic impact assessment. Then the benefits of installing a new control technology can be assessed in terms of reduced emissions or effluent. These can then be combined in a cost-effectiveness calculation — for example, cost per ton of pollutant removed. As the focus on use of cost-benefit assessments increases, EERAS will be a valuable tool to support DOE decision-making.

C. Organization of the Report

Following this introductory section, the report is organized into two major sections. Section II of the report addresses the development of the national Energy and Environmental Risk Analysis System. EERAS design, current development, and future development options are discussed. Section III of the report addresses a methodology to assess the risks of groundwater contamination from injection operations. This section discusses the methodology developed, problems encountered in developing and applying the methodology, the results of the risk assessment that was performed, and potential data needs for improving the risk assessment.

II. National Energy and Environmental Risk Analysis System (EERAS)

A. EERAS Design

The database and interfaces of EERAS have been designed to be compatible with DOE's Tertiary Oil Recovery Information System (TORIS) and Gas Systems Analysis Model (GSAM). This will allow environmental data from EERAS to be used in assessments of future oil and gas recovery potential, typically in evaluating the economic impact of potential changes in environmental regulations. EERAS is designed to bring together data at several different levels of aggregation in a single assessment to provide the best possible approximation of site-specific differences.

Conceptually, EERAS is designed as shown in Figures 1 and 2. Figure 1 illustrates that a locational translation file serves as a "gatekeeper" to match reservoir data in TORIS and GSAM with data aggregated at other locational levels (such as county, basin, or state). Because of the differing characterization of reservoirs in TORIS and GSAM, a separate locational file exists for each model, but these files are consistently structured. Figure 2 shows an example of the modular format of the environmental database and examples of the types of information that may be included in each module. The examples in this figure have not been limited to UIC-related data, but are described more broadly to provide an indication of the potential of the system in its full development. The EERAS database has been developed in FoxPro for DOS, which was selected after a careful examination of current state-of-the-art database systems.

The database structure is straightforward, with different files containing data at different levels of aggregation. For example, several variables that are aggregated at the state level may be contained in the same file, while data that exists only at the national level (even if it is from the same data source) would be in a separate file. Each module in Figure 2 may include several files, reflecting the varying aggregation levels of data in this category.

The database module provides relevant data for estimating compliance costs, determining which fields/reservoirs could be affected by an environmental regulation, selecting appropriate technologies, and so forth. To estimate the incremental costs of compliance with a regulation being analyzed, data at the appropriate levels of aggregation can be transferred from the

Figure 1. Energy and Environmental Risk Analysis System (EERAS)

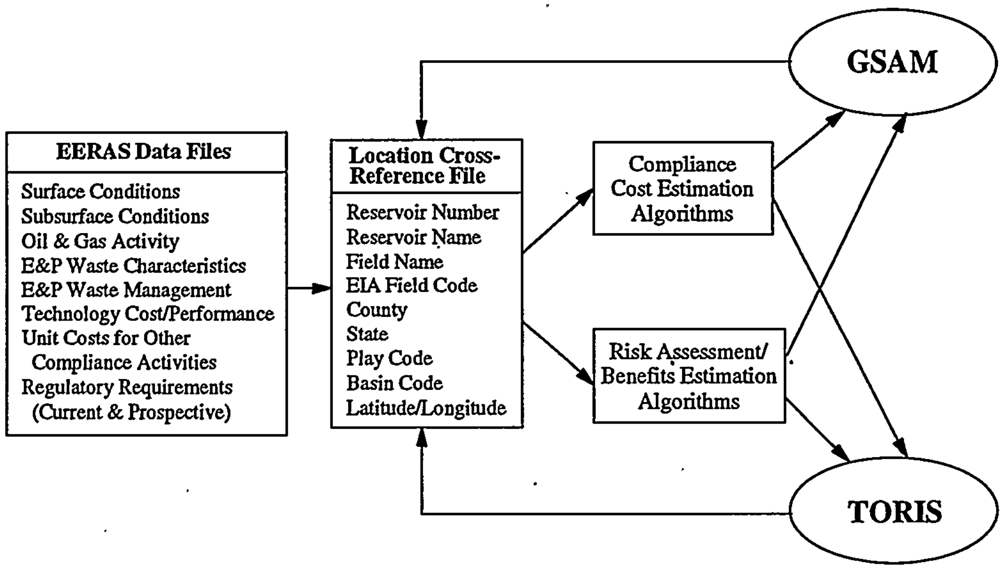


Figure 2. EERAS Data Files and Example Contents

Surface Conditions Files
- Federal lands
- Wetlands
- Endangered species habitat
- Wilderness lands
- OCS moratoria areas
- Non-attainment areas (ozone, other?)
- Distance to urban areas
- Distance to surface water
- Annual rainfall
- Evaporation rate
- Surface water quality
- Water depth (for offshore fields)
- Background radiation level

Subsurface Conditions Files
- Presence of groundwater
- Groundwater currently used for human consumption
- Name of primary/secondary aquifer systems
- Depth to shallowest groundwater
- Depth of 3000 TDS groundwater
- General soil type (snad, clay, etc.)
- Corrosivity indicator
- Groundwater quality (TDS, salinity, etc.)

Oil & Gas Activity Files
- Disposal well locations
- Depth of injection zone
- Number of injection wells
- Est. number of abandoned wells
- Typical depth of surface casing
- Location of gas processing plants

E&P Waste Characterization Files
- Produced water volumes/ratio
- Assoc. waste volumes by type
- Est. volumes of SO2, NOx, VOCs, etc.
- NORM level
- Produced water quality

E&P Waste Management Files
- Methods of produced water disposal (distribution)
- Methods of associated waste disposal
- Methods of drilling waste disposal

Compliance Cost Files
- Pit liner cost
- Cost to install & operate groundwater monitoring
- Cost of offsite disposal by method
- Cost to excavate contaminated soil
- Bioremediation costs
- Cost of closed drilling system
- Costs for barging wates to shore
- Costs for various aspects of upgrading ASTs
- Injection well drilling costs
- MIT costs
- AOR costs
- Permit costs
- Insurance costs

Technology Cost/ Performance File
- Membrane filtration:
  - Size, weight
  - Installation cost, operating cost
  - Effectiveness
- Hydrocyclones:
  - Size, weight
  - Installation cost, operating cost
  - Effectiveness
- Improved Gas Flotation:
  - Retrofit cost, incremental operating Cost
  - Effectiveness
- NOx controls:
  - Type, effectiveness, cost

Regulatory Requirements File
- Current regulatory requirements
- Potential regulatory requirements

(Format & content of this file dependent on how cost & benefit algorithms developed) database to a spreadsheet model. [Development of this spreadsheet model was not part of this effort, but the approach is consistent with that typically used in performing economic impact assessments for DOE.] Once incremental environmental compliance costs or similar required data have been developed, an interface system that is part of EERAS provides an output file that becomes an input to a run of TORIS or GSAM. This interface translates the data to a reservoir-specific cost input file for TORIS or GSAM.

B. UIC-Related Data

For this effort, the concept and utility of EERAS were to be demonstrated using data related to underground injection control. To that end, an assessment of previous reports that might have useful data was performed. This assessment was supplemented by an analysis of the types of data likely to be required to support DOE in both economic impact and risk assessments.

Existing Data Sources

Oil and Gas Industry Water Injection Well Corrosion (Michie, 1988). In a 1987 EPA Report to Congress concluding that full-scale federal regulation of exploration and production wastes as hazardous under the Resource Conservation and Recovery Act (RCRA) was not necessary at this time, EPA assumed a 100 percent probability of simultaneous failures of all levels of protection in injection wells resulting in direct contamination of USDWs. Because the risks associated with modeling releases of injection well water were overstated, API contracted with Michie and Associates to perform a study to determine realistic probabilities of simultaneous failures of all levels of protection in injection wells due to corrosion. To perform this task, Michie identified areas of the U.S. where the potential exists for corrosion related failures that could allow the release of injection water into a USDW; developed a method to analyze and examine failure data; and developed upper bound limits for potential USDW contamination frequency.

Midcourse Evaluation Economics Study (Gruy, 1989). When EPA conducted its review of the UIC program for Class II wells (the MCE in 1988) to determine whether regulatory changes were necessary to ensure adequate and consistent protection of USDWs, API initiated a study to determine the potential costs of the three proposed revisions to UIC regulations — MIT, AOR and CA, and construction requirements. The study was performed by Gruy Engineering Corporation. Results of the study estimated costs for the following:

- Proposed revised MIT of injectors drilled prior to 1984, both with and without consideration of Michie basin corrosion potential;
- The proposed weekly monitoring of positive pressure on the tubing-casing annulus;
- AOR analyses and obtaining authorized permits for all current injectors drilled prior to 1984 and for corrective actions;
- Logging to test for fluid movement behind the casing;
- Squeeze cement the production casing at the lowermost USDW; and
- Plug and redrill those that fail tests.

In developing these costs, Gruy and API developed a database of state/basin-level information on the number of injection wells, active wells, abandoned wells; casing and injection depths; assumed depth to lowermost USDWs; and other UIC-related data that is useful in development of EERAS.

Evaluation of Class II Regulatory Impacts (Cadmus, 1993). As EPA began developing regulations based on the FAC recommendations, it asked The Cadmus Group to assess the economic impacts on Class II well operators of complying with the improved standards of the proposed rule and the potential for impedance of oil and gas production. Compliance costs for construction standards, increased MIT frequency, and requirements for AOR studies were determined, impacts were assessed, a range of regulatory alternatives in terms of degree of protection offered to USDWs were considered, and both quantifiable and non-quantifiable benefits likely to result from the rule were evaluated. This study also developed an extensive database of information on well construction practices and costs of various compliance activities that has been included in EERAS.

Data Requirements

In conducting an economic impact analysis, data that are necessary in developing the costs of compliance with the different requirements of the regulation include:

- Information on the condition of the injection wells that currently exist, such as construction types of those wells and well depth;
- Distance between the injection zone and groundwater; and
- Incremental unit costs associated with each requirement.

When performing a comprehensive assessment of the potential risks of USDW contamination from injection operations, information that is required includes the following:

- An inventory of current injection wells, including the condition and construction of the wells to assist in identifying potential contamination pathways, on a statewide or countywide basis to identify areas where potential risks may be higher; and
- Factors affecting risk of contamination that are specific to the areas under consideration, such as the potential corrosivity, pressure differentials between the injection zone and the USDW, location of and depth to USDWs, construction and cementing history, location of idle and abandoned wells, etc.

Ranking of Required Data

Class II Well Inventory. As discussed above, characterization of the status of current injection wells is important to both the policy analysis and risk assessment functions. Therefore, an inventory of injection wells is necessary. This inventory includes such information as depth of wells; surface casing depth; construction of both conventional and unconventional (i.e., short casing, annular, packerless, etc.) wells; wells permitted by rule; a breakdown of injection wells by function (enhanced recovery or disposal); and the density of producing abandoned, and idle wells that may exist within an AOR.

The data currently available exists on a statewide basis. However, since some areas within different states may be more vulnerable to contamination from injection wells than others, it would be ideal to have this type of information on a more disaggregate (countywide or fieldwide) basis. Having more detailed information would improve the degree of confidence in performing assessments on the relative risk of contamination.

Unit Compliance Costs. After determining which wells will be required to have conventional construction, conduct MITs more frequently, and conduct an AOR and possibly perform CA, costs of compliance with the proposed regulations may be calculated using the unit cost data. This includes the cost of performing an AOR; costs of performing a CA if determined necessary; and costs associated with MIT (i.e., pulling tubing and a packer, performing a remedial squeeze, performing pressure testing, replugging wells, etc.).

Several alternative sources of this information exist, including the Midcourse Evaluation Economics Study (Gruy, 1989) and the Evaluation of Class II Regulatory Impacts (Cadmus, 1993). The differences between these sources reflect not only the date the studies were performed, but also the views of industry and government sources regarding the costs. ICF Resources has also developed unit cost data for selected items for DOE. Research will continue to identify future sources (including a study being completed for API) which may include more disaggregated or more recent estimates of AOR, CA, or MIT unit costs.

Groundwater. The FAC recommended that construction standards for new wells require casing set to protect aquifers of up to 3,000 TDS. Prior to the FAC recommendations, a requirement to protect up to 10,000 TDS aquifers was discussed. To analyze the potential impacts of these requirements, data on depth to the base of freshwater or other groundwater aquifers, thickness of the aquifer, and TDS values, is necessary. This will help in determining the costs associated with compliance.

Some of this information is available in the Midcourse Evaluation Economics Study (Gruy, 1989) on a statewide basis, however, concerns about the quality of the data have been expressed. For example, depth to lowermost USDW was determined by using the assumption that surface casing depth plus 300 feet equals depth to lowermost USDW (which assumed water of 10,000 TDS). However, this option may be too simplistic for the purposes of EERAS and may limit the flexibility of the system when performing other analyses. It also limits the capability to distinguish among aquifers of different TDS levels. The second option is to characterize specific aquifers within the EERAS database, inputting parameters such as depth to the aquifer (ft), thickness of the aquifer (ft), and TDS. This option is preferable since it would enable the calculation of important information for a policy review, such as depth to 3,000 TDS (the lowermost depth at which the FAC recommended that surface casing be set and cemented to protect USDWs) or depth to 10,000 TDS (the depth at which other groups, including EPA's Office of Enforcement, believe USDWs should be protected), and would support a better assessment of risks since aquifer location would be specified in greater detail. However, to this point a source of data to implement the second data option is not available.

State sources have also been utilized to develop groundwater data. For California, a state publication includes the depth to base of freshwater for each field in the state, based on an analysis of well logs. For Alabama and Kansas, studies have been conducted on depth to base of freshwater as well. Some data are available for Texas. However, many states do not have comparable data available.

Corrosion Potential. One potential pathway for USDW contamination is the failure of an existing injection well due to corrosion. Subsurface fluids affect corrosion potential. The Michie study (1988) has developed a ranking for basins nationwide that reflects their potential for corrosion. The Michie data has been included in EERAS as an indicator of the risk factors related to corrosion.

Data Input to EERAS

Based on this assessment of data needs and available data sources, relevant UIC data was input to the EERAS database. Table 1 lists the UIC-related data that has been input to the EERAS database.

C. Future Development Options

EERAS holds substantial potential to assist DOE in its mission. It can provide valuable input to the regulatory development process, through economic impact, risk, and cost-benefit assessments. EERAS can also support DOE's environmental research program planning, by helping to estimate the benefits of DOE activities in various areas.

To reach this potential, the EERAS database must be expanded to broadly cover environmental issues related to the production of oil and gas. In addition to UIC-related analyses, the data must be available to support analysis of air, water, and production waste issues. Much of the data required to support the traditional economic impact assessment in these other areas is available, having been collected during prior assessments for DOE. However, much of this

Table 1
UIC-Related Data Currently in the EERAS Database

At the National level:

Average injection well depth (feet)	Gruy 1989
Cost of AOR analysis ($)	Gruy 1989
Base cost to abandon a well ($/well)	Gruy 1989
Incremental cost to abandon a well ($/ft)	Gruy 1989
Disposal well capacity (bbl/day)	EPA, 1993 (development doc)
Fraction of abandoned wells with adequate surface casing %	Gruy 1989
Fraction of abandoned wells within AOR that require plugging %	Gruy 1989
Fraction of abandoned wells without adequate surface casing %	Gruy 1989
Fraction of existing injection wells having tubing and packer %	Gruy 1989
Fraction of existing injection wells without tubing & packer %	Gruy 1989
Fraction of injection wells in AOR undergoing variable logging %	Gruy 1989
Fraction of injection wells drilled prior to 1984 %	Gruy 1989
Fraction of injection wells requiring redrilling %	Gruy 1989
Fraction of injection wells that need remedial squeeze %	Gruy 1989
Number of variable logs assumed for injection wells in AOR	Gruy 1989
Number of variable logs assumed for producing wells in AOR	Gruy 1989
Noise or temperature log base cost ($/well)	Gruy 1989
Noise or temperature log incremental cost ($/ft)	Gruy 1989
Pressure monitoring equipment installation cost ($/well)	Gruy 1989
Pressure testing cost ($/well)	Gruy 1989
Average pressure testing frequency (every..years)	Gruy 1989
Base cost to pull tubing and packer to run OA logs ($/well)	Gruy 1989
Incremental cost to pull tubing and packer to run OA logs ($/ft)	Gruy 1989
Base cost of radioactive tracer log ($/well)	Gruy 1989
Incremental cost of radioactive tracer log ($/ft)	Gruy 1989
Base cost to replug a well that has adequate sc ($/well)	Gruy 1989
Incremental cost to replug a well that has adequate sc ($/ft)	Gruy 1989
Base cost to replug a well that lacks adequate sc ($/well)	Gruy 1989
Incremental cost to replug a well that lacks adequate sc ($/ft)	Gruy 1989
Base cost of remedial squeeze ($/well)	Gruy 1989
Incremental cost of remedial squeeze ($/ft)	Gruy 1989
Base cost for variable logging ($/well)	Gruy 1989
Incremental cost for variable logging ($/ft)	Gruy 1989
Weekly pressure monitoring costs ($/well/week)	Gruy 1989
Newly permitted wells as a % of current Class II wells (5.4%)	Holditch 1994
Newly permitted drilled injectors as a % of total new injectors (12.6%)	Cadmus 1993
Percentage of injectors that are disposal wells (20%)	Cadmus 1993
Percentage of total produced water that is from gas wells (19%)	Gruy 1991
% of injectors covered by overlap in AOR studies (20.7%)	Cadmus 1993
% of wells within an AOR that are abandoned (34%)	Holditch 1994
Frequency of CA within AOR for abandoned wells (3.3%)	Cadmus 1993, 2-29
Frequency of CA within AOR for active wells (2.9%)	Cadmus 1993, 2-29
% of CA wells requiring casing repair (13%)	Cadmus 1993, 2-29
% of CA wells requiring plugging and/or replugging (abandoned and active) (35.7% for both)	Cadmus 1993, 2-29
% of CA wells requiring testing (logging) (51.3%)	Cadmus 1993, 2-29

At the State/District level:

Number of production wells per injector within AOR	Gruy 1989
Number of abandoned wells per injector within AOR	Gruy 1989
Number of injectors	Holditch 1994, 21
Number of injectors without AORs	Holditch 1994, 21
Average depth of injectors	Holditch 1994, B-2
Avg CA costs to re-enter & plug existing abandoned well ($/well)	Holditch 1994, B-2
Avg CA costs to P&A active or idle well ($/well)	Holditch 1994, B-2
Avg CA costs to cement squeeze casing ($/well)	Holditch 1994, B-2
Avg CA costs for fluid migration logging ($/well)	Holditch 1994, B-2
Percent of no. injectors having < 2 protective layers	Holditch 1994, B-3
< 2 layer incremental annual MIT cost	Holditch 1994, B-3
Percent of no. injectors having 2 protective layers	Holditch 1994, B-3
2 layer incremental annual MIT cost	Holditch 1994, B-3
Number of conventional injection wells	Cadmus 1993, 1-6
Number of unconventional injection wells	Cadmus 1993, 1-6
Number of types on unconventional injection wells (short, annular, tubingless, packerless, slimhole, dual, other)	Cadmus 1993, 2-7
Surface casing practices and requirements (% inj w/short casing)	Cadmus 1993, 2-16
Frequency of CA within AOR for abandoned wells	Cadmus 1993, 2-29
Frequency of CA within AOR for active wells	Cadmus 1993, 2-29
Frequency of CA within AOR for total wells	Cadmus 1993, 2-29
% of CA wells requiring casing repair	Cadmus 1993, 2-29
% of CA wells requiring plugging and/or replugging (abandoned)	Cadmus 1993, 2-29
% of CA wells requiring plugging and/or replugging (active)	Cadmus 1993, 2-29
% of CA wells requiring testing (logging)	Cadmus 1993, 2-29

At the Basin/Province level:

Depth of injection well surface casing (ft)	Gruy 1989
Depth of injection well perforation (ft)	Gruy 1989
Depth of lowermost USDW	Gruy 1989
Michie basin corrosion code	Michie 1988

Disaggregate State Information

Base of fresh water (3,000 TDS) in California fields	CA O&G Fields
Base of fresh water (10,000 TDS) in most Alabama counties	AL GS map
Base of fresh water (10,000 TDS) in Kansas counties	KCC, Gen. Rules & Regs.

data is at a fairly aggregate level and assessments could be improved through the collection of more disaggregate-level data. Performing risk and cost-benefit assessments will require the inclusion of data that has not traditionally been collected for economic impact assessments. This includes factors that affect or measure risks posed, along with the volume of effluents, emissions, or other contaminants of concern associated with industry operations. It will also require data on the performance of environmental technologies in reducing these pollutants. The effort involved in identifying, collecting, and applying these data will be substantial.

During the period of performance for this effort, DOE's Morgantown Energy Technology Center (with funding from the Metairie Site Office) also began the development of an environmental module to the Gas Systems Analysis Model (GSAM). Since ICF Resources is also the contractor for that effort, we were able to develop that module so that it builds on the development of EERAS under this effort. The basic structure developed for EERAS has been used for the GSAM environmental module. Since much of the environmental data related to oil and gas production is equally applicable to both oil and gas, a common database is a reasonable approach. The EERAS database developed for this effort will be combined with the database developed for the GSAM environmental module, thereby avoiding any duplication of effort using government funds. The continued development of the GSAM environmental module can serve the same purpose as continued development of EERAS. Since the database and analytical structure will be equally applicable to TORIS- and GSAM-based analyses, this effort should serve to further the development of the EERAS concept to it full potential in supporting DOE policy analysis and decision-making.

III. Assessment of Groundwater Contamination Risks

A. Background/Purpose

Underground injection of fluids has the potential to contaminate aquifers that are, or could be, used as sources of drinking water. However, documented cases of contamination due to underground are very few in number, and most of these cases are attributable to operating practices that were in violation of existing state and federal regulations governing underground injection. The General Accounting Office (GAO) has reported finding 23 cases since 1970 where Class II injection operation are believed responsible for contamination of a drinking water aquifer (GAO, 1989). This compares with over 160,000 active Class II injection wells nationwide. Nine of the cases reported by GAO resulted from purposeful injection directly into a USDW, which would be a violation of existing law. Only a small number of reported occurrences of contamination are believed to be due to mechanical integrity failure of abandoned wells serving as a conduit for contaminants. In an earlier study based on data from Texas in the early 1970s, the Office of Technology Assessment (OTA) estimated that contamination has occurred only 2 times per 1 million well years (OTA, 1978).

Federal UIC program changes from the mid-1980s have been followed by increasing requirements at the state level. The implementation of new UIC requirements, by eliminating some of the prior problems and strengthening protection, has reduced the risk of future groundwater contamination below the levels observed by GAO and OTA. Thus, in absolute terms, the risk of groundwater contamination from Class II injection operations in quite low.

Given the low *absolute* risk of contamination, it is more appropriate to focus on the *relative* risk for groundwater contamination between areas. Even an older producing area with numerous inadequately plugged abandoned wells and highly corrosive subsurface conditions is unlikely to have an occurrence of groundwater contamination due to injection. But the relative risk of such an area compared with an area discovered and developed after 1984 may be considerably higher. To lower the risk of groundwater contamination occurring, it may be appropriate to focus limited resources on the area with the higher relative risk potential.

The potential pending revisions to the Class II UIC program based on the Federal Advisory

Committee recommendations includes a provision allowing states to establish variance programs from areas-of-review requirements for low risk injection wells. A methodology for evaluating variance eligibility has been developed by the Underground Injection Practices Research Foundation (UIPRF) and industry, under a grant from DOE (UIPRF, 1994). This methodology is highly effective for evaluating wells in a specific area, but is rather data intensive, making it impractical for a national assessment.

DOE has made major investments in supporting state UIC programs, including the development and implementation of risk-based data management systems. As DOE moves into an environment where it is more crucial to understand the potential benefits associated with its research investments, the need for a broad national assessment of relative risk of contamination was determined to be helpful in decision-making. The purpose of this assessment was not to focus efforts solely in those areas with the highest relative risk, but rather to understand the problems faced in specific geographic areas (dealing with high risk areas, justifying variances for numerous low risk areas, etc.) as a basis for determining appropriate federal action.

This project was designed to develop a methodology for such an assessment and demonstrate this methodology with an assessment of relative risks for the oil reservoirs in DOE's TORIS database. While a broad national assessment was planned, data problems (explained below) have prohibited a meaningful assessment of all oil reservoirs nationwide. Rather, this methodology has been demonstrated with a sampling of 39 reservoirs from across the nation. The approach developed is a useful assessment tool, if data difficulties can be overcome.

B. Methodology Developed

Several previous assessments of the risk of groundwater contamination from Class II injection have been performed (Michie, 1988, 1989, 1991; ICF Incorporated, 1990; Warner and McConnell, 1990; Dunn-Norman, et al., 1995). The intention of this effort was to build on these prior efforts, using the most appropriate data and approaches for a broad national assessment. Some of the prior assessments focused on a single potential pathway for contaminants to reach a USDW, such as a casing failure or an abandoned well serving a conduit. To provide a comprehensive risk assessment, the methodology developed considers these alternative pathways for contamination in a single assessment.

All assessments agree that the single most important factor affecting whether groundwater contamination could occur is the presence or absence of groundwater. In certain producing areas, there are no principle aquifers that could be used as a source of drinking water. In Alaska, the presence of permafrost conditions prohibit the use of groundwater. Logically, if no groundwater sources exist to be contaminated, then the risk of contamination is zero.

The second most important factor affecting the risk of groundwater contamination is the distance between the injection zone and the lowermost drinking water aquifer and whether sufficient pressure exists for contaminants to overcome the forces of gravity and travel that distance. If the subsurface pressure is insufficient to force injected fluids to travel the required distance (assuming that a pathway is available), then risks are minimal, unless injection operations or other factors subsequently raise the pressure to a level that could pose concern. Even if pressure were sufficient and a pathway for contaminants to migrate through existed, the probability is high that the fluids would migrate to one of the formations between the reservoir and the USDW, given pressure differentials, permeability, and other factors. This would lower or eliminate the potential for contamination of the USDW. However, for the purposes of this assessment, the presence of intervening formations has not been considered. It has been assumed that if the pressure is sufficient to cover the required distance, then the risk of contamination exists.

If the pressure is sufficient to force fluids the required distance, then the likelihood of a pathway for contaminants to travel through must be assessed. Two categories of wells must be considered: 1) current production and injection wells, and 2) abandoned wells and wells that are currently idle. Based on field experience, prior risk assessments, and other relevant literature, the key factors affecting the potential for a pathway for contaminants to exist have been summarized as follows:

- Current production/injection wells
  - Quality of the cement job, which affects whether a small annulus or channel may exist behind pipe
  - Corrosion potential, which affects the likelihood of tubing or casing failures due to corrosive influences
  - Use of construction practices that include short surface casing strings, which could mean that surface casing does not cover the lowermost aquifer, removing a layer of protection

— Use of unconventional injection well construction practices (such as tubingless or packerless construction), which can also remove one or more layers of protection for groundwater.

- Abandoned and idle wells
  — Density of abandoned wells, which determines the number of potential conduits
  — Density of idle wells, which also determines the number of potential conduits
  — Historic plugging/construction practices, which affects the potential for abandoned or idle wells to serve as conduits.

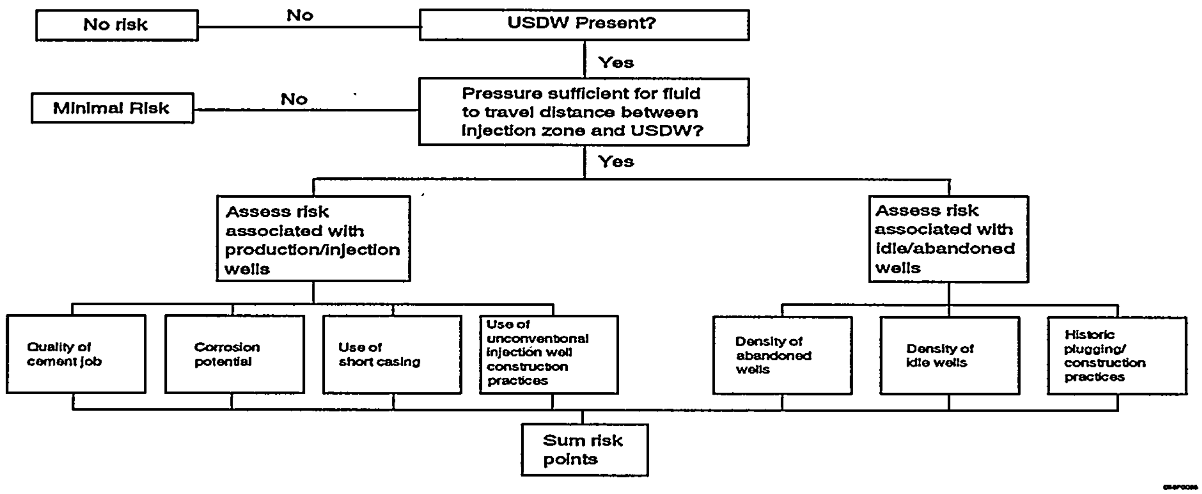
To combine these diverse factors in a single assessment of *relative* risk, risk points are assigned to each key factor, using a scale of one (low) to five (high), based on the potential for contamination to occur. These risk points can be summed and used as a basis for comparing the relative risk of contamination across areas. A consistent scale of one to five was used for all factors to avoid introducing bias based on differing scales. The methodology developed weights all of the above factors equally, since data upon which to determine more appropriate relative weights is not available. While it may be possible to postulate that historic construction and plugging practices is more important than the density of idle or abandoned wells, no basis for determining whether it is one and one-half, two, or more times as important exists. Since the focus of this analysis is on *relative* risk, and substantial uncertainty is associated with some of the data used (as described below), a uniform weighting of the key factors provides a reasonable basis for an assessment.

The basic methodology described above is illustrated in Figure 3. The basis for assigning risk points to each factor is described below in the section on problems encountered, since the uncertainty associated with certain data items affects the approach used.

C. Uncertainties/Problems Encountered

Substantial data problems were encountered in attempting to apply this methodology on a national scale. When assessing the potential risks associated with an individual well, data are available: from well logs to provide specifics on the location of aquifers relative to the injection zone; from completion records, to determine well construction; from operational data, to calculate injection zone pressures; from cement bond logs, to assess the quality of the cement job; etc.

Figure 3
Assessing Relative Risk of Groundwater Contamination from Underground Injection



Performing a national assessment still requires information for each of these key risk factors, but the data are much less readily available. For certain aspects, data are not available and surrogates must be used. Moreover, the quality of the data that are available is often uncertain.

As noted above, data on the presence and depth of groundwater aquifers is probably the single most important risk factor. Yet no reliable, national source for data on groundwater is available, as described in Section II of this report. In proceeding with an assessment, the conservative assumption that groundwater is present can be made. However, to evaluate whether subsurface pressure is sufficient for contaminants to travel to the USDW, it is necessary to know the depth of the lowermost USDW. The only available data for use in this assessment is from a report prepared by Gruy Engineering for API (Gruy, 1989). Gruy had data for a limited number of states, so in other areas made the assumption that the lowermost USDW was 300 feet below the typical depth of surface casing. Gruy's estimate was intended to estimate the depth of the lowermost aquifer of 10,000 parts per million (ppm) total dissolved solids (TDS). In its recommended changes to UIC rules, EPA's Federal Advisory Committee suggested that protection focus on aquifers of 3,000 ppm TDS or less. These aquifers would be shallower than Gruy's assessment, but for purposes of making a conservative assumption, the Gruy data has been used.

Another rationale for not adjusting the Gruy data is the uncertainty associated with these data. The Gruy assumption is based on casing depth plus 300 feet. But as shown in Table 2, data recently prepared for the Gas Research Institute on casing depths differs substantially in many areas from that used by Gruy. Part of this discrepancy may be explained by the fact that the GRI data focus on gas wells, which tend to be deeper than oil wells. However, there is still substantial uncertainty regarding typical casing depths and consequently, the use of casing depth as a means for estimating the depth of the lowermost USDW. Lacking better data, the Gruy data have been used in this assessment, but to the extent that these data are inaccurate, they lead the resulting risk assessment into question.

In addition to knowing the distance contaminants must travel to move from the injection zone to the aquifer, whether sufficient subsurface pressure exists to force fluids to travel this distance must be evaluated. Using the Gruy data on depth of the lowermost USDW and reservoir depth from TORIS, the distance to be traveled can be calculated. The pressure required to travel this distance can also be calculated using a standard pressure gradient for saltwater:

$$\text{Required pressure} = (0.46)\ (\text{distance in feet})$$

This pressure can be compared with the pressure in the injection zone to determine whether it is feasible for fluids to travel the required distance to contaminate groundwater. Data on the current pressure in the injection zone is not readily available. For disposal wells, no data are generally available on pressure in the formation being injected. For enhanced recovery wells, which comprise nearly 80 percent of injection wells (Gruy, 1989), the original reservoir pressure can be used as an upper bound. As the reservoir is produced, natural reservoir pressure falls. Injection operations increase the pressure, but rarely return the reservoir to its original pressure. Most reservoirs in the TORIS database include an estimate of original reservoir pressure which can be used for this assessment. For some TORIS reservoirs, sufficient data are available to estimate current reservoir pressure, using standard engineering equations. The 39 reservoirs selected to demonstrate this methodology were selected in part because current reservoir pressure could be estimated. However, there is substantial uncertainty associated with these estimates.

Data on the quality of the cement job, which determines the potential for a micro-annulus

Table 2
Comparison of GRI and Gruy Surface Casing Depths

State	EERC for GRI, 1995		Gruy, 1989	
	Province/Basin	Casing Depth	Basin	Casing Depth
Alabama	Appalachian	700	Smackover	1,470
	Black Warrior	700	Black Warrior	356
	Mid-Gulf Coast	2,500		
Alaska	No Data		Beaufort Shelf	590
			Cook Inlet	514
Arkansas	Arkla	700	Sabine/Lasalle/Monroe Uplift	304
	Arkoma	700	Arkoma	350
Arizona	Black Mesa	no data	San Juan	711
California	Eel River	no data	Ventura	506
	Sacramento	700	Sacramento	250
	San Joaquin	2,100	San Joaquin	1,387
Colorado	Anadarko	no data		
	Denver	1,400	Denver	241
	Green River	1,400		
	Las Animas Arch	700	Canon City-Florence	130
	Las Vegas - Raton	700		
	Paradox	2,100	Paradox	0
	Piceance	2,100	Piceance	1,315
	San Juan	700	San Juan	405
Illinois	Illinois	700	Illinois	178
Indiana	Cincinnati Arch	700		
	Illinois	700	Illinois	178
	Michigan	250		
Kansas	Anadarko	1,400	Hugoton Embayment	719
	Central Kansas Uplift	200		
	Cherokee	600		
	Forest City	500	Forest City	186
	Las Animas Arch	700		
	Nemaha Anticline	300		
	Sedgwick	250	Sedgwick	427
Kentucky	Appalachian	700	Appalachian	337
	Cincinnati Arch	700		
	Illinois	700	Illinois	280

State	EERC for GRI, 1995		Gruy, 1989	
	Province/Basin	Casing Depth	Basin	Casing Depth
Louisiana	Arkla	700	Sabine/Lasalle/Monroe Uplift	853
	Gulf Coast	2,100	Gulf Coast	902
	Gulf Coast CCL	2,100		
	Mid-Gulf Coast	no data		
Michigan	Michigan CL	1,400	Michigan	533
	Michigan UL	1,400		
Missouri	Forest City	200	Forest City	85
Mississippi	Black Warrior	700	Black Warrior	818
	Mid-Gulf Coast	2,500	Smackover	2,300
			Mississippi Salt Dome	614
Montana	Big Horn	700	Big Horn	317
	Central Montana Uplift	700		
	Powder River	200	Powder River	257
	Sweetgrass Arch	700	South Alberta	400
	Williston	1,400	Williston	715
Nebraska	no data		Denver	357
			Forest City	250
			Powder River	0
			Sedgwick	380
Nevada	no data		Eocene	297
North Dakota	Williston	2,100	Williston	2,495
New Mexico	Las Vegas - Raton	700		
	Orogrande	700	North & Central Texas Area	850
	Permian	2,200	Permian	496
	San Juan	700	San Juan	185
New York	Appalachian	700	Appalachian	145
Ohio	Appalachian	700	Appalachian	369
	Cincinnati Arch	700	Findlay Arch	45
Oklahoma	Anadarko	1,400	Anadarko & Dalhart	588
	Arkoma	700	Arkoma	0
	Chautauqua Platform	700	Central OK	465
	Quachita Folded Belt	700		
	Palo Duro	700		
	S OK Folded Belt	2,100		
Oregon	Western Columbia	600	No data	

State	EERC for GRI, 1995		Gruy, 1989	
	Province/Basin	Casing Depth	Basin	Casing Depth
Pennsylvania	Appalachian	700	Appalachian	43
South Dakota	Powder River	200	Powder River	346
			Williston	1,531
Tennessee	Appalachian	700	Appalachian	670
	Cincinnati Arch	700		
Texas	Anadarko	1,400		
	Bend Arch	450		
	East Texas	2,100	East Texas Salt	747
	Ft. Worth Syncline	1,000		
	Gulf Coast	2,100	Gulf Coast	1,183
			South Texas Area	1,300
	Llano Uplift	no data	Delaware	826
			North & Central Texas Area	553
	Palo Duro	700		
	Permian	2,100	Anadarko & Dalhart	967
			Permian	782
	Permian VV	1,000		
	S OK Folded Belt	1,000		
	Strawn	1,000		
Utah	C. Western Overthrust	1,400	Great Basin	no data
	Paradox	2,100	Paradox	324
	Uinta	2,100	Uinta	288
Virginia	Appalachian	700	Appalachian	0
West Virginia	Appalachian	700	Appalachian	384
Wyoming	Big Horn	700	Big Horn	499
			Denver	413
	C. Western Overthrust	1,400		
	Green River	1,400	Green River	890
			Washakie	227
	Powder River	200	Powder River	760
	Powder River UL	200		
	Wind River	1,400		

or channel to exist behind pipe, is not available on a broad, national basis, since this is very well-specific. Consequently, a surrogate for this factor based on available data was required. A surrogate was developed based on the age of currently producing wells in each field. The decade in which currently producing wells were drilled was available from Dwight's Energydata.[1] While the potential for a bad cement job in completing a well always exists, it was assumed that over time, both the materials and practices used have improved to reduce this potential. Thus, risk points were assigned to each decade, as shown in Table 3. This assignment was somewhat arbitrary, but did consider the period when many states were revising their well construction requirements (based on IOGCC, 1992).

Table 3
Risk Points Assigned by Decade of Well Construction

Decade	Risk Points
pre-1940	5
1940	4
1950	3
1960	2
1970	1
1980	0
1990	0

The distribution of wells within the field by age were then used to calculate the number of risk points associated with a particular field, as illustrated in Table 4. This approach works for most areas of the country. However, Dwight's Energydata does not cover Appalachia, so an alternative approach was required for reservoirs in this area. For these areas, risk points were

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1 These data were purchased for DOE's Morgantown Energy Technology Center as part of efforts being completed for the Gas Systems Analysis Model, and were made available to this effort. Use of these data, which are the best available for this analysis, was one of the difficulties associated with performing a national assessment. Since the U.S. does not have a standard nomenclature for reservoirs and fields, many different names can apply to the same field. An initial attempt to match the Dwight's data by field with that in TORIS resulted in few exact matches. Sorting out the differences between these data sets was a time- and resource-consuming activity that is beyond the scope of this effort. Therefore, a sampling of TORIS reservoirs was selected and the matching performed for those reservoirs only.

assigned based on the date of discovery of the field (EIA, 1992). While it is possible that a substantial portion of the development in the field took place decades later, and thus may have lower risk of cement problems, use of the discovery date produces a conservative result.

Table 4
Example Calculation of Risk Points for Marcotte Field, Kansas
Based on Age of Producing Wells

Decade	Active Wells[1]	Distribution	Risk Points	Weighted Risk Points
1940	16	22.54%	4	0.9016
1950	29	40.85%	3	1.2255
1960	3	4.23%	2	0.0846
1970	6	8.45%	1	0.0845
1980	16	22.54%	0	0
1990	1	1.41%	0	0
Total		100.00%		2.2962

[1] Number of currently active wells that were drilled and completed during that decade.

In his report for API, Michie assigned a low, moderate, or high risk of corrosion to basins throughout the country (Michie, 1988). Michie's assessment was based on historical data on corrosion problems, as well as available data on the quality of subsurface brines and the current use of cathodic protection (to prevent corrosion). No alternative to Michie's assessment is available, and his data are regarded as generally accurate. For this assessment, a score of low was assigned one risk point, moderate was assigned three risk points, and high was assigned five risk points.

Data on injection well construction practices by state is available from Cadmus (1993). This report includes the use of a short surface casing string as an unconventional construction practice. For purposes of this assessment, use of short casing has been separated from other types of unconventional construction practices. Data on the use of short surface casing in producing wells was not available, so the data for injection wells has been used to represent both production and injection wells. The portion of wells constructed in this manner is probably roughly similar for production and injection wells in most states, especially since most injection wells are converted from producing wells. Thus, this assumption probably introduces little bias into the result. Since data are available only by state, this risk assessment has applied the same data to all fields and reservoirs within the state. If unconventional construction practices were evenly distributed throughout the state, this assumption would not introduce any bias into the result. However, use of these practices is sometimes confined to a geographic area within a state (e.g., the use of slimhole completions in southeastern Kansas). But no basis for modifying the distribution for different areas of the state exists, so for this analysis, all reservoirs in the state were assigned risk points consistent with the state distribution.

No basis for assigning risk points for use of short casing and unconventional construction practices exists from the data available. Points have been assigned somewhat arbitrarily for this purpose, and the extent to which these points represent the risks posed is uncertain. This is an area of substantial uncertainty associated with this effort, but data are not available to improve this assessment. This uncertainty does not, however, necessarily invalidate the conclusions, merely suggest that more investigation is required, and that an analysis of the sensitivity of the final result to this assumption is warranted. The risk points assigned for use of short casing and unconventional construction practices are shown in Table 5 and Table 6, respectively. The scales differ because the use of short casing does not necessarily mean that the aquifer is not protected (depending on depth), although it may mean that. Unconventional well construction practices do indicate that at least one layer of protection (as defined by EPA's Federal Advisory Committee) is missing.

The density of abandoned wells used in this analysis is based on data from Gruy (1989). Gruy estimated the number of wells that have been abandoned since the initiation of drilling in each state-basin combination, using data from Petroleum Information Corporation and other sources. Using Gruy's data on injection well populations, the average number of abandoned wells per injection well were calculated. But the risk points that should be assigned for the number of abandoned wells per injector was problematic. No good basis is available for determining whether one abandoned well or ten abandoned wells per injector poses a risk. While ten wells clearly pose a higher risk than one well, it is unclear whether the risk is two, five, ten, or twenty times as great. The figures for abandoned wells per injection well by state-basin were arrayed to determine whether any logical break points in the data existed that could be used to

Table 5
Risk Points Assigned Based on Percentage of Wells Constructed with Short Surface Casing

Wells with Short Casing	Risk Points
0%	0
0.01% - 9.99%	1
10% - 24.99%	2
25 - 39.99%	3
40 - 59.99%	4
60% or more	5

Table 6
Risk Points Assigned Based on Percentage of Wells Constructed Using Unconventional Practices

Unconventionally Constructed Wells	Risk Points
0%	0
0.01% - 4.99%	1
5% - 9.99%	2
10 - 19.99%	3
20 - 29.99%	4
30% or more	5

determine how to assign risk points to the resulting distribution. Based on this assessment, but still largely arbitrarily, risk points were assigned as shown in Table 7. Because this assignment of risk points is not data-based, it introduces substantial uncertainty into the result.

Determining the risk points associated with the density of idle wells generated the same problems as with the density of abandoned wells, since no data for determining the level of risk exist. However, data on idle well populations have a greater degree of uncertainty than the data for abandoned wells. Data on idle wells are taken from an IOGCC/DOE report (1992), which includes estimates by state regulatory personnel of wells that are idle without state permission.

Table 7
Risk Points Based on Density of Abandoned Wells

Abandoned Wells/ Injector	Risk Points
0.01 - 0.99	1
1 - 1.99	2
2 - 4.99	3
5 - 9.99	4
10 or more	5

Table 8
Risk Points Based on Density of Idle Wells

Idle Wells/ Injector	Risk Points
0.01 - 0.99	1
1 - 1.99	2
2 - 4.99	3
5	4
>5	5

This analysis has included all three categories of idle wells from the IOGCC/DOE report: 1) wells idle with state approval, 2) wells idle without state approval, operator known, and 3) wells idle without state approval, operator unknown (orphan wells). The total number of idle wells of all three types have been divided by Gruy (1989) data on the number of injection wells to develop density data. These data have been assigned risk points as shown in Table 8. As with abandoned well density, this assignment is largely arbitrary and introduces substantial uncertainty. Data on idle wells include counts at the state level only, so the same data have been applied to all reservoirs within a state. As with unconventional construction, this supposes that idle wells are evenly distributed throughout the state, but no alternative basis for application of these data exists.

It was also necessary to use a surrogate to represent historic construction and plugging practices. Similar to the analysis for cement job quality, the age of abandoned wells has been used as a surrogate. Using data from Dwight's Energydata on the number of wells drilled within a field each decade and how many of those wells are still active, the number of abandoned wells by decade can be estimated. Applying the risk points associated with construction practices during a decade (from Table 4) the weighted risk score based on the distribution of abandoned wells can be calculated. This approach is conservative. For example, if all of the abandoned wells in a field were drilled during the 1960s (using 1960 construction practices) the field would receive two risk points. Yet many of these wells probably produced for a number of years, and may not have been abandoned until the 1970s or 1980s, when improved plugging practices probably lower the risk of a problem. But since data on when wells within a field were abandoned is not readily available, this conservative approach provides a reasonable basis for assigning risk points.

The risks associated with underground injection operations are very site specific. Any time a national, or aggregate-level, assessment is being performed, certain simplifying assumptions are required due to the infeasibility of a well-by-well assessment for a large area. The methodology developed to perform a nationwide assessment of the relative risks of groundwater contamination follows these principles. Reasonable data or surrogates that could be used to represent key risk factors have been identified. But as the discussion above makes clear, some of these data, or their application, have substantial uncertainty associated with them. Nonetheless, using available data, the relative risks associated with selected reservoirs throughout the country have been assessed, and the results are consistent with what would be expected. Tables 9 and 10 summarize the data values used by state or state-basin combination and the risk points assigned to each value.

D. Results of Analysis

Forty reservoirs were selected from the TORIS database for this analysis, but one of the reservoirs selected was located offshore Louisiana. Since the focus of UIC requirements is onshore operations, this reservoir was omitted from the analysis, leaving 39 reservoirs located throughout the nation. Two criteria were used for selecting these reservoirs: 1) sufficient data available to estimate current reservoir pressure, and 2) geographic diversity. Two reservoirs within the same field were also selected, so that any difference in relative risks could be

Table 9
Data Used In Assessment

	Basin Code	Gruy (1989) Table 1 Code (1)	Gruy (1989) Table 2 Depth to Lower USDW (2)	Gruy (1989), Table 6 Total Injectors (3)	Pre–1984 Injectors ER (4)	Pre–1984 Injectors SWD (5)	Abd. Wells W/in AOR (6)	Calc. Col.6/Col.3 Abd.Wells/ Injector (7)	IOGCC (1992), Table IV Idle Wells St Approv (8)	Idle Wells No St Appr (9)	Calc. Col.(8+9)/ Col.2 Idle Wells/ Injector (10)
Alabama	1	L	656	26	12	10	27	1.04			
	2	L	1,770	189	104	58	40	0.21			
	Total			215	116	69	67	0.31	1,715	0	7.98
Alaska	49	L	890.	426	347	19	138	0.32			
	50	L	814	85	71	3	103	1.21			
	Total			511	418	22	241	0.47	26	0	0.05
Arizona	3	M	1,011	5	0	4	19	3.80	16	0	3.20
Arkansas	5	L	650	10	0	9	5	0.50			
	6	L	604	1,225	206	848	6,995	5.71			
	Total			1,235	206	857	7,000	5.67	0	0	0.00
California	8	M	750	4,830	3,777	377	18,139	3.76			
	9	M	1,000	14,609	12,000	563	38,678	2.65			
	44	L	1,500	42	0	36	2,147	51.12			
	Total			19,481	15,778	976	58,964	3.03	30,041	0	1.54
Colorado	3	M	705	7	4	2	8	1.14			
	10	H		0	0	0	0				
	12	M	541	315	207	64	719	2.28			
	13	H	1,615	417	339	20	496	1.19			
	14	L	430	244	160	50	405	1.66			
	Total			983	710	135	1,628	1.66	2,674	200	2.92
Florida	15	H	2,000	57	39	10	71	1.25			
	2	L	2,500	20	10	7	18	0.90			
	Total			77	49	17	89	1.16	111	0	1.44
Illinois	19	L	478	14,548	10,864	1,648	76,628	5.27	594	3,030	0.25
Indiana	19	L	514	3,307	2,522	322	29,833	9.02	55	610	0.20
Kansas	22	L	486	1,497	810	477	14,109	9.42			
	23	H	1,019	3,299	1,781	1,050	14,742	4.47			
	35	H	727	10,065	5,452	3,204	80,282	7.98			
	Total			14,861	8,049	4,732	109,134	7.34	3,100	600	0.25
Kentucky	24	L	637	5,331	4,567	17	23,280	4.37			
	19	L	580	86	0	74	698	8.12			
	Total			5,417	4,567	91	23,978	4.43	700	5,000	1.05
Louisiana	6	L	1,400	1,529	898	417	9,519	6.23			
	25	L	1,000	2,630	224	2,037	8,335	3.17			
	Total			4,159	1,122	2,454	17,854	4.29	19,168	0	4.61
Michigan	20	L	833	1,657	894	531	6,860	4.14	1,309	0	0.79
Mississippi	1	L	1,118	34	0	29	88	2.59			
	2	L	2,600	527	139	314	923	1.75			
	26	M	914	420	123	238	1,062	2.53			
	Total			981	262	581	2,072	2.11	892	1,848	2.79
Missouri	22	L	385	.402	336	9	1,066	2.65	67	50	0.29
Montana	28	H	1,015	222	138	52	353	1.59			
	29	L	557	245	153	58	751	3.07			
	31	L	700	768	619	41	4,382	5.71			
	48	M	617	95	59	22	495	5.21			
	Total			1,330	970	174	5,981	4.50	4,100	0	3.08
Nebraska	12	M	657	287	219	28	924	3.22			

Table 9 (Continued)
Data Used in Assessment

	Basin Code	Gruy (1989) Table 1: Code (1)	Gruy (1989) Table 2: Depth to Lower USDW (2)	Gruy (1989), Table 6: Total Injectors (3)	Pre-1984 Injectors: ER (4)	Pre-1984 Injectors: SWD (5)	Abd. Wells W/in AOR (6)	Calc. Col.6/Col.3: Abd.Wells/ Injector (7)	IOGCC (1992), Table IV: Idle Wells: St Approv (8)	IOGCC (1992), Table IV: Idle Wells: No St Appr (9)	Calc. Col.(8+9)/ Col.2: Idle Wells/ Injector (10)
	22	L	5,550	31	24	3	12	0.39			
	29	L		0	0	0	0				
	35	H	680	399	304	39	1,344	3.37			
	Total			717	548	69	2,280	3.18	542	0	0.76
Nevada	33	L	597	12	0	10	21	1.75	15	0	1.25
New Mexico	3	M	485	573	328	165	325	0.57			
	42	H	796	3,629	2,834	287	7,069	1.95			
	43	L	1,150	249	201	13	270	1.08			
	Total			4,451	3,363	465	7,664	1.72	4,200	0	0.94
New York	24	L	445	3,254	2,793	5	4,483	1.38	1,356	1,178	0.78
North Dakota	28	H	2,795	529	269	186	385	0.73	464	274	1.40
Ohio	21	L	345	3	0	3	3	1.00			
	24	L	669	3,953	112	3,288	21,521	5.44			
	Total			3,956	112	3,290	21,523	5.44	30	500	0.13
Oklahoma	5	L		0	0	0	0				
	37	L	765	10,645	5,927	3,228	80,633	7.57			
	38	M	888	14,271	8,107	4,166	68,943	4.83			
	Total			24,916	14,034	7,393	149,576	6.00	1,782	0	0.07
Pennsylvania	24	L	343	6,183	3,711	1,606	237,440	38.40	297	0	0.05
South Dakota	28	H	1,831	22	13	6	20	0.91			
	29	L	646	19	12	4	27	1.42			
	Total			41	25	10	47	1.15	23	0	0.56
Tennessee	24	L	970	10	6	3	5	0.50	0	0	0.00
Texas	25	L	2,200	1,841	1,073	510	9,637	5.23			
	34	H	1,500	3,411	2,674	260	29,820	8.74			
	38	M	1,500	870	524	224	3,975	4.57			
	40	M	2,000	4,638	3,103	886	22,148	4.78			
	41	H	2,000	1,839	1,207	374	13,427	7.30			
	42	H	1,500	20,557	16,437	1,242	66,225	3.22			
	43	L	1,000	19,584	14,439	2,404	188,069	9.60			
	Total			52,740	39,457	5,900	333,302	6.32	51,336	0	0.97
Utah	10	H	624	495	415	10	1,442	2.91			
	46	L	588	159	105	32	114	0.72			
	33	L		0	0	0	0				
	Total			654	520	42	1,556	2.38	873	0	1.33
Virginia	24	L		0	0	0	0				
West Virginia	24	L	684	572	369	123	1,997	3.49	0	4,516	7.90
Wyoming	11	M	527	187	153	8	1,017	5.44			
	12	M	713	18	15	0	20	1.11			
	29	L	1,060	1,803	1,480	71	2,267	1.26			
	45	M	1,190	796	654	31	539	0.68			
	48	M	799	2,175	1,785	86	3,870	1.78			
	Total			4,979	4,087	195	7,715	1.55	10,892	0	2.19
Indian Lands	Total										
U.S.	Total			172,183	116,157	31,921	1,109,407	6.44	136,378	17,806	0.90

Table 9 (Continued)
Data Used in Assessment

	Basin Code	Cadmus (1993) p. 2–7 Injection Well Construction Type (Conv. Incl. in total) Short Casing (11)	Annular (12)	Tubingless (13)	Packerless (14)	Slimhole (15)	Dual (16)	Other (17)	Total (18)	Calc. Col.11/Col.18 Short Casing % of Total (19)	Calc. Col.(12–17)/Col.18 Oth. Unconv. % of Total (20)
Alabama	1										
	2										
	Total	174		9	3				288	60.42%	4.17%
Alaska	49										
	50										
	Total								628	0.00%	0.00%
Arizona	3	1							1	100.00%	0.00%
Arkansas	5										
	6										
	Total	1,202			27				1,363	88.19%	1.98%
California	8										
	9										
	44										
	Total	11,702		55	55		55		23,568	49.65%	0.70%
Colorado	3										
	10										
	12										
	13										
	14										
	Total	391	4	51	4	4			846	46.22%	7.45%
Florida	15										
	2										
	Total	14							70	20.00%	0.00%
Illinois	19					69	69		13,792	0.00%	1.00%
Indiana	19	878							1,756	50.00%	0.00%
Kansas	22										
	23										
	35										
	Total	2,874		50	300	7,001	100		13,199	21.77%	56.45%
Kentucky	24										
	19										
	Total	4,292		150		150	10		4,602	93.26%	6.74%
Louisiana	6										
	25										
	Total	1,418	101	46	296	15			3,609	39.29%	12.69%
Michigan	20	547							1,215	45.02%	0.00%
Mississippi	1										
	2										
	26										
	Total	750		6	12				1,153	65.05%	1.56%
Missouri	22				32	160			639	0.00%	30.05%
Montana	28										
	29										
	31										
	48										
	Total	1,234		14		7	7		1,391	88.71%	2.01%
Nebraska	12										

Table 9 (Continued)
Data Used in Assessment

	Basin Code	Cadmus (1993) p. 2-7 Injection Well Construction Type (Conv. incl. in total) Short Casing (11)	Annular (12)	Tubingless (13)	Packerless (14)	Slimhole (15)	Dual (16)	Other (17)	Total (18)	Calc. Col.11/Col.18 Short Casing % of Total (19)	Calc. Col.(12–17)/ Col.18 Oth. Unconv. % of Total (20)
	22										
	29										
	35										
	Total			10	2	18	4		729	0.00%	4.66%
Nevada	33								19	0.00%	0.00%
New Mexico	3										
	42										
	43										
	Total			23	23		23		4,693	0.00%	1.47%
New York	24	388		3				320	840	46.19%	38.45%
North Dakota	28	13							655	1.98%	0.00%
Ohio	21										
	24										
	Total		719						1,035	0.00%	69.47%
Oklahoma	5										
	37										
	38										
	Total	433			217	1,733	2,382		21,658	2.00%	20.00%
Pennsylvania	24	898		320				535	2,215	40.54%	38.60%
South Dakota	28										
	29										
	Total	2	1		41				71	2.82%	59.15%
Tennessee	24			4					13	0.00%	30.77%
Texas	25										
	34										
	38										
	40										
	41										
	42										
	43										
	Total	19,440		544	272	544	544		54,446	35.71%	3.50%
Utah	10										
	46										
	33										
	Total	56					7		109	51.38%	6.42%
Virginia	24										
West Virginia	24	100		118			6		487	20.53%	25.46%
Wyoming	11										
	12										
	29										
	45										
	48										
	Total								5,188	0.00%	0.00%
Indian Lands	Total	2,165		163		65	33		3,268	66.25%	7.99%
U.S.	Total	48,969	825	1,566	1,285	9,766	3,241	855	163,547	29.94%	10.72%

Table 10
Risk Points Assigned by Area

	Gruy Basin Code	Corrosion Risk Pts	Abd. Wells Risk Pts	Idle Wells Risk Pts	Short Casing Risk Pts	Unconventional Construction Risk Pts
Alabama	1	1	2			
	2	1	1			
	Total			5	5	1
Alaska	49	1	1			
	50	1	2			
	Total			1	0	0
Arizona	3	3	3	4	5	0
Arkansas	5	1	1			
	6	1	4			
	Total			1	5	1
California	8	3	3			
	9	3	2			
	44	1	5			
	Total			3	4	1
Colorado	3	3	2			
	10	5				
	12	3	3			
	13	5	2			
	14	1	2			
	Total			3	4	2
Florida	15	5	2			
	2	1	1			
	Total			3	2	0
Illinois	19	1	4	1	0	1
Indiana	19	1	4	1	4	0
Kansas	22	1	4			
	23	5	4			
	35	5	4			
	Total			1	2	5
Kentucky	24	1	4			
	19	1	4			
	Total			3	5	2
Louisiana	6	1	4			
	25	1	3			
	Total			4	3	3
Michigan	20	1	4	1	4	0
Mississippi	1	1	2			
	2	1	2			
	26	3	2			
	Total			3	5	1
Missouri	22	1	2	1	0	4
Montana	28	5	2			
	29	1	3			
	31	1	4			
	48	3	4			
	Total			4	5	1
Nebraska	12	3	3			
	22	1	1			
	29	1				
	35	5	3			

Table 10 (Continued)
Risk Points Assigned by Area

	Gruy Basin Code	Corrosion Risk Pts	Abd. Wells Risk Pts	Idle Wells Risk Pts	Short Casing Risk Pts	Unconventional Construction Risk Pts
	Total			2	0	1
Nevada	33	1	2	3	0	0
New Mexico	3	3	1			
	42	5	2			
	43	1	2			
	Total			2	0	1
New York	24	1	2	2	4	5
North Dakota	28	5	1	3	1	0
Ohio	21	1	2			
	24	1	4			
	Total			1	0	5
Oklahoma	5	1				
	37	1	4			
	38	3	4			
	Total			1	1	3
Pennsylvania	24	1	5	1	4	
South Dakota	28	5	1			
	29	1	2			
	Total			1	1	5
Tennessee	24	1	1	1	0	5
Texas	25	1	4			
	34	5	4			
	38	3	4			
	40	3	4			
	41	5	4			
	42	5	3			
	43	1	4			
	Total			2	3	1
Utah	10	5	2			
	46	1	1			
	33	1				
	Total		2	3	4	2
Virginia	24	1				
West Virginia	24	1	3	5	2	4
Wyoming	11	3	4			
	12	3	2			
	29	1	2			
	45	3	1			
	48	3	2			
	Total			3	0	
Indian Lands	Total				5	
U.S.	Total		4	2	3	

demonstrated. Table 11 provides some basic information about each of these reservoirs, which cover 15 states.

Based on the data in Tables 10 and 11, along with the distribution of active and abandoned wells by decade from Dwight's, Table 12 presents the calculated risk score for each reservoir assessed. In all cases, groundwater was assumed to exist even though this may not be true (e.g., McArthur River in Alaska).

The second key factor determining risk is whether it is feasible, based on pressure and distance, for injected fluids to reach a USDW. The distance between the reservoir and the lowermost USDW is calculated, then the required pressure for fluids to travel that distance is estimated. This pressure is compared with the original and estimated current reservoir pressure. For ten of the reservoirs assessed, even original reservoir pressure would be insufficient to force contaminants to the aquifer. For these ten reservoirs, risk is minimal and no further assessment is required. However, the risk points that could be associated with these reservoirs are shown for comparative purposes. If the estimate of current reservoir pressure is accurate, only seven of the 39 reservoirs evaluated are likely to have pressure sufficient to result in migration of injected fluids to USDWs. This is consistent with the very low absolute risk of groundwater contamination.

The reservoir with the highest number of risk points (implying highest relative risk of contamination) is Canadaway reservoir in Kane field, Pennsylvania. This reservoir received 26 out of a total of 35 possible risk points. While the Appalachian basin in not highly corrosive, this older producing area has numerous abandoned wells and substantial use of short casing and unconventional construction practices. This reservoir is one of those not covered by Dwight's, so its risk points for cement quality (producing well age) and historic construction/plugging practices (abandoned well age) are based on the field's year of discovery, which is 1876. These risk points may be overstated depending on when most field development actually occurred, but a finding of greater *relative* risk in this area is not surprising. It is important to remember that this does not imply that groundwater contamination has or will occur in this area, merely that compared with other areas of the country, there is a higher probability that it could occur based on conditions in this area. Mitigating this is an assessment that current reservoir pressure is unlikely to be sufficient for fluids to travel from the reservoir to a USDW.

Table 11
TORIS Reservoir Data

REF	ST	FIELD NAME	RESERVOIR NAME	MICHIE BASIN	DEPTH Feet	OOIP MBBL	ROIP MBBL	INITIAL PRESSURE Psi	CURRENT PRESSURE Psi
3079	AK	MCARTHUR RIVER	TYONEK MIDDLE KENAI G ZONE	50	8,850	130,008	62,014	4,009	3,000
42	CA	ALISO CANYON	PORTER	8	5,050	50,377	25,591	1,795	450
71	CA	CYMRIC	SALT CREEK MAIN	9	2,400	67,791	41,895	1,100	500
93	CA	KRAEMER	KRAEMER	8	4,500	83,374	39,436	1,750	650
3227	CA	NEWHALL POTRERO	7TH ZONE	8	10,250	51,178	36,643	5,878	2,650
3225	CA	NEWHALL POTRERO	5TH ZONE	8	8,300	59,981	41,927	3,940	1,400
125	CA	RAMONA	KERNDEL VALLEY	8	4,265	124,451	104,290	2,000	500
2920	CA	RICHFIELD EAST AREA	CHAPMAN	8	3,128	139,786	71,011	1,371	350
129	CA	ROSEDALE RANCH	LERDO	9	4,370	64,296	57,224	1,825	750
3427	CA	VENTURA FIELD	B SANDS	8	4,700	101,323	69,812	2,600	1,700
145	CA	WHITTIER	2ND & 3RD ZONES	8	2,700	63,394	34,486	950	355
3012	IL	JOHNSONVILLE CONSOLIDATED	MC CLOSKY LIMESTONE	19	3,170	90,278	51,097	1,020	600
2886	IL	NEW HARMONY CONSOL	CYPRESS	19	2,404	116,153	79,332	1,250	800
237	IN	CABORN CONSOLIDATED	MANSFIELD	19	659	53,341	43,580	330	300
3029	KS	MARCOTTE	ARBUCKLE	35	3,800	61,403	20,631	1,000	950
3574	LA	BAY MARCHAND BLOCK 2	O SAND RESERVOIR D UNIT	25	12,200	117,177	67,025	6,680	3,050
3486	LA	OLD LISBON FIELD OPER COMMITTEE	PETTIT LIME	6	5,250	61,613	44,731	2,338	2,200
3065	MI	WEST BRANCH	DUNDEE	20	2,600	101,423	89,151	1,000	800
3545	MT	CORAL CREEK	RED RIVER	28	8,700	52,293	32,945	3,300	2,200
629	MT	FLAT LAKE	RATCLIFFE	28	6,500	68,542	48,734	2,944	2,000
2810	NE	SLEEPY HOLLOW	REAGAN	12	3,450	78,001	35,257	550	400
3622	NM	CATO	SAN ANDRES	42	3,600	99,698	83,746	2,000	1,153
2828	NM	CHAVEROO	SAN ANDRES	42	4,250	129,459	105,768	1,340	600
3832	NM	LOCO HILLS	WEST UNIT	42	2,665	50,275	26,093	1,161	812
2834	NM	LOVINGTON	PADDOCK	42	6,100	67,252	50,910	2,100	1,500
3024	OK	CARTHAGE DISTRICT NE	MORROW	38	4,300	109,664	101,110	1,420	940
1128	OK	NAVAL RESERVE	BURBANK	37	2,630	104,320	47,570	1,238	1,200
1145	OK	PAPOOSE	CROMWELL	5	3,350	70,593	46,309	700	660
1146	OK	PAULS VALLEY	BASAL PENNSYLVANIAN	38	3,900	56,578	25,686	1,800	1,520
2667	PA	KANE	CANADAWAY	24	2,250	100,295	60,177	1,050	400
3435	TX	BIG MINERAL CREEK	BARNES SAND	43	5,258	55,802	34,374	2,477	1,440
1265	TX	CLAYTONVILLE	CANYON LIME	42	5,750	135,010	71,015	2,335	2,335
1271	TX	CROSSETT	DEVONIAN	42	5,300	52,985	26,810	2,500	2,000
2941	TX	EL MAR	DELAWARE SAND	42	4,500	71,701	53,919	2,151	250
1419	TX	FOREST HILL	HARRIS SAND (BF SEGMENTS)	41	4,800	53,260	39,838	2,078	1,000
1710	TX	HITTS	PAULUXY	41	7,200	31,079	13,644	3,160	300
3489	UT	UPPER VALLEY UNIT	KAIBAB	10	7,000	67,394	41,313	1,685	1,000
2368	WY	GRASS CREEK	FRONTIER	48	750	84,198	40,836	400	200
2817	WY	RYCKMAN CREEK	NUGGET	29	6,900	77,989	54,904	2,900	2,660

Table 12
Risk Assessment Results

REF	ST	MICHIE BASIN CODE	FIELD NAME	RESERVOIR NAME	RESERVOIR DEPTH	DEPTH TO LOWERMOST USDW	DISTANCE FLUIDS MUST TRAVEL	PRESSURE REQUIRED FOR DISTANCE (PSI)	ORIGINAL RESERVOIR PRESSURE (PSI)	ESTIMATED CURRENT RESERVOIR PRESSURE (PSI)	PRESSURE SUFFICIENT TO TRAVEL REQUIRED DISTANCE ORIGINAL	PRESSURE SUFFICIENT TO TRAVEL REQUIRED DISTANCE CURRENT	PROD/INJ WELL AGE (RISK PTS)	CORROSION POTENTIAL (RISK PTS)	USE OF SHORT CASING (RISK PTS)	USE OF UNCONV. CONSTR. (RISK PTS)	ABD WELL DENSITY (RISK PTS)	IDLE WELL DENSITY (RISK PTS)	HISTORIC CONSTR/PL PRACTICES (RISK PTS)	TOTAL RISK POINTS
3029	KS	35	MARCOTTE	ARBUCKLE	3,800	727	3,073	1,414	1,000	950	N	N	2.3	5	2	5	4	1	1.8	21.1
3489	UT	10	UPPER VALLEY UNIT	KAIBAB	7,000	624	6,376	2,933	1,685	1,000	N	N	1.6	5	4	2	2	3	2	19.6
3545	MT	28	CORAL CREEK	RED RIVER	8,700	1,015	7,685	3,535	3,300	2,200	N	N	0	5	5	1	2	4	0.4	17.4
3024	OK	38	CARTHAGE DISTRICT NE	MORROW	4,300	888	3,412	1,570	1,420	940	N	N	2	3	1	3	4	1	1.1	15.1
3012	IL	19	JOHNSONVILLE CONSOLIDATED	MC CLOSKY LIMESTONE	3,170	478	2,692	1,238	1,020	600	N	N	4	1	0	1	4	1	4	15
42	CA	8	ALISO CANYON	PORTER	5,050	750	4,300	1,978	1,795	450	N	N	0.4	3	4	1	3	3	0.4	14.8
2810	NE	12	SLEEPY HOLLOW	REAGAN	3,450	657	2,793	1,285	550	400	N	N	2	3	0	1	3	3	0.7	12.7
2828	NM	42	CHAVEROO	SAN ANDRES	4,250	796	3,454	1,589	1,340	600	N	N	0.3	5	0	1	2	2	0.5	10.8
2834	NM	42	LOVINGTON	PADDOCK	6,100	796	5,304	2,440	2,100	1,500	N	N	0	5	0	1	2	2	0.2	10.2
1145	OK	5	PAPOOSE	CROMWELL	3,350	650	2,700	1,242	700	660	N	N	0	1	1	3	1	1	1.1	8.1
2667	PA	24	KANE	CANADAWAY	2,250	343	1,907	877	1,050	400	Y	N	5	1	4	5	5	1	5	26
2941	TX	42	EL MAR	DELAWARE SAND	4,500	1,500	3,000	1,380	2,151	250	Y	N	1.8	5	3	1	3	2	2.5	18.3
1710	TX	41	HITTS	PAULUXY	7,200	2,000	5,200	2,392	3,160	300	Y	N	1	5	3	1	4	2	1.9	17.9
1419	TX	41	FOREST HILL	HARRIS SAND (BF SEGMENTS)	4,800	2,000	2,800	1,288	2,078	1,000	Y	N	1.1	5	3	1	4	2	1.6	17.7
629	MT	28	FLAT LAKE	RATCLIFFE	6,500	1,015	5,485	2,523	2,944	2,000	Y	N	0.3	5	5	1	2	4	0.4	17.7
2886	IL	19	NEW HARMONY CONSOL	CYPRESS	2,404	478	1,926	886	1,250	800	Y	N	5	1	0	1	4	1	5	17
3574	LA	25	BAY MARCHAND BLOCK 2	O SAND RESERVOIR D UNIT	12,200	1,000	11,200	5,152	6,680	3,050	Y	N	1	1	3	3	3	4	1	16
3435	TX	43	BIG MINERAL CREEK	BARNES SAND	5,258	1,000	4,258	1,959	2,477	1,440	Y	N	1.7	1	3	1	4	2	2.7	15.4
145	CA	8	WHITTIER	2ND & 3RD ZONES	2,700	750	1,950	897	950	355	Y	N	0.9	3	4	1	3	3	0.1	15
125	CA	8	RAMONA	KERNDEL VALLEY	4,265	750	3,515	1,617	2,000	500	Y	N	0	3	4	1	3	3	0.5	14.5
3427	CA	8	VENTURA FIELD	B SANDS	4,700	750	3,950	1,817	2,600	1,700	Y	N	0.2	3	4	1	3	3	0.2	14.4
2920	CA	8	RICHFIELD EAST AREA	CHAPMAN	3,128	750	2,378	1,094	1,371	350	Y	N	0.2	3	4	1	3	3	0.2	14.4
3227	CA	8	NEWHALL POTRERO	7TH ZONE	10,250	750	9,500	4,370	5,878	2,650	Y	N	0	3	4	1	3	3	0.1	14.1
3225	CA	8	NEWHALL POTRERO	5TH ZONE	8,300	750	7,550	3,473	3,940	1,400	Y	N	0	3	4	1	3	3	0.1	14.1
93	CA	8	KRAEMER	KRAEMER	4,500	750	3,750	1,725	1,750	650	Y	N	0	3	4	1	3	3	0	14
71	CA	9	CYMRIC	SALT CREEK MAIN	2,400	1,000	1,400	644	1,100	500	Y	N	0	3	4	1	2	3	0.1	13.1
129	CA	9	ROSEDALE RANCH	LERDO	4,370	1,000	3,370	1,550	1,825	750	Y	N	0	3	4	1	2	3	0	13
3622	NM	42	CATO	SAN ANDRES	3,600	796	2,804	1,290	2,000	1,153	Y	N	0.7	5	0	1	2	2	0.8	11.5
3832	NM	42	LOCO HILLS	WEST UNIT	2,665	796	1,869	860	1,161	812	Y	N	0.2	5	0	1	2	2	0.5	10.7
3065	MI	20	WEST BRANCH	DUNDEE	2,600	833	1,767	813	1,000	800	Y	N	0	1	4	0	4	1	0	10
2817	WY	29	RYCKMAN CREEK	NUGGET	6,900	1,060	5,840	2,686	2,900	2,660	Y	N	0.5	1	0	0	2	3	0.4	6.9
3079	AK	50	MCARTHUR RIVER	TYONEK MIDDLE KENAI G ZONE	8,850	814	8,036	3,697	4,009	3,000	Y	N	0.7	1	0	0	2	1	1.4	6.1
237	IN	19	CABORN CONSOLIDATED	MANSFIELD	659	514	145	67	330	300	Y	Y	5	1	0	4	4	1	5	20
1271	TX	42	CROSSETT	DEVONIAN	5,300	1,500	3,800	1,748	2,500	2,000	Y	Y	2	5	3	1	3	2	1.9	17.9
1265	TX	42	CLAYTONVILLE	CANYON LIME	5,750	1,500	4,250	1,955	2,335	2,335	Y	Y	1.1	5	3	1	3	2	1.9	17
3486	LA	6	OLD LISBON FIELD OPER COMMITTEE	PETTIT LIME	5,250	1,400	3,850	1,771	2,338	2,200	Y	Y	0.5	1	3	3	4	4	0.7	16.2
1146	OK	38	PAULS VALLEY	BASAL PENNSYLVANIAN	3,900	888	3,012	1,386	1,800	1,520	Y	Y	0.2	3	1	3	4	1	0.3	12.6
1128	OK	37	NAVAL RESERVE	BURBANK	2,630	765	1,865	858	1,238	1,200	Y	Y	0.2	1	1	3	4	1	0.3	10.5
2368	WY	48	GRASS CREEK	FRONTIER	750	799	0	0	400	200	Y	Y	0.3	3	0	0	2	3	0.4	8.7

Among the seven reservoirs where current pressure is sufficient to force fluid migration to a USDW, the total number of risk points ranges from 20 for the Mansfield reservoir in the Caborn Consolidated field in Indiana to 8.7 for the Frontier reservoir in the Grass Creek field of Wyoming. In both of these reservoirs, minimal distance separates the injection zone from the estimated depth of the lowermost USDW, so minimal pressure is required fluid migration. But the Caborn Consolidated field is an older producing area with many abandoned wells and substantial use of unconventional well construction. As with the Pennsylvania example above, this field is in an area not covered by Dwights, so risk points for certain factors have been based on the field discovery date of 1939. This could overstate the relative risks in this area. By contrast, the Grass Creek field has been largely developed since 1970, so the number of abandoned wells is much lower and those that exist have been plugged using fairly modern techniques. The known differences between these fields and the differences in their relative risk scores tend to support the validity of the assessment methodology used.

For reservoirs with sufficient current pressure to facilitate contamination, the second and third ranked reservoirs are located in the Permian basin, which is considered highly corrosive. This corrosive potential increases the relative risk of contamination for reservoirs in this basin, where substantial enhanced oil recovery operations are underway. Michie (1988) found the Permian basin to have the highest risk of simultaneous casing and tubing failures that could create the potential for contamination, so this result is consistent with his findings. The problem of well corrosion is well understood and operators often take steps to minimize the chances for corrosion. However, this operating practice has not been factored into the risk assessment methodology since it does not affect the *risk* of contamination, only the probability of occurrence.

Two reservoirs in the Newhall Potrero field of California were selected: the 5th zone at 8,300 feet and the 7th zone at 10,250 feet. Since most of the data used in this aggregate-level assessment is at the field, state, or state-basin level, the only difference expected between these two reservoirs relates to the distance contaminants must travel and the pressure required for this fluid migration. In both cases, however, the original reservoir pressure would have been sufficient to force fluids to travel the substantial distance between these deep reservoirs and shallow USDWs (750 feet). The current pressure estimated for both reservoirs is unlikely to be sufficient to allow contamination to occur.

The results of this analysis tend to support the validity of the methodology developed. If data difficulties could be overcome, this methodology could be used to perform a national risk assessment that would provide DOE with additional data for planning its research investments.

E. Data Needs to Improve Assessment

To perform a relative risk assessment, it is not necessary that all data items be totally accurate or detailed, but the uncertainties associated with the data used and the biases that they may introduce must be well understood. It will always be possible to envision the availability of "better" data for performing a risk assessment. Yet this "better" data may have little impact on the outcome if it introduces the same type of bias or contains the same systematic error. It is important to distinguish these types of data needs from those that could have a major impact on the relative risk ranking.

The above section on problems encountered highlights many of the data needs for performing a more accurate assessment of the relative risks. These data needs fall into two general categories:

- More reliable data on the key factors affecting risks
- Data to determine the appropriate assignment of risk points to various factors.

Each of these categories of data needs and the availability of methods to address them are discussed in more detail below.

Data on Key Risk Factors

The lack of data on groundwater presence does not pose a major impediment to the analysis, since it is possible to make the simplifying assumption that all reservoirs are in locations where USDWs exist. The inadequacy of data on the depth of USDWs is more problematic. Assessing the feasibility of groundwater contamination based on distance and pressure is hampered by substantial uncertainty across several aspects of this assessment. Yet, assuming that groundwater exists, this is the single most important factor affecting risk. Thus, it may be prudent to direct efforts toward improving these data and resolving the uncertainties associated with them:

- *Depth of USDWs.* No comprehensive national source for this data currently exists. The U.S. Geological Survey (USGS) has performed numerous studies of individual aquifers, but sorting through these reports would be impractical and is likely to be incomplete. The USGS is currently developing groundwater resource atlases that should include much of the data needed, but these atlases are not scheduled for completion before 1998. When available, these data could provide a more accurate assessment of the distance and pressure required than the current Gruy estimates.

- *Current reservoir pressure.* The TORIS data being used to calculate current reservoir pressure and the validity of the calculations themselves should be verified against some actual field data.

- *Pressure sufficiency.* The calculations used in this methodology are comparable to those used in the AOR variance methodology developed by UIPRF and API. Since that methodology has now been applied in several field studies, the results of those studies could be compared with the calculated results for this analysis to determine whether any adjustments to the equation are required.

Use of Dwights data on the age of producing and abandoned wells is a reasonable surrogate for data on the quality of cement jobs and historic construction/plugging practices. The matching of Dwights data with TORIS and GSAM reservoirs will be accomplished as part of other ongoing efforts, solving that current impediment to a broader analysis. For areas not covered by Dwights, it is conceivable that state data could provide better information regarding the timing of development in fields. However, given that the Appalachian basin is an older producing area, it is not clear that the result would differ dramatically, therefore this data may not be worth the substantial effort that could be required to collect it.

Producing states have been actively addressing the issue of idle wells, limiting the time wells are allowed to be idle, encouraging wells to be placed back on production, requiring periodic integrity tests, and attempting to locate the responsible parties for idle wells. The IOGCC is planning to update its idle wells survey with funds recently received from DOE. Given the changes that may have occurred since the 1992 assessment, updating these data when available should provide a more accurate assessment of relative risks.

Appropriate Assignment of Risk Points

For four of the key risk factors, the assignment of risk points based on factor data was somewhat arbitrary. While these assignments considered the obvious break points within the data, the assignment was not based on an understanding of how these factors affect risk. No obvious data that could improve this understanding exists. Two possible approaches could potentially be useful for improving this assessment:

- *Regression equations.* Rather than selecting arbitrary break points and assigning points on that basis, it may be possible to perform a regression analysis and develop a linear equation that describes the relationship of abandoned wells to injection wells, for example. This equation could then be used to assign fractional risk points based on the characteristics of the particular state-basin. This would still, however, require an assumption about what ratio merited five risk points. Moreover, it would not provide any additional insight about whether two abandoned wells per injector is two, five, ten, or twenty times as great a risk as one abandoned well per injector.

- *Sensitivity analysis.* Using a larger data set, it may be possible to determine whether use of an alternative scheme for assigning risk points would have much affect on the outcome. Based on the sensitivity performed for this assessment, it does not appear to make much difference, however, the 39 reservoirs used in this assessment may not be adequate to make this determination. Nonetheless, as long as all risk points are maintained on a five point scale, the variability among any alternative schemes would be limited.

Either of these approaches could somewhat improve the quality of the risk assessment performed, but since neither leads to an improved understanding of the underlying risks, they are likely to add little value. Given the data constraints that exist in attempting to perform a broad-based, national assessment, the factors used in this analysis appear to adequately provide a basis for evaluating the *relative* risks of groundwater contamination.

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