EVALUATION OF UNDERGROUND INJECTION OF INDUSTRIAL WASTE IN ILLINOIS

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DEDICATION

This report is dedicated to the many individuals who have contributed to the design, construction, operation, testing, regulating, and scientific evaluation of deep disposal wells for industrial wastes in Illinois. Special tribute is directed to Ward E. Akers of the Illinois Sanitary Water Board and later of the IEPA for his pioneering work in regulation of waste disposal wells and to Robert E. Bergstrom, Chief Emeritus, of the State Geological Survey and Harmon F. Smith of the State Water Survey for their direction in scientific and technical assistance with deep well disposal activities in Illinois.

ACKNOWLEDGMENTS

EXECUTIVE SUMMARY

PROJECT MANDATE, SCOPE, AND APPROACH

State legislation (Environmental Protection Act, January 1, 1985, Title I: General Provisions, Section 62: Study of Underground Injection) enacted in 1984 required that the Department of Energy and Natural Resources conduct an in-depth assessment of the regulations and regulatory practices of the Illinois Underground Injection Control (UIC) program as it relates to injection of hazardous industrial wastes in Class I waste disposal wells. Class I wells are wells into which hazardous and nonhazardous industrial and municipal wastes are injected below all Underground Sources of Drinking Water (USDW).

The objectives of this assessment were (1) to determine whether underground injection of hazardous wastes is an appropriate method of waste disposal in Illinois and (2) to provide recommendations to the Legislature, Legislative Council, the Governor's Office, and State agencies concerning this disposal practice. Because the injection of nonhazardous wastes in Class I wells is governed by the same basic regulations as hazardous waste injection, nonhazardous Class I wells have been included in the study.

In this assessment, investigative attention was focused on the geological, technical, and environmental feasibility of deep well injection, the adequacy of current regulations and regulatory practices, the ultimate fate of the injected waste in the disposal system, and the comparative risks, benefits, and costs of deep well injection and alternative disposal options. The assessment also identified the need for (1) a broader spectrum of data from the deep well injection system and the disposal operations, (2) additional research on deep well injection, and (3) strengthening of UIC regulations and regulatory practices to increase the safety of the deep well disposal option.

The process of drawing conclusions was a complex activity. Well-established, tested principles of geology and hydraulics of fluid flow in earth materials provided the basis for evaluating available evidence and making reasonable assumptions about the processes affecting injection into a disposal system. The lack of data collection at all significant positions in a disposal system required extrapolation of data from known points and establishment of reasonable inferences to evaluate the fate of injected wastes. Thus, these conclusions must be used with the clear understanding that certain aspects of the input were based on reasonable assumptions, not on directly collected data.

DEEP WELL INJECTION IN ILLINOIS

Underground injection, the controlled emplacement of fluids into selected, deeply buried geologic formations through specially designed and monitored wells, was developed and used by the oil and gas industry in the 1930s. The same concept was first applied to the disposal of industrial wastes in the early 1950s, and the first operating permit for deep well injection of industrial wastes in Illinois was issued in 1965. Nine deep injection wells, including one operational standby well and one abandoned standby well, have been operated at seven Illinois industrial sites (Figure ES-1). Two replacement wells (one scheduled for construction in mid-1987, the other with an indefinite construction date) have been permitted at two of these sites.

These injection wells are regulated by the Illinois Environmental Protection Agency (IEPA) as Class I wells under the UIC regulations in Title 35 Illinois Administrative Code. Illinois was granted primacy by the USEPA to operate this regulatory program in February 1984 under the authority established by amendments to the Safe Drinking Water Act (1974) to set up the federal UIC program. Previously, the program had been operated under State statutory authority.

In 1986, approximately 308 million gallons of industrial wastes were disposed of in these wells. The wastestreams are classified as hazardous at four sites and nonhazardous at the other three sites. Water is the major component of wastestreams (70 to 95 percent of the total waste volume). Acids (HCl, H_2SO_4, and HF) used in industrial processes are the most common constitutents of the wastestreams. Other important constituents include caustic soda, pesticides, fluoride, mercury, arsenic, vanadium and chromium compounds, and chlorinated hydrocarbons.

The feasibility of the deep well injection system depends primarily on the geologic environment beneath the disposal site. At each well site this system consists of a permeable injection zone to hold the waste; thick, impermeable rock layers above and below the disposal zone to confine the wastes; and a sequence of rock units between the upper confining interval and the USDW.

The wells range in depth from 1540 feet to 5524 feet and average about 3800 feet. Porous and permeable dolomite and limestone formations are used as injection zones for seven wells, and a thick sandstone formation is used for two wells. According to UIC regulations, each formation used for disposal must contain groundwater with a total dissolved solids (TDS) content greater than 10,000 mg/L (all groundwater containing less than 10,000 mg/LTDS has been reserved as potential USDW).

The regional geology of Illinois is characterized by widespread distribution of numerous rock units deposited in a broad depositional basin. Selected limestone, dolomite, and sandstone formations lying below the USDW across the central two-thirds of the state meet regulatory requirements for disposal of industrial wastes in Class I wells. Figure ES-1 is a map view of the uppermost geologic units that contain potential disposal zones. The accompanying north-south profile view shows the subsurface relationship of these units.

The practice of underground injection of industrial wastes (particularly hazardous wastes) in Class I wells is currently being reviewed at both state and national levels in response to legislation enacted by state legislative bodies and the Congress. The IEPA considers underground injection a disposal option of last resort-to be used when the typical disposal options of waste reduction, recycling, and other treatments are not feasible and when the geologic environment beneath the proposed disposal site meets established regulatory requirements. Assessment of the feasibility of deep well disposal must include technical considerations as well as environmental, societal, and economic impacts.

The regulations adopted by Illinois when it received primacy to operate the UIC program required the IEPA to issue new permits for the Class I wells. In the interim, while the review process for new permits is being conducted, the existing wells are authorized to operate under rule (that is, they are allowed to continue injection operations until permit decisions can be made under the new regulations) as long as they are in compliance with rules applicable to permittees. As of June 1987, permits had been issued for three wells, including two replacement wells; draft permits had been issued for five wells; permit denials had been issued for two wells; and a draft denial had been prepared for one well. The temporary moratorium on the construction of new wells, mandated by the Environmental Protection Act of January 1, 1985, is no longer in effect. Several unresolved issues related to the 1984 amendments of the Safe Drinking Water Act of 1974 are undergoing extensive review by the USEPA, and the outcome of the review may affect the disposal of certain wastes and selected operational aspects of some wells.

STUDY METHODS

To carry out the study mandate, the authors

- reviewed Illinois Class I UIC regulations and regulatory practices documents to determine whether the regulatory framework and the regulatory practices were adequate to protect the underground sources of drinking water from degradation through injection activities by Class I disposal wells.

- reviewed Class I waste disposal permit applications and monthly summary operational reports submitted by industries in Illinois and used this information to (1) characterize each of the seven wastestreams, (2) compile and evaluate construction details and operational data at each plant
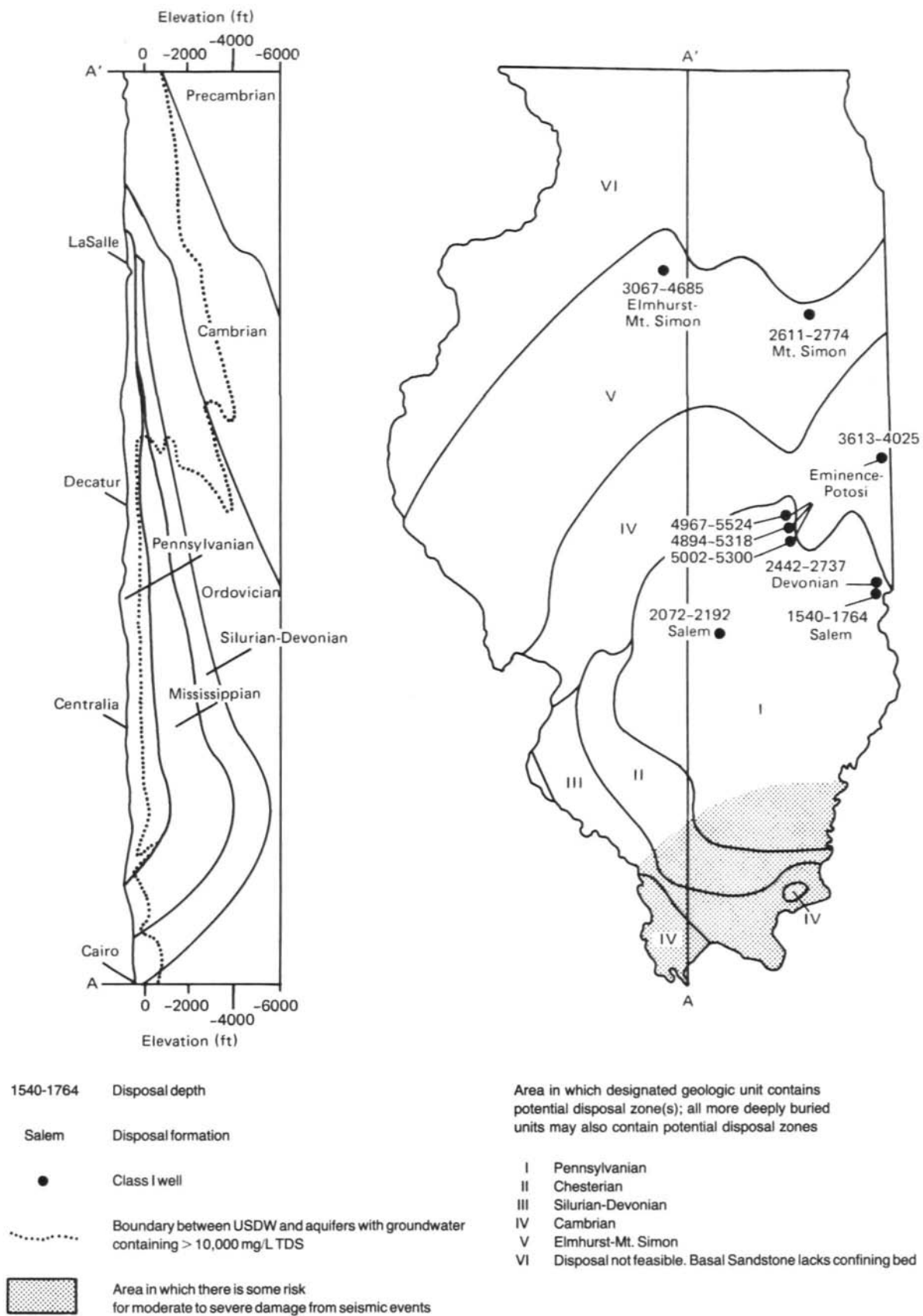
Figure ES-1 Potential disposal zones for Class I wells in Illinois: map and cross section.

Legend (left):

1540-1764 — Disposal depth

Salem — Disposal formation

● — Class I well

········· — Boundary between USDW and aquifers with groundwater containing > 10,000 mg/L TDS

▨ — Area in which there is some risk for moderate to severe damage from seismic events

Legend (right):

Area in which designated geologic unit contains potential disposal zone(s); all more deeply buried units may also contain potential disposal zones

I   Pennsylvanian
II   Chesterian
III Silurian-Devonian
IV Cambrian
V   Elmhurst-Mt. Simon
VI Disposal not feasible. Basal Sandstone lacks confining bed

site, and (3) identify significant operational problems at individual wells. The potential interactions between the injected wastes, rock, and formation fluid in the subsurface environment were determined and the implications of potential interactions were reviewed.

- contacted state and USEPA regional regulatory offices and consultants working with UIC facilities to obtain information about UIC programs in other states and discuss current issues and possible trends.

- reviewed selected Illinois State Geological Survey and Water Survey publications, maps, reports, and files to describe and evaluate the geologic environment and groundwater resources of Illinois, as related to deep well injection.

- compiled a review of current issues associated with Class I injection.

- subcontracted with an engineering consulting firm (Engineering-Science Incorporated) to investigate alternatives to deep well injection, perform comparative cost estimates for alternative waste disposal options, and summarize the potential environmental and economic impacts of these alternatives.

The following conclusions and recommendations resulted from consideration of the adequacy of current Class I UIC regulations and regulatory practices to protect human health and the environment and provide an appropriate option for disposal of selected hazardous and nonhazardous industrial wastes.

CONCLUSIONS

General Findings

- Injection in Class I wells is an acceptable option for hazardous waste disposal on the basis of: (1) prediction of fluid flow and containment in the subsurface disposal system, using well-established principles, (2) geologic conditions existing in certain parts of Illinois, (3) evaluation of testing and monitoring evidence from deep well injection activities, and (4) regulatory requirements placed on this disposal practice. Limitations exist with the currently available evidence, and there is some degree of uncertainty as to the geologic environment. Although acceptable estimates of waste and pressure distributions have been made, more rigorous (factual) delineation of these distributions may be desirable to verify that no contamination of USDW is occurring. There is some uncertainty as to the character and degree of verification that would be adequate; this also appears to be a concern on the national level.

- Deep well injection is not considered a primary disposal option for hazardous wastes, but is a potential option when waste reduction, recycling, and other disposal options are technically, environmentally, and economically unacceptable.

- The current regulations—designed specifically to protect underground sources of drinking water and the near-surface environment—are adequate in basic concept and scope but deficient to varying degrees in some areas noted in the report. In general, the regulatory practices of the IEPA carry out the intent of the regulations. Some modifications should be made to the current regulations and regulatory practices (see Chapter 1 for details).

- The risks of underground injection are acceptable; alternative options requiring disposal of hazardous wastes and residual/indestructable inorganic components in landfills may pose more of a risk for surface waters, shallow potable aquifers, and USDW than would deep well injection. But even though no contamination of USDW from injected wastes has ever been reported in Illinois, there is currently no way to *verify* that contamination has not occurred or is not occurring until methods have been developed to monitor aquifers overlying the disposal zone. Before comprehensive monitoring guidelines can be set up, some aspects of waste and pressure distributions in the waste disposal system need further investigation.

- Study findings suggest strongly that selected regulatory practices—particularly those concerned with waste sampling protocol, chemical analysis of wastestream samples, and evaluation of well

testing and monitoring data and procedures—should be reviewed periodically, updated, and strengthened to reflect developing technology, research results, and experiences of those responsible for carrying out the regulations.

• A review of IEPA files for Class I wells has shown that reestablishment of the position of Class I Program Manager in the Division of Land Pollution Control of the IEPA and adequate staffing have improved the permitting, compliance surveillance, and field inspection aspects of the UIC Class I program, resulting in stricter enforcement of the UIC regulations, particularly after Illinois was granted primacy to operate the program.

Fate of Wastes in the Disposal Zone: Knowns and Unknowns

Geology.   The geologic formations currently being used for deep well disposal at the seven Illinois sites appear to be adequate to accept and confine a large volume of wastes for more than the life expectancy of the wells (which is about 20 years). This report identifies the areal distribution of major geologic units in which one or more potential disposal zones may be present, as well as geologic units and regions in which injection conditions are limited or unfavorable. Detailed information is available for the immediate vicinity of the well bore at each well site, but at most sites less is known about geologic conditions as the radial distance from the well increases.

Injection Pressures.   The injection wells at six of the seven disposal sites have maintained adequate capacity to accept the maximum permitted waste volume at low to moderate injection pressures. Injection pressures used at the wells are considerably lower than the limit at which fractures might begin to develop in the strata used for injection. Regulations requiring continuous monitoring of annular and injection pressures are strictly enforced because assessment of these two parameters is currently the principal way to evaluate the performance of the injection well.

Wastestreams.   The wastestreams at the sites are relatively stable in composition and volume, and have not, for the most part, interacted adversely with fluid or rocks of the disposal zone to reduce or limit significantly the capacity of the disposal zone to accept the injected wastestream. To date, some minor and a few major problems have been reported with injected waste/disposal formation interactions; however, in each case the affected well was repaired or restored to comply with the regulations then in effect, and no contamination of any USDW was detected. Some chemical and physical changes in waste components are expected to occur after the waste is injected into a disposal formation, but these changes cannot be directly evaluated with current monitoring procedures.

An evaluation of waste analysis requirements shows that current regulations for wastestream analysis are inadequate. A comprehensive chemical analysis of the injection waste should be conducted at the time of permitting the well and whenever the character of the wastestream changes, and annually thereafter, using an adequate sampling protocol to collect representative samples of the waste. Such analyses, which would determine all the major constituents of the wastestream, would provide vital information if contamination of a USDW were ever discovered near a Class I well.

Monitoring.   There is currently no mechanism in Illinois for verifying the occurrence or extent of leakage through the confining bed overlying a specific disposal formation. Verification monitoring can best be done in a saline aquifer (not a USDW) above the primary confining bed, where any waste passing through the confining bed can be detected. Direct monitoring in the disposal zone through monitoring wells is not advisable because each monitoring well completed in the injection zone could provide a potential pathway for escape of the injected wastes. Development of a monitoring strategy is recommended to determine the need for and degree of subsurface monitoring that should be considered for Class I injection in Illinois.

Fluid movement rates in deep subsurface environments range from much less than a few inches per year under natural groundwater flow conditions to much higher rates where injection occurs. During injection, the rate of movement is higher next to the well bore and decreases radially away from the well; the highest rates occur in the most permeable zones and adjacent to the well bore. Nonhomogeneous and anisotropic conditions that are typically present in the disposal zone rock affect both the rate and pattern of flow. A general picture of the flow characteristics and the radial

uniformity of geologic conditions in the disposal zone can be obtained by evaluating monitoring and testing data. However, specific detailed information for these parameters is generally not available beyond the immediate vicinity of the well bore.

Waste components tend to move at different rates in response to flow characteristics of the disposal system and interactions with materials in it. Solutes in the waste tend to move at a slower rate than the injected water because of chemical interactions and/or sorption. The distribution pattern of the waste in the disposal zone is controlled by many factors and can be roughly estimated, using currently available monitoring and testing data. However, detailed information on the fate and distribution of waste components beyond the immediate vicinity of the well bore cannot be determined from these data.

Pressure buildup in an injection zone is greatest adjacent to the well bore and decreases to nearly zero at a considerable radial distance from the operating well. This pressure buildup tends to increase with continued use of the well and after a certain time an area develops around the well in which the pressure buildup is large enough to produce an upward hydraulic gradient. Currently available testing and monitoring data can be used to estimate the general pattern of this area and the general capacity of the overlying primary confinement to retain the waste affected by this upward gradient. These data cannot be used to determine the specific location and hydraulic character of each potential fracture present in the confinement interval or to verify detailed aspects of waste and pressure distributions in the disposal zone or its primary confinement intervals. All Class I wells in Illinois are operated at injection pressures well below fracture pressure thresholds. Artificial fracturing of the disposal zone is not permitted.

Area of Review.   The area of review includes that area around a disposal well in which injection generates or is expected to generate over a specified period of time an upward hydraulic gradient relative to USDW. Past determinations for this parameter have been based on a fixed radial distance (¼ mile in the regulations, later increased in regulatory practice to 2½ miles) from the well or calculated using a simple flow equation. The nature of subsurface conditions may cause the area of positive upward hydraulic gradient to extend beyond the calculated area of review as determined above. An adequate flow equation and rigorously defined assumptions can provide more realistic estimates of areas of review and identify those injection operations in which a fixed radius area of review is inadequate.

RESEARCH NEEDS OF THE UIC PROGRAM

To increase understanding of the geochemical and hydrogeological processes taking place in the injection zone, improve monitoring practices, and raise the level of public confidence in the deep well disposal option, research should be conducted to

- Investigate in situ chemical interactions of wastestream components with formation fluids and rocks and the effects of such interactions on waste movement in the injection zone.

- Investigate more economic methods of determining the degree of anisotropy and inhomogeneity in hydraulic properties at each site that may result in wastes migrating farther than expected from the well in a particular direction. (The technology required for making such determinations is available but expensive.)

- Develop methods and equipment for sampling and testing formation fluids under typical subsurface temperature and pressure conditions.

- Conduct modeling studies to show the distribution of pressure and rate and extent of movement of fluids and solutes in the disposal zone and confining units under a full expected range of possible subsurface conditions and well operations modes. Results from modeling can be used to determine permit conditions, well operating and monitoring requirements, and thresholds for conditions that could cause failures in the disposal system.

- Evaluate the effectiveness of the in-well monitoring currently used for surveillance of conditions in the disposal zone to determine the need for radial observation points within or above the disposal zone, and develop procedures, technology, and a protocol to improve monitoring practices.

ALTERNATIVE WASTE DISPOSAL OPTIONS: RISK/BENEFIT ASSESSMENTS

Proven alternative waste disposal options are available for most hazardous and nonhazardous waste components found in wastestreams that are currently injected into Class I wells or are candidates for deep well disposal. Each option has its own economic, environmental, and societal impacts, and each option poses some risks to public health and safety. The environmental risks associated with some waste disposal options other than deep well disposal appear to be significant but have not been evaluated in this study.

Alternatives to deep well disposal must either destroy the waste components, reduce them to insoluble residues that can be stored in secure disposal sites, or treat them to acceptable standards for discharge into the surface environment. However, burying residual/ indestructible inorganic components in landfills may place shallow potable aquifers at greater risk than would deep well disposal, and water or gases generated by alternative disposal options must be safely released into the surface/near surface environment.

A comparison of the economic and environmental impacts of deep well disposal with those of other disposal options shows that deep well injection ranks among the least costly options and has a less severe impact on USDW and the surface environment than does the land burial option. Class I injection places wastes in deep disposal zones that are relatively far removed from sources of drinking water. On the other hand, if contamination should occur from injected wastes, detection and clean-up may be more difficult, costly, and uncertain than for contamination from surface or near-surface sources.

The current evaluation of deep well disposal in Class I wells could result in three possible scenarios for deep well disposal: (1) deep well injection will be continued, with some modifications in the regulations, but no pretreatment will be required; (2) pretreatment may be required to destroy, remove, or reduce the concentration of all or part of the hazardous components prior to injection; or (3) deep well injection may be banned completely.

Pretreatment to remove selected hazardous components from wastestreams should be considered if such removal does not generate a significantly negative impact or increased risk. Pretreatment would very roughly increase the estimated annual treatment and disposal costs by factors of about 3, 5, 6, and 40 for the four industries producing waste classified as hazardous. A complete ban on deep well injection would require total treatment of the seven existing wastestreams in Illinois to meet surface-water effluent discharge standards; estimated average annual treatment and disposal costs for this option could be about 15 times higher than current costs for deep well disposal for the seven wastestreams. The combined estimated annual economic impact on the seven industries would total about $24.0 million (in 1985 dollars).

The following procedures are recommended in selecting a disposal option for industrial wastes: (1) identify and evaluate the significance of all possible risks; (2) establish guidelines for acceptable risk; and (3) determine the costs/benefits/ environmental impacts associated with each disposal option or level of pretreatment. In some situations, a combination of disposal methods (including recycling and reuse) may be the most effective, least risky method of handling liquid industrial wastes.

It has been assumed that any hazardous residues generated during treatment prior to deep-well injection or other forms of disposal would require solidification and chemical fixation prior to landfill disposal to reduce the possibility that hazardous materials may leach from the landfills into near-surface aquifers. Solidification and fixation do not prevent leachate formation but do reduce the rate at which hazardous substances leach out of the landfill. Even so, enough of the hazardous materials may leave the landfill over a period of time to pose a threat to the groundwater in the area. The long-term impact of landfill disposal is a serious concern, but the more specific concern here is whether surface disposal (landfills) represents a better solution than subsurface (injection well)

disposal. In most cases, a comparison of the tightness (lack of overall permeability) and thickness of confining materials, the existence of conditions that can cause changes in the characteristics of confining materials, and the magnitude of hydraulic head gradients between the disposed wastes and the nearest USDW shows that conditions are generally less favorable for safe disposal in the near-surface landfill environment than in the environment of a deep disposal zone.

Banning deep well injection appears to be an inappropriate option in light of the increased risk resulting from disposal of some waste components in or near the surface environment. Placing pre-injection restrictions on deep well disposal may be much more protective of USDW and human health than banning Class 1 wells would be.

INTRODUCTION

BACKGROUND

Underground injection is the controlled emplacement of fluids into selected geologic formations through specially designed and monitored wells. In the 1930s underground injection was developed and employed by the oil industry for disposal of brines related to oil and gas production and for secondary recovery of oil. The same concept was applied to the disposal of liquid industrial wastes in the early 1950s. As disposal of wastes into surface waters and on land became more restricted with the enactment of federal and state environmental laws, underground injection of liquid wastes gradually increased.

The feasibility of deep well underground injection depends on (1) selecting an area where geologic and hydrologic conditions are favorable for injection practice, and (2) designing and monitoring the injection well to minimize the potential for pollution of usable waters (waters with less than 10,000 mg/L total dissolved solids (TDS)). Injection is feasible where a rock formation has sufficient permeability, thickness, and areal extent to accommodate large volumes of injected waste; where the injection zone is confined between adequate rock formations of such integrity and low permeability as to assure containment of wastes in the injection zone; where the waste does not chemically interact with the injection zone rock and confining interval rocks or the native water in a way that would impede injection; and where no improperly abandoned wells penetrate the injection zone or geologic faults exist in the vicinity of the injection well to cause leakage from the injection zone. Given these conditions, an injection well must be constructed and operated in such a way as to assure the containment of fluids both in the well and in the injection zone. Containment is accomplished through the use of casings, grouting, tubing, annular protection systems, continuous monitoring, proper injection practices, and periodic testing of the mechanical integrity of the well.

The capacity of the subsurface geologic environment to provide both sources of drinking water and repositories for injected liquid wastes indicates the diversity of characteristics in this environment and the need to thoroughly understand these characteristics to prevent adverse interactions between disposed wastes and underground sources of drinking water (USDW). A number of moderately to deeply buried geologic units across the central two-thirds of Illinois provide conditions necessary for successful disposal of industrial wastes by deep well injection. Potential injection zones must (1) have the capacity to accept the waste for the proposed life of the well (usually 20 years) at an acceptable injection pressure; (2) lie below the deepest underground source of drinking water (USDW)--all groundwater with <10,000 mg/L total dissolved solids (TDS); and (3) be bound above and below by confining units capable of retaining the waste. The sedimentary rock sequence in which the disposal zones are found ranges in thickness from about 1,500 feet in northern Illinois to more than 20,000 feet near the mouth of the Wabash River. The Illinois Basin and the structural margin surrounding this basin form a large sedimentary feature that underlies all of Illinois. Many of the geologic units deposited in this sedimentary feature have widespread distribution across the state, and, similarly, the characteristics of the units that qualify them for deep well injection are fairly widely distributed.

Deeply buried geologic formations have been used as disposal zones for industrial waste in Illinois for more than 20 years. The first permit for Class I deep well injection was issued by the Illinois Sanitary Water Board, predecessor of the Illinois Environmental Protection Agency (IEPA), in 1965. By 1976, when the last new well was constructed, nine injection wells, including two standbys, were in operation at seven industrial sites. In 1986, permits were under review for two replacement wells at sites F and G. Recently, the replacement well at site G was scheduled for construction in mid-1987 and operation by the fall of 1987. [This well was constructed.]
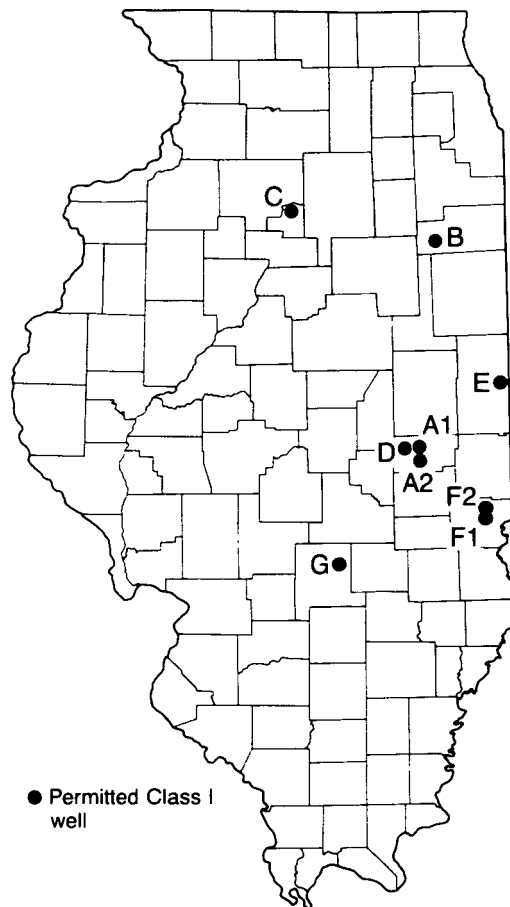
Figure I-1 Locations of Class 1 wells In Illinois

The locations of the seven industrial sites with disposal wells are shown in Figure I-1. These sites (hereafter referred to by the following letter designations) are:

A. Cabot Corporation, near Tuscola; two wells located in Section 31, T. 16 N., R. 8 E., Douglas County

B. Natural Gas Pipeline Company of America, at Herscher; well located in the Herscher Gas Storage field in Section 33, T 30 N., R. 10 E., Kankakee County

C. Jones & Laughlin Steel Corporation (LTV Steel Company), at Hennepin; well located in Section 3, T 32 N., R. 2 W., Putnam County

D. U.S. Industrial Chemicals Company, near Tuscola; well located in Section 31, T. 16 N., R. 8 E., Douglas County

E. Allied Chemical Corporation, at Danville; well located in Section 12, T. 19 N., R. 11 W., Vermilion County

F Velsicol Chemical Corporation, near Marshall; two wells located in Section 12, T. 11 N., R. 12 W., Clark County

G. National Gas Pipeline Company of America in the Louden Gas Storage field, near St. Elmo; well located in Section 28, T. 8 N., R. 3 E., Fayette County

A test hole (H) was finished to the Precambrian, tested, and determined to have inadequate geologic conditions for disposal; it was partially plugged back and finished with casing for potential use of the water supply from deep freshwater sandstones.

   (H) American Potash Company, in West Chicago; a test well that was not completed as a disposal well, located in Section 9, T. 39 N., R. 9 E., DuPage County

The disposal zones for these wells range in depth from 1540 feet to 5524 feet and have an average maximum depth of 3817 feet. Certain carbonate rocks are most often used as injection zones because of their porous and permeable character. Four wells inject into the Eminence-Potosi Dolomites (Cambrian System), two wells use the Salem Limestone (Mississippian System), and one well is open to Devonian limestones. Two wells inject waste into the Mt. Simon Formation, a thick, basal sandstone of the Cambrian System.

In 1986 almost 308 million gallons of industrial wastes were disposed of in these wells. Figure I-2 shows the volume of wastes injected annually and the cumulative volume injected since 1965. Industrial acids (HCl, H_2SO_4, and HF) were the most common constituents of the wastestreams. Other important constituents included caustic soda, fluoride, compounds of mercury, arsenic, vanadium, and chromium, and chlorinated hydrocarbons, including chlordane. Runoff from precipitation on plant property accounted for a significant percentage of the wastestream at several sites.

All nine of the waste injection wells are regulated by the Illinois Environmental Protection Agency (IEPA) as Class I wells under the Underground Injection Control (UIC) program of the Safe Drinking Water Act (1974). Five classes of disposal wells have been defined by the UIC regulation:

• Class I -   wells used to inject municipal and both hazardous and nonhazardous industrial wastes below USDW

• Class II - wells associated with oil and gas production and storage

• Class III - wells used in special process (mining) operations

• Class IV - wells used to inject hazardous and radioactive wastes into or above USDW (this class is presently banned)

• Class V - wells used to inject all other nonhazardous wastes into or above USDW

Illinois was granted primacy to operate this program in February 1984. The Class I wells are being operated under rule while permit reviews are being conducted under the regulations of the UIC program for Class I wells; by June 1987, three permits had been granted and two permits had been denied. Staff from the State Geological and Water Surveys provide technical consultation to the IEPA, the primary regulatory agency for the program.

SCOPE OF STUDY

Legislation (SB1954/HB3176) approved in 1984 (IEPA, January 1, 1985: Environmental Protection Act) required that the Department of Energy and Natural Resources conduct an in-depth assessment of the regulations and practices of the Illinois UIC program as it relates to Class I hazardous waste disposal. A study was initiated to determine whether underground injection is an appropriate method of disposal in Illinois and to provide sound recommendations to the Legislature, Legislative Council, the Governor's office, and State agencies concerning this disposal practice.

This study focuses on the practice of deep well disposal of hazardous and nonhazardous wastes into saline disposal zones through Class I wells and the potential effect of this method of disposal on groundwater resources used for drinking water purposes. Nonhazardous Class I wells have been included in this study because the basic regulatory requirements for hazardous waste wells also apply to those disposing of nonhazardous wastes.

Groundwater is an important resource to the people of Illinois. Average daily consumption is estimated at 475 million gallons per day in 1984 (Kirk et al., 1985). Illinois is ranked fourth among the states of this country in the use of groundwater as a source for public water supply (Solly et al., 1985). In addition, industry and agriculture make even more extensive use of fresh groundwater.
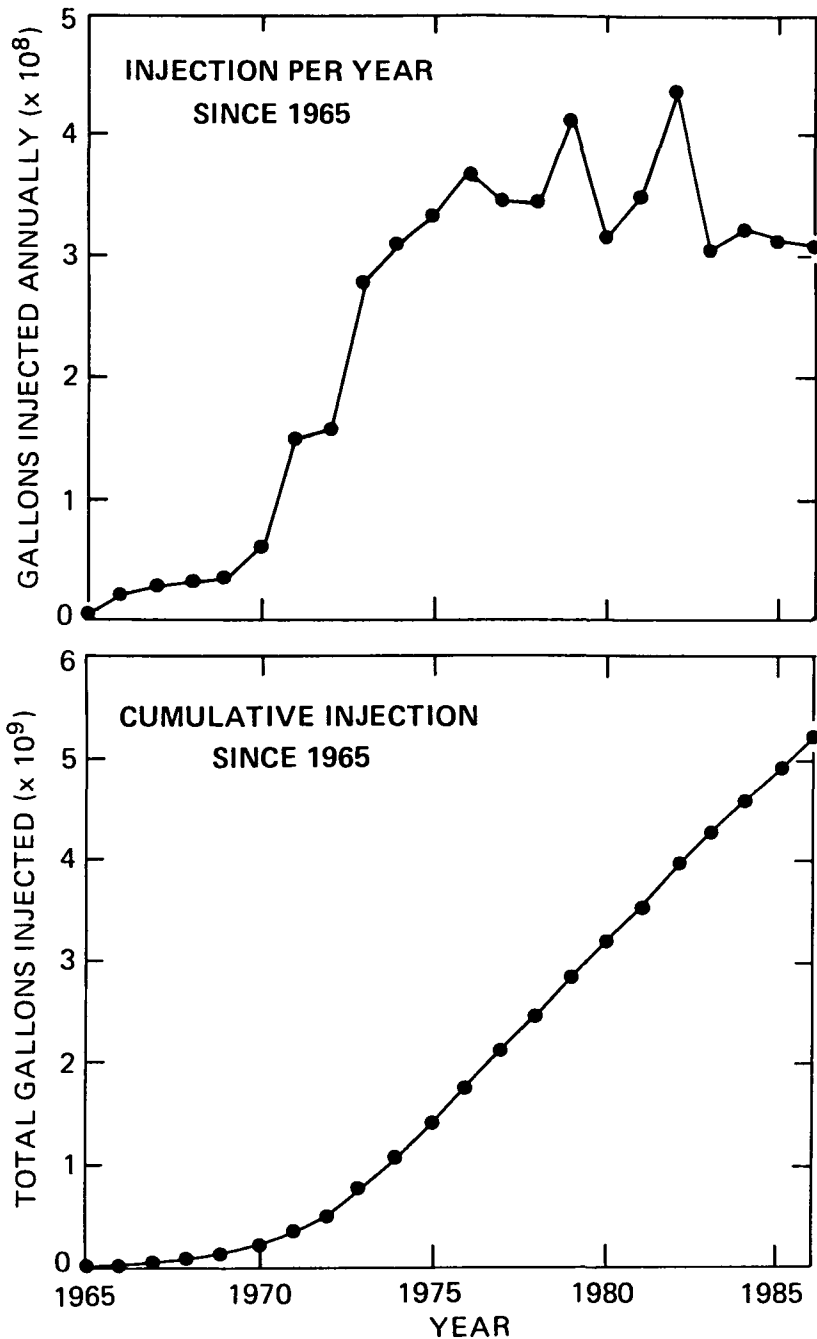
Figure I-2 Volume of wastes injected in Class I wells in Illinois (ISWS, 1987).

That portion of the groundwater resource containing less than 10,000 mg/L TDS has been reserved as a potential drinking water source. The freshest portion of this reserved resource is presently being used as a drinking water source by 35 percent of the population; therefore, the citizens of Illinois have a vital interest in protecting all underground drinking water resources from potential sources of contamination.

REGULATORY STRUCTURE RELATED TO WASTE DISPOSAL

Before separate programs were developed to regulate different methods of industrial waste disposal, deep disposal wells and other surface disposal facilities (such as holding ponds, surface impound-

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merits, and storage tanks) were operated under a single permit granted for the operation of the entire facility. Problems not related to a facility's injection well, such as pond leaks, discharges to waters of the State, or surface equipment leaks, were dealt with under the same operational permit that regulated the deep injection well.

The regulatory structure has changed over the years with the development of separate programs to regulate different aspects of industrial waste disposal. The National Pollutant Discharge Elimination System (NPDES) regulates discharges to surface waters of the State. The Resource Conservation and Recovery Act (RCRA) regulates land disposal on the surface of the earth via landfills and surface impoundments. The Comprehensive Environmental Response/Compensation Liability Act (CERCLA, or Superfund) oversees the cleanup and restoration of hazardous waste disposal sites at which significant contamination of the environment has occurred through neglect or accident. The Underground Injection Control (UIC) program regulates disposal of liquid wastes via injection beneath the surface of the earth.

The status of this last program is the focus of this report. The study of environmental problems that occurred at Class I facilities in Illinois in the past but involved surface facilities or disposal methods not currently regulated under the present UIC regulations is beyond the scope of this report. However, incidents involving such methods or facilities that were directly related to Class I well failures or downtimes are mentioned.

1 REGULATIONS AND PERMITTING PRACTICES

This chapter provides a summary of specific regulations adopted by the Illinois Pollution Control Board (IPCB) (IEPA, March 1, 1984) and reviews in detail regulatory practices of the Illinois Environmental Protection Agency (IEPA, 1984) concerning the Underground Injection Control (UIC) program in Illinois. The review of permitting practices includes instructions for filing permit applications, application handling procedures, provisions for permit modification and revocation, and standard and special conditions for UIC permits issued by the IEPA. Also included in this chapter is a summary of November 1984 amendments to the Resource Conservation and Recovery Act (RCRA) pertaining to land disposal of hazardous wastes.

ILLINOIS POLLUTION CONTROL BOARD REGULATIONS

Specific regulations related to the Underground Injection Control (UIC) Program have been adopted by the Illinois Pollution Control Board (IPCB). They are covered in Title 35 Illinois Administration Code Parts 702 (RCRA and UIC Permit Programs), 704 (UIC Permit Program), 705 (Procedures for Permit Issuance), and 730 (Underground Injection Control Operating Requirements). Illinois received primacy for the UIC program on February 1, 1984, which is the date when most portions of the regulations became applicable.

Part 702 (RCRA and UIC Permit Programs) contains definitions and basic permitting requirements that apply to both the RCRA (Resource Conservation and Recovery Act) and UIC programs. Regulations governing permit applications, permit conditions, and transfer, modification, and revocation of permits are covered in this Part.

Part 704 (UIC Permit Program) sets forth additional requirements specific to the UIC permit program. All owners and operators of Class I injection wells must be authorized either by permit or rule. ("Authorization by rule" allows facilities that had already been permitted at the time Illinois received primacy to continue injection operations until permit decisions can be made under the new regulations.) To carry out the mandate of the Safe Drinking Water Act (SDWA) of 1974, Part 704 provides that no injection shall be authorized by permit or rule if it results in movement of fluid containing any contaminant into a USDW (Underground Source of Drinking Water) if the presence of that contaminant may cause a violation of any primary drinking water regulation under 40 CFR 142 or may otherwise adversely affect human health. Part 704 also includes regulations governing prohibited injections, authorization of underground injection by rule, permit application, permit conditions, and hazardous waste wells.

Clarification is needed in Section 704.193 (Corrective Action) concerning improperly sealed, completed, or abandoned wells within the area of review. Section 704.193 (a) (Coverage) states that:

> Applicants for Class I or II injection well permits shall identify the location of all known wells within the injection well's area of review which penetrate the injection zone. For such wells which are improperly sealed, completed, or abandoned, the applicant shall also submit a plan consisting of such steps or modifications as are necessary to prevent movement of fluid into underground sources of drinking water ("corrective action"),

and section 704.193 (b) (3) (Requirements-Injection pressure limitation) reads as follows:

> The Agency may require as a permit condition that injection pressure be so limited that pressure in the injection zone does not exceed hydrostatic pressure at the site of any improperly completed or abandoned well within the area of review. This pressure limitation shall satisfy the corrective action requirement. Alternatively, such injection pressure limitation can be part of a compliance schedule and last until all other required corrective action has been taken.

Our understanding is that the requirement in 704.193 (b) (3) pertains to improperly completed or abandoned wells that penetrate the injection zone within the area of review. It is physically impossible for injection pressure to be so limited that it will not exceed the hydrostatic pressure in the injection zone, as pressure must be greater than hydrostatic in order for injection to occur. Paragraph 704.193 (a) provides the requirement for identifying all known wells in the area of review and gives the procedure to be followed for all wells that are improperly sealed, completed, or abandoned.

Part 705 (Procedures for Permit Issuance) sets forth procedures the IEPA must follow in issuing UIC permits; it also specifies rules on effective dates of permits and provides for a public comment period and a hearing in some cases. Permit applicants and any other participants must raise any issues during this proceeding that they want to have reviewed.

Part 730 (Underground Injection Control Operating Requirements) sets forth technical criteria and standards for the UIC program, pertaining to exempted aquifers, area of review, corrective action, mechanical integrity, plugging and abandonment, and construction, operating, monitoring, and reporting requirements. The laws authorizing these and all other UIC program regulations are included in the Environmental Protection Act (Ill. Rev. Stat. 1979, ch. 111 1/2, par. 1001), as amended.

ILLINOIS ENVIRONMENTAL PROTECTION AGENCY PRACTICES

Instructions for Filing a Permit Application

No person (individual, corporation, or other legal entity) may begin drilling or converting an existing well into a Class I disposal well without first obtaining a permit from the IEPA. Existing Class I wells were authorized by rule until permit actions were taken by the IEPA. All authorization by rule in the United States expired on February 1, 1989. UIC permits for Class I wells are effective for fixed terms, determined by the IEPA on a case-by-case basis and not to exceed 10 years.

In accordance with Section 7 of the Illinois Environmental Protection Act, certain information submitted to the IEPA may be claimed as confidential by the submitter. If no such claim is made, the IEPA may make the information available to the public without further notice. Claims of confidentiality for information concerning name and address of the applicant, identity of waste to be injected, or information dealing with the existence, absence, or level of contaminants in drinking water will be denied.

A UIC permit application consists of a set of completed application forms, a Feasibility Report, and any other documents required for proper consideration of the application. Application forms are designed to provide a summary of information about the applicant, injection well, waste, and other pertinent data on the project. The Feasibility Report is a narrative description of the technical information about the project and is primarily an evaluation of the hydrogeological conditions based on the available data.

The Feasibility Report is prepared in order to evaluate whether or not subsurface conditions are suitable for the injection of a specific fluid or waste. This report may be based on existing information or information developed by the applicant. The Feasibility Report is to be prepared under the direction of a professional engineer or geologist; it includes information on local topography and geology pertinent to the injection program; the subsurface hydrology and reservoir mechanics of the injection interval; characteristics of the wastestream(s); surface installations; construction, completion, and testing plans for proposed injection wells; other subsurface disposal operations in the area; plans for any corrective action required; injection well operation and monitoring; proposed abandonment procedure; and other maps and data required by the IEPA.

Justification for subsurface disposal, in the form of treatability studies of alternate methods of waste disposal, must be included in the feasibility report. The justification must include a detailed explanation of why each method is considered to be less satisfactory in terms of environmental protection than the proposed subsurface disposal method.

Permit Application Handling Procedures

Six flow diagrams at the end of this chapter (Figure 1-1) outline general IEPA procedures for handling various aspects of UIC permit application. The applicable section of the text of the Code provides details not included in these generalized flow diagrams:

1. Procedures for Permit Issuance
2. Modification Process
3. Application Process
4. Application Review Process
5. Public Comment Process
6. Permit Issuance or Denial

The IEPA will mail notice of application to interested or affected persons and certain governmental agencies and will publish notice of a draft permit or a tentative decision to deny the permit in a local newspaper.

While the application is being reviewed for completeness, the applicant may be contacted for clarification or additional information. When complete, the application will be forwarded to the appropriate state and federal government agencies interested in water-quality control and subsurface disposal practice. A notice of completeness will be sent to the applicant within 30 days (of the date the application was received) for a new facility and within 60 days for an existing facility. If the application is incomplete, notice will be sent within the same time frame, along with a list of informational deficiencies.

The IEPA will prepare and send applicants for new UIC facilities a decision schedule containing specific target dates by which the IEPA intends to prepare a draft permit, give public notice, complete the public comment period (including any public hearing), and issue a final permit.

Following a technical review of the application and any comments received in response to it, a draft permit will be prepared. A draft permit is a document indicating the lEPA's tentative decision to issue, deny, modify, revoke and reissue, terminate, or reissue a permit; this may also include a notice of intent to deny a permit. A public notice of intent to grant or deny the permit will be prepared, allowing a 30-day comment period for major UIC facilities. A public hearing can be scheduled by the IEPA or can be scheduled because of public interest. The applicant will be notified by the IEPA when the application is set for final consideration and will receive a copy of the draft permit or notice of intent to deny the permit when this notification is published.

The permittee shall submit a Notice of Completion to the IEPA before well operation begins. The permittee shall also submit a Well Completion Report based on data developed during well construction (drilling, sampling, casing, cementing, testing, and laboratory tests), and shall include any changes from programs proposed or results anticipated in the Feasibility Report. Present practice appears to allow commencement of well operation before the Well Completion Report is formally submitted to the regulatory agency. However, this is done only after a thorough review is made of all data gathered during construction and testing of the well. After receiving the notice of well completion, IEPA may schedule as part of the review a pre-operation inspection of the injection well, related surface equipment, and facilities to ensure that the applicant has complied with all conditions of the UIC permit.

Permit Modification and Revocation

Provisions and causes for permit modification are set forth in Title 35 Ill. Adm. Codes 702.183 (Modification), 702.184 (Causes for Modification), 702.185 (Facility Siting), and 702.187 (Minor Modification). Causes for permit revocation are listed in Section 702.186 (Revocation).

Standard and Special Conditions for UIC Permits Issued by the IEPA

Standard Conditions. The Illinois Environmental Protection Act (Illinois Revised Statutes, Chapter 111 1/2, Paragraph 1039), as amended, grants the IEPA authority to impose conditions on permits it issues. The IEPA informs UIC permit applicants of the following standard conditions set forth in sections of the Title 35 Ill. Adm. Code:

1) Duty to Comply: 702.141
2) Noncompliance Authorized by Emergency Permit: 704.18I(a)
3) Duty to Reapply: 702.142
4) Need to Halt or Reduce Activity Not a Defense: 702.143
5) Duty to Mitigate: 702.144
6) Proper Operation and Maintenance: 702.145
7) Permit Actions: 702.146
8) Property Rights: 702.147
9) Duty to Provide Information: 702.148
10) Inspection and Entry: 702.149
11) Monitoring and Records: 702.150
12) Retention of Records: 704.181 (b)
13) Signatory Requirement: 702.151
14) Reporting Requirements: 702.152, 702.162(c), 704.181(c)
15) Transfer of Permit: 702.182
16) Conversion or Abandonment: 702.181 (e)
17) Financial Responsibility: 704.189
18) Revocation of Permits: 702.186

UIC permit applicants are also informed of the following provisions:

19) In the event of the bankruptcy of a trustee or issuing institution of the financial mechanism, or a suspension or revocation of the authority of the trustee institution to act as trustee or the institution issuing the financial mechanism to issue such an instrument, the permittee must submit an alternative demonstration of financial responsibility acceptable to the Agency within 60 days after such event.

20) Issuance of the permit does not relieve the permittee of the responsibility of complying with the provisions of Illinois State Mining Board Rules and Regulations and an Act in Relation to Oil, Gas, Coal, and other Surface and Underground Resources (Rule II, Illinois Department of Mines and Minerals Rules and Regulations).

21) The permittee shall not make any false statement, representation or certification in any application, record, report, plan, or other document submitted to the Agency or the USERA or required to be maintained under this permit.

22) In case of conflict between the standard conditions and any other condition(s) included in this permit, the other condition(s) shall govern.

23) The provisions of the permit are severable, and if any provision of the permit, or the application of any provision of the permit is held invalid, the remaining provisions of the permit shall continue in full force and effect.

There are within the State Treasury two special funds known as the "Hazardous Waste Fund" and the "Hazardous Waste Research Fund," constituted from fees collected pursuant to Paragraph 22.2 of the Environmental Protection Act (Ill. Rev. Stat. Ch. 111 1/2, 1985). The IEPA procedures relating to collection of these fees include, but are not limited to (1) necessary records identifying the quantities of hazardous waste disposed; (2) the form and submission of reports to accompany the payment of fees to the IEPA; and (3) the time and manner of payment of fees to the IEPA, which payments are not more often than quarterly. Uses and amounts of monies collected by these fees are delineated in Paragraph 22.2.

Special Conditions. In addition to the standard conditions, the IEPA imposes special conditions on UIC permits. These conditions cover operating, monitoring, reporting and construction requirements, compliance schedules, corrective action, logs and tests, mechanical integrity tests, plugging and abandonment, and reporting of conversion or abandonment, all as required by Title 35 Ill. Adm. Codes.

In order to protect aquifers from waste injection activities, disposal wells must be properly designed, constructed, tested, and monitored. The first level of protection is provided by the various strings of casing that are an integral part of the well. Surface casing must be set through the unconsolidated material into the top of the bedrock, and the annulus between the casing and borehole must be cemented back to land surface. An intermediate casing is set inside the surface casing to a point below the lowermost USDW, and the annular space outside the casing is cemented back to the surface. The innermost casing (long string) is then set and anchored into the top of the injection zone and cemented back to the surface. Open borehole continues below the long string through the injection zone. Some well completions may extend the long string to the base of the injection zone, and perforations are made in the casing opposite the injection zone.

Injected waste is conducted through the well to the injection zone by means of injection tubing suspended from the top of the well or seated on a packer placed immediately above the base of the long string. The tubing normally extends below the long string and is separated from it by a packer placed at the bottom of the long string. The packer allows fluid to be placed under pressure in the tubing-long string annulus as a protection to the casing. If the injected waste is of a corrosive nature, then the tubing and lower portion of long string casing must be constructed of corrosion-resistant materials, and the grouting used outside the long string must also be corrosion-resistant. Alternatives to a packer may be allowed with the written approval of the IEPA.

Monitoring of injection conditions is critical to the successful operation of an injection well and to the safeguarding of underground water resources. The basic monitoring requirements are equally stringent for hazardous and nonhazardous injection wells. Wellhead instrumentation normally includes flow meters and both injection pressure and annulus pressure gauges and recorders. At a minimum, Illinois Class I facilities must include automatic warning systems; all Class I hazardous waste facilities must also include automatic shutoff systems. Annulus pressure is maintained at a level higher than the pressure maintained in the tubing. *[The authors recommend that the IEPA practices include a requirement that pressure differentials between the annulus and the tubing be maintained above a specified minimum amount and that calculations of such pressure differentials take into account the density differences of all fluids involved. This requirement should also include other operational parameters that can cause variation in pressure differentials.]*

Periodic tests are made of the mechanical integrity of the injection well to ensure that there are no significant leaks in the casing, tubing, and packer or that there is no significant fluid movement into a USDW through vertical channels adjacent to the well casing. Although Federal regulations require such testing every 5 years, Illinois regulations require that mechanical integrity tests (MITs) be carried out at a time interval specified in the facility UIC permit (a recently approved permit for a new well at Facility F specified every 2 years). Additionally, cement bond logs are required once during the duration of the permit, and casing inspection logs are required at the discretion of the agency. It is recommended that MITs be performed more frequently than every 5 years for wells older than 15 years. Typically a 15-year-old well would undergo a total of four MITs. Subsequent testing should be more frequent than every 5 years. MITs for permitted wells consist of a series of pressure tests and downhole geophysical logging tests to assess the structural integrity of the various well components (tubing, casing, grout, and packer) and to determine the presence of significant fluid movement outside the well casing. Pressure testing of the tubing consists of plugging and pressurizing the tubing and observing any losses of pressure over a specified period of time. A similar and corresponding procedure is repeated on the tubing-casing annulus, wherein the annulus is pressurized and monitored for pressure losses.

To determine whether significant fluid movement is taking place outside the well casing, Illinois regulations require that temperature or noise logs be run. The "ideal" approach for evaluating the cement in an injection well, suggested by Thornhill and Benefield (1986), includes a combination of various sonic tools. They suggested running a "second-generation" tool having eight ultrasonic transducers spiraled around it, and a calibrated "cement bond" tool with single transmitter/dual

receiver with 3- to 5-foot spacing. Their research data indicated, however, that even state-of-the-art logging techniques are not adequate for detecting small channels that might be present outside the casing. They concluded that until more sensitive logging is developed, and to minimize channelization, greater emphasis must be placed on planning and carrying out the cement procedure to achieve the best cement bonding possible. They recommended the use of (1) a caliper log, to determine the hole size and better estimate the required volume of cement; (2) properly conditioned drilling mud; (3) centralizers; (4) pre-flushing, to help clean out the drilling mud; (5) rotation and/or reciprocation of the casing during cementing, to promote circulation of the cement and further aid in cleaning out the hole; and (6) at least 100 percent excess cement. The Illinois experience has demonstrated, however, that it is not always possible to circulate cement grout to the surface and that the annulus between the long string and the borehole or between the various casing strings is sometimes open (uncemented) for some distance below the top of the well. *[The authors recommend that such casings be properly cemented; should cementing fail or be impractical, the open portion of the annulus should be filled with a suitable fluid, pressurized, and monitored as part of the standard monitoring program (as is done with the 7-inch casing at Facility E; the uncemented portion of the annulus is filled with water and a kerosene pack is used at the top for freeze protection.]*

Radioactive Waste

Radioactive wastes have not been and currently are not injected into Class I wells in Illinois. In the regulations (35 Ill. Adm. Code 730.105) the definitions of Class IV and Class V wells include those wells receiving radioactive wastes, whereas the definition of Class I wells in the regulations makes no mention of such wastes. Since Class IV wells are banned in Illinois, this class will not be discussed further in this section. The term "radioactive waste" as used in the definition of Class V wells is assumed to represent low-level radioactive wastes, but no intensity levels are identified. Gilkeson et al. (1983) and the IPCB (1985) identified public water supply facilities using wells that yield water in which the intensity of radioactive decay exceeds drinking water standards. Groundwater heat pump systems that tap aquifers yielding radioactive water and are coupled with return wells also represent another potential source of radioactive water injected into the subsurface. *[The authors recommend that a decision be made as to what constitutes a radioactive waste and what class or classes are appropriate for subsurface disposal of radioactive waste of various intensity levels. Pumped groundwater that has a very low concentration of naturally occurring radioactive components and is returned to the subsurface by injection should also be covered in this decision.]*

EFFECTS OF 1984 RCRA AMENDMENTS ON HAZARDOUS WASTE INJECTION

In November 1984, Congress passed amendments to the Resource Conservation and Recovery Act of 1976. These amendments were designed to restrict the disposal of hazardous waste on the land.

The amended Act prohibits land disposal of a hazardous waste unless the USERA determines that one or more methods of land disposal of the waste are not hazardous to human health and the environment. Land disposal, by definition, includes underground injection of wastes through injection wells. A method of land disposal may not be determined to be protective of human health and the environment unless a petitioner demonstrates that there will be no migration from the disposal unit/injection zone for as long as the waste remains hazardous.

The USEPA must also promulgate regulations specifying levels or methods of treatment, if any, that substantially diminish the toxicity of the waste or substantially reduce the likelihood of migration of hazardous constituents from the waste, so that threats to human health and the environment are minimized. "Otherwise banned" wastes so treated are exempt from the ban.

In November 1986, the USEPA published a schedule for making land disposal restriction decisions for all hazardous wastes. High hazard/high volume wastes were scheduled first. The new law sets the general framework for the schedule, requiring the USEPA to reach decisions on one-third of the wastes listed in the regulations within 45 months (August 1988); the second third of listed wastes in 55 months (June 1989); and all remaining wastes within 66 months (May 1990). As new

hazardous wastes are identified and listed in the future, decisions on land disposal must be made within 6 months after listing.

The proposed regulation dealing with the USEPA schedule for making determinations on land disposal prohibitions of all hazardous wastes was published in the *Federal Register* on May 31, 1985 (p. 23250) and the final rule was published in November 1986.

A second proposed regulation dealing with the framework for the regulatory program to implement these land disposal prohibitions of hazardous wastes was published in the *Federal Register* on January 14, 1986. A final rule was issued November 7, 1986. This proposed regulatory framework, however, does not apply to the disposal of hazardous wastes through underground injection wells, although underground injection was included in the definition of land disposal. New deadlines can be expected after these dates to establish the USEPA's mandate to restrict hazardous waste disposal through underground injection wells.

COMMENTS AND SUGGESTIONS ON SPECIFIC REGULATORY PRACTICES

• Generators of solid waste must determine if their wastes are hazardous, using methods outlined in 35 Ill. Adm. Code 721.102. It is possible that in some cases a waste not deemed hazardous by strict interpretation of the regulations may, in fact, be hazardous. *[The authors recommend that the IEPA should have the authority to identify potentially hazardous wastestreams; the IPCB can then act to determine whether the waste in question is, in fact, a hazardous waste.]*

• In 35 Ill. Adm. Code 704.193 corrective action requirements are established for improperly sealed, completed, or abandoned wells that penetrate the waste injection zone within the area of review of a Class I well. *[The authors believe that proper procedures for sealing, completing, or abandoning such wells must be carried out before injection begins.]*

• Good well completion practice requires (1) that the surface casing be landed at a point below the freshwater zone (aquifers with <2500 mg/L TDS), and the intermediate casing string be set inside surface casing and landed below the lowermost USDW, and (2) that the annular space outside each casing be cemented back to the surface. These requirements have not been formalized by the IEPA. *[The authors recommend that the requirements be incorporated in an official written statement]*

• Disposal of any liquid radioactive wastes by injection wells requires further evaluation. Radioactive intensity ranges must be defined for wastestreams to be injected into the subsurface. Injection of low-level radioactive wastes into Class I wells is neither currently practiced nor proposed in Illinois. *[The authors recommend that wastes classified as radioactive waste under the proposed new "intensity level definitions" be injected only in Class I wells.]*

SELECTED DEFINITIONS AND TERMS

Aquifer

An aquifer is a saturated, permeable geologic unit capable of yielding usable quantities of water to a well or spring.

Area of Review

The area of review is the lateral distance from the well in which pressures in the injection zone may cause the migration of the injection and/or formation fluids into a USDW. This lateral distance may be determined by computation based on hydrogeologic parameters, or may be a fixed lateral distance of not less than 1/4 mile. (A 2 1/2-mile area of review is currently under consideration for the federal regulations: regulatory practice in Illinois currently follows a 2 1/2-mile area of review.) If the area of review is determined by computation, the permissible radius is the result of such computation, even if it is less than the established minimum lateral distance.

Applicants for Class I well permits must identify the location of all known wells that penetrate the injection zone within the area of review. If any of these wells is improperly sealed, completed, or

abandoned, the applicant shall also submit a plan consisting of steps or modifications necessary to prevent fluid movement into underground sources of drinking water. The applicant must also identify any known or suspected faults existing within the area of review.

Fracture Gradient

Injection pressure is one of the operational parameters that directly affects the injection process. Bottom-hole injection pressure must be closely controlled, however, in order to prevent artificial fracturing of the confining layer and the migration of waste or formation fluids into other permeable units. Wolff et al. (1975) report that vertical fracturing could be induced at the well bore when the bottom-hole injection pressure reaches approximately two-thirds of the overburden pressure (the weight of the overlying rocks and pore water). Injection pressure, therefore, must be limited so that the bottom-hole pressure does not exceed this amount. If pressure losses due to flow through the injection tubing are significant, they are normally taken into account when setting injection pressure limits as part of permit application.

Hazardous Waste

"Solid waste" is defined in 35 Ill. Adm. Code 721.102; the term "solid" can include solid, liquid, semisolid, and contained gaseous materials. "Hazardous waste" is defined in 35 Ill. Adm. Code 721.103; "liquid hazardous waste" is defined and discussed in 35 Ill. Adm. Code 729, Subpart C. Exclusions to these definitions are listed in 35 Ill. Adm. Code 721.104. A solid waste (unless excluded in Section 721.104) is defined as a hazardous waste if it exhibits any of the following characteristics defined in Subpart C of Part 721: ignitability, corrosivity, reactivity, or EP toxicity.

A listing of some hazardous wastes is presented in Subpart D of Part 721, along with one or more of the appropriate hazard codes: ignitable (I), corrosive (C), reactive (R), EP toxic (E), acute hazardous (H), or toxic (T). A liquid hazardous waste is defined as a hazardous waste that yields any fluid when subjected to the paint filter test described in 35 Ill. Adm. Code 729.320.

A generator of solid waste, as defined in Section 721.102, must determine if that waste is a hazardous waste, using the following method:

1. Determine if the waste is excluded from regulation under Section 721.104.

2. Determine if the waste is listed as a hazardous waste in Subpart D of Part 721. Even if a waste is listed, the generator still has an opportunity under Section 720.122 (Waste Delisting) and 40 CFR Section 260.22 to demonstrate that the waste from his particular facility or operation is not a hazardous waste.

3. Determine if the waste is identified in Subpart C of Part 721 (if it is not listed as a hazardous waste in Subpart D of Part 721) by (1) testing the waste according to the methods set forth in Subpart C of Part 721, or according to an equivalent method approved by the Board under Section 720.120; or (2) inferring the hazard characteristic of the waste on the basis of the materials or processes used. (It is possible that in some cases a waste not deemed as hazardous by a strict interpretation of the regulations may, in fact, be hazardous.)

USDW

A USDW (underground source of drinking water) is an aquifer, or part of an aquifer, that (1) supplies, or contains a sufficient quantity of groundwater to supply a public water system and currently supplies drinking water for human consumption; or (2) contains water with less than 10,000 mg/L total dissolved solids and is not an exempted aquifer (an aquifer is designated "exempted" if it can be demonstrated that it has no real potential as a drinking water source).

Additional definitions pertinent to the UIC program are found in the sections covering underground injection in 35 Illinois Administrative Code (IEPA, 1984) reproduced here.

CLASSIFICATION OF INJECTION WELLS (source: 35 Ill. adm. code 730.105)

Injection wells are classified as follows:

a) Class I.

1) Wells used by generators of hazardous wastes or owners or operators of hazardous waste management facilities to inject hazardous waste beneath the lower most formation containing, within 402 meters (1/4 mile) of the well bore, an underground source of drinking water.

2) Other industrial and municipal disposal wells which inject fluids beneath the lowermost formation containing, within 402 meters (1/4 mile) of the well bore, an underground source of drinking water.

b) Class II. Wells which inject fluids:

1) Which are brought to the surface in connection with conventional oil or natural gas production; and may be commingled with waste waters from gas plants which are an integral part of production operations, unless those waters are classified as a hazardous waste at the time of injection;

2) For enhanced recovery of oil or natural gas; and

3) For storage of hydrocarbons which are liquid at standard temperature and pressure.

c) Class III. Wells which inject for extraction of minerals, including:

1) Mining of sulfur by the Frasch process;

2) In situ production of uranium or other metals. This category includes only in-situ production from ore bodies which have not been conventionally mined Solution mining of conventional mines such as stopes leaching is included in Class V

3) Solution mining of salts or potash

d) Class IV.

1) Wells used by generators of hazardous wastes or of radioactive wastes, by owners or operators of hazardous waste management facilities, or by owners or operators of radioactive waste disposal sites to dispose of hazardous wastes or radioactive wastes into or above a formation which within 402 meters (1/4 mile) of the well contains an underground source of drinking water.

2) Wells used by generators of hazardous waste or of radioactive waste, by owners or operators of hazardous waste management facilities, or by owners or operators of radioactive waste disposal sites to dispose of hazardous waste or radioactive waste above a formation which within 402 meters (1/4 mile) of the well contains an underground source of drinking water.

3) Wells used be generators of hazardous waste or owners or operators of hazardous waste management facilities to dispose of hazardous waste, which cannot be classified under 35 Ill. Adm. Code 730.105(a)(1) or 730.105(d)(1) and (d)(2) (e.g., wells used to dispose of hazardous wastes into or above a formation which contains an aquifer which has been exempted pursuant to 35 Ill. Adm. Code 730.1040

e) Class V. Injection wells not included in Class I, II, III or IV.

Class V wells includes:

1) Air conditioning return flow wells used to return to the supply aquifer the water used for heating or cooling in a heat pump;

2) Cesspools, including multiple dwelling, community or regional cesspools, or other devices that receive wastes, which have an open bottom and sometimes have perforated sides. The UIC requirements do not apply to single family residential cesspools or to non-residential cesspools which receive solely sanitary wastes and have the capacity to serve fewer than 20 persons a day;

3) Cooling water return flow wells used to inject water previously used for cooling;

4) Drainage wells used to drain surface fluid, primarily storm runoff, into a subsurface formation;

5) Dry wells used for the injection of wastes into a subsurface formation;

6) Recharge wells used to replenish the water in an aquifer;

7) Salt water intrusion barrier wells used to inject water into a fresh water aquifer to prevent the intrusion of salt water into the fresh water;

8) Sand backfill and other backfill wells used to inject a mixture of water and sand, mill tailings or other solids into mined out portions of subsurface mines whether what is injected is a radioactive waste or not;

9) Septic system wells used to inject the waste or effluent from a multiple dwelling, business establishment, community or regional business establishment septic tank. The UIC requirements do not apply to single family residential septic system wells, or to non-residential septic system wells which are used solely for the disposal of sanitary waste and have the capacity to serve fewer than 20 persons a day.

10) Subsidence control wells (not used for the purpose of oil or natural gas production) used to inject fluids into a non-oil or gas producing zone to reduce or eliminate subsidence associated with the overdraft of fresh water;

11) Radioactive waste disposal wells other than Class IV;

12) Injection wells associated with the recovery of geothermal energy for heating, aquaculture or production of electric power;

13) Wells used for solution mining of conventional mines such as stopes leaching;

14) Wells used to inject spent brine into the same formation from which it was withdrawn after extraction of halogens or their salts; and

15) Injection wells used in experimental technologies.

PROCEDURES FOR PERMIT ISSUANCE

MODIFICATION PROCESS

Figure 1-1 Flow diagrams outlining permit UIC application procedures in Illinois.

(Note: This and the appendices which follow provide a general outline of the procedures for RCRA and UIC permit issuance by the Illinois EPA. This is intended for the convenience of the public only Because many details have been omitted, the text of the rules should always be consulted.)

APPLICATION PROCESS

APPLICATION REVIEW PROCESS

START

4

APPLIC.
RECEIVED
§ 705 121

FROM
MODIFICATION
PROCESS

yes

no   APPLICATION
COMPLETE?
§ 705 122

yes

no   MAJOR
FACILITY?
§ 705.126

DECISION
SCHEDULE
§ 705.126

NOTICE OF
INCOMPLETE
APPLIC
§ 705 122

yes

NOTICE OF
COMPLETE
APPLIC
§ 705 125

no

MORE
INFORMATION
RECEIVED?
§ 705.123

5   TO APPLICATION
REVIEW
PROCESS

FROM
APPLICATION   5
PROCESS

REVIEW
APPLICATION

7

FROM
MODIFICATION   3
PROCESS

grant   deny

9

DRAFT
PERMIT
§ 705.141

TENTATIVE
DECISION?
§ 705 141(a)

NOTICE OF
INTENT
TO DENY
§ 705 141

8

no   yes

STATEMENT
OF BASIS
§ 705.142

MAJOR FACILITY OR
WIDESPREAD PUBLIC
INTEREST?
§ 705 143

FACT
SHEET
§ 705 143

ADMIN.
RECORD
PREPARED
§ 705 144

8   9   7

FROM PUBLIC
COMMENT
PROCESS

6   TO PUBLIC
COMMENT
PROCESS

1-11

Figure 1-1   (continued).

PUBLIC COMMENT PROCESS

PERMIT ISSUANCE OR DENIAL

(Source Amended at 7 Ill Reg 14252, effective as noted in 35 Ill Adm Code 700 106)

Figure 1-1 (continued).
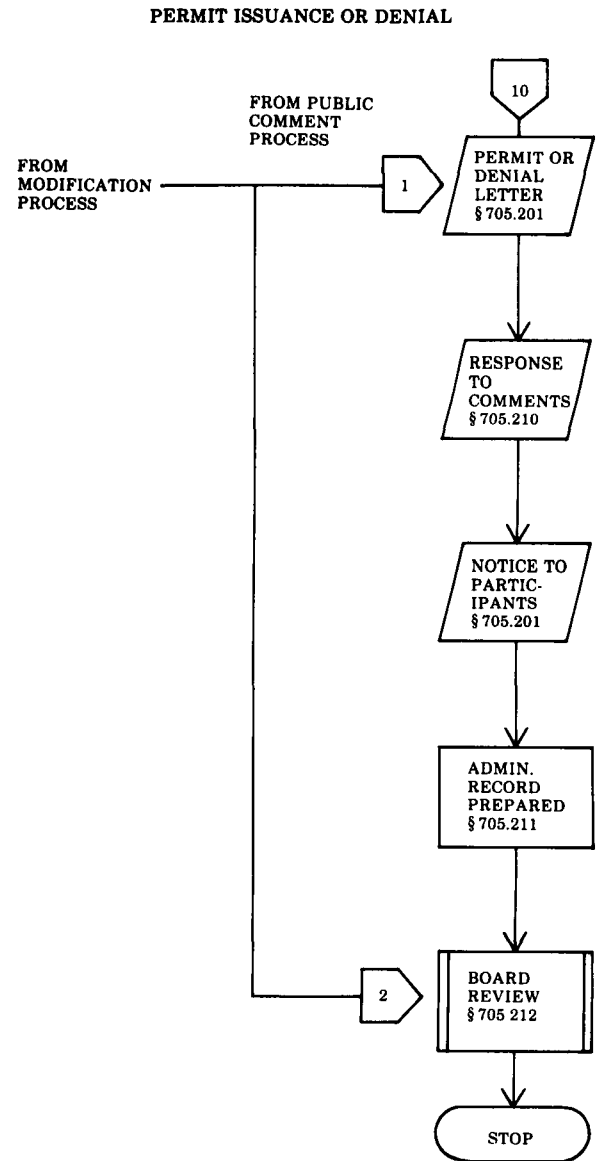
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2 GEOLOGIC ENVIRONMENT

GEOLOGIC FRAMEWORK OF ILLINOIS: AN OVERVIEW

The feasibility of injection in Class I wells depends on the capacity of the geologic environment at the well site to accept injected wastes during the life expectancy of each disposal well and to provide long-term confinement within the injection zone and its primary confining units. All injected wastes must be isolated within specific disposal horizons to ensure immediate and long-term protection of other geologic resources vital to man's physical existence, particularly all underground sources of drinking water (USDW).

Regional and site-specific geologic characteristics determine the suitability of each potential site for injection and control the design, construction, testing, operation, and monitoring practices of each well. The geologic environment of specific concern at each potential well site encompasses all rock units influenced by injection in the deep well, the fluids these rock units contain, the dynamics of both natural and artifically induced flow systems operating on these fluids, and the naturally occurring resources found in these rock units. The deep well disposal system consists of the rock strata that accept and confine injected wastes and displaced formation fluid and the well that transports the waste from the surface to the disposal zone. Each well includes three basic components: (1) the wellhead, which provides the entry point for the waste, forms the upper seal for well components, and is the site for most surface monitoring devices; (2) the well body, the secured mechanism for transporting waste from the surface to the disposal zone; and (3) the well terminus, the entry port to the disposal zone.

The geologic framework of Illinois consists of a sequence of sedimentary rock units (of variable thickness) deposited in and on the margins of a large sedimentary basin. These rocks rest on Precambrian age igneous and metamorphic rocks that form an impermeable basal boundary. The depth to this impermeable boundary ranges from about 1500 feet near the Wisconsin border north of Rockford to more than 20,000 feet in the southeast corner of Illinois (Sargent and Buschbach, 1985). The sedimentary rock sequence consists of a thick interval of consolidated bedrock (the Paleozoic Erathem, which is subdivided into six systems), a thin interval of semiconsolidated bedrock units (Cretaceous and Tertiary Systems) in limited areas of southern and western Illinois, and a blanket of unconsolidated glacial and surficial deposits covering the bedrock. The Paleozoic bedrock units consist of dolomite, limestone, shale, sandstone, and siltstone lithologies, predominantly of marine origin. Deep well injection is limited to certain Paleozoic units in part of the sedimentary basin.

Figure 2-1 shows the areal distribution of the rock units forming the bedrock surface beneath the glacial and surficial deposits. The structural configuration of these units, reflected in the patterns on the geologic map, is shown in greater detail in Figure 2-2. The Illinois Basin and its relatively broad marginal areas to the east, north, and west are the dominant structural features in Illinois; there are several other noteworthy structures, including regional flexures and fault systems. This structural configuration developed over a long period of geologic time, resulting in a broad region of relatively flat-lying units that have a gentle regional dip toward the center of the Illinois Basin. Toward the center of the basin the rock units are thicker and often have additional interbedded units. During major episodes of erosion, sediment loss was less severe in the central portion of the basin where subsidence was more active.

There is a considerable degree of regional uniformity in the general character of the rock units in the lower part of the Paleozoic (Cambrian through Devonian Systems), and characteristics of specific units can often be traced over broad areas. Subsequent Mississippian and Pennsylvanian deposition is characterized by more rapid geographical shifts in depositional environments and generally less widespread occurrence of specific mappable characteristics in the units of these
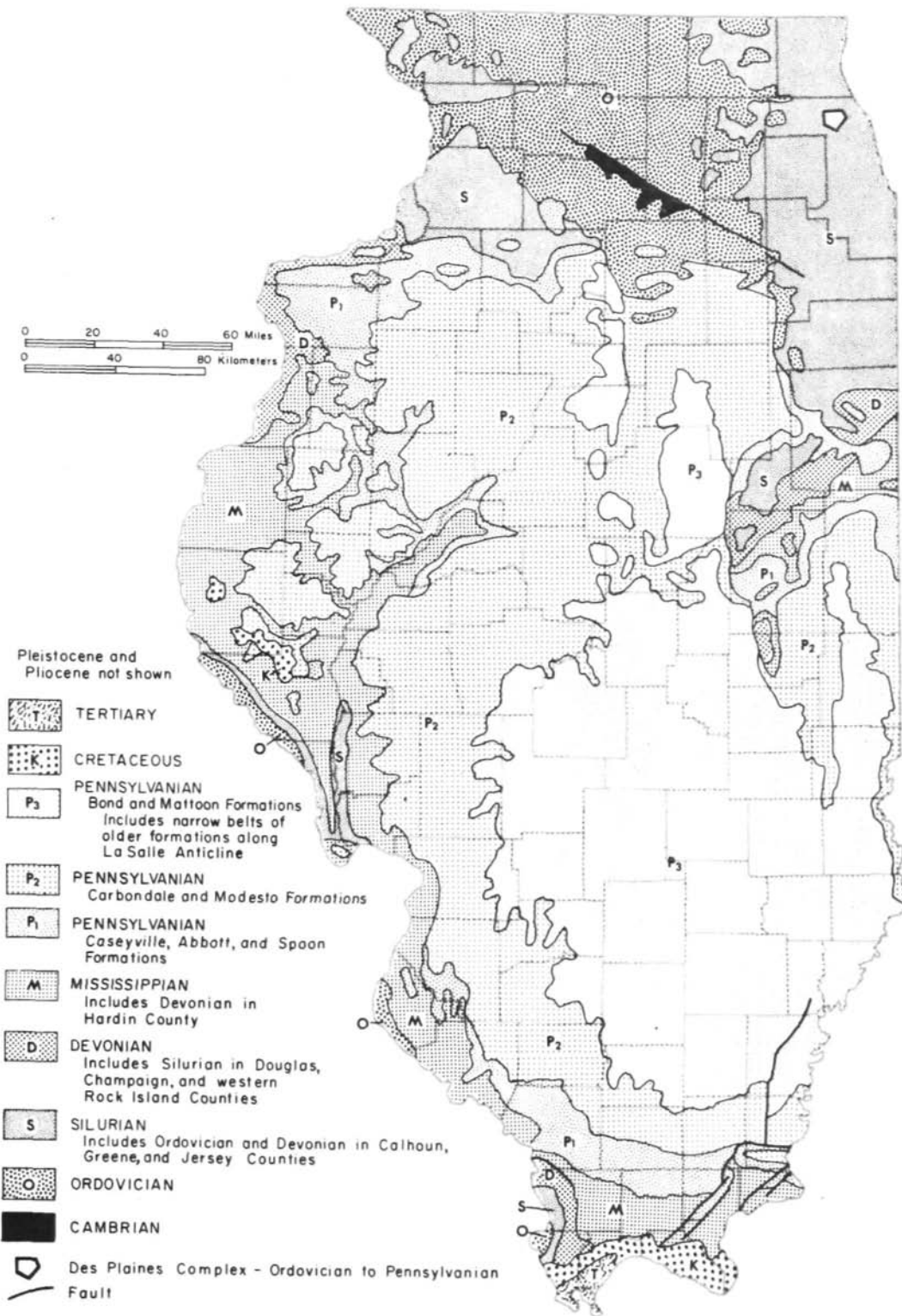
Figure 2-1 Generalized areal geology of the bedrock surface (Willman and Frye, 1970).

Pleistocene and
Pliocene not shown

TERTIARY

CRETACEOUS

PENNSYLVANIAN
Bond and Mattoon Formations
Includes narrow belts of
older formations along
La Salle Anticline

PENNSYLVANIAN
Carbondale and Modesto Formations

PENNSYLVANIAN
Caseyville, Abbott, and Spoon
Formations

MISSISSIPPIAN
Includes Devonian in
Hardin County

DEVONIAN
Includes Silurian in Douglas,
Champaign, and western
Rock Island Counties

SILURIAN
Includes Ordovician and Devonian in Calhoun,
Greene, and Jersey Counties

ORDOVICIAN

CAMBRIAN

Des Plaines Complex - Ordovician to Pennsylvanian

Fault

0   20   40   60 Miles
0   40   80 Kilometers

Figure 2-2 Principal geologic structures (Willman et al., 1975).

2-3

systems. The cyclical nature of units in these upper systems is a product of deltas and marine shorelines shifting across the state in response to cyclical changes in sea level.

Several area-wide to regional features associated with major erosional events have produced geologic conditions favorable to deep well injection. In some carbonate units, the development of karst features (i.e., caves, sinkholes) below several such erosional horizons has produced moderate to very high permeability zones that can accept large quantities of wastes. Porous sandstones deposited above major erosional surfaces also provide potential injection zones.

UNITS CONTAINING CURRENTLY USED OR POTENTIAL DISPOSAL ZONES

This section provides descriptions of each principal rock unit and its associated confining interval currently being used for injection in Class I wells or having potential for deep well injection. Units containing underground sources of drinking water are also discussed.

Figure 2-3 provides an overview of the formation names, lithologies, potential uses as aquifers or confining units, general hydraulic properties, and degree of mineralization of the groundwater. More detailed geologic information for specific units is given in the Handbook for Illinois Stratigraphy (Willman et al., 1975) and reports prepared by Cluff (1981), Kolata (1981), and Piskin and Bergstrom (1975). Additional references are given in the Bibliography and Index of Illinois Geology (Willman et al., 1968).

Precambrian Rocks

Precambrian-age igneous and metamorphic rocks form an impermeable basal boundary for the overlying sedimentary units. The surface configuration and depth of burial of these rocks is shown in Figure 2-4. Prior to accumulation of the basal sandstone (Cambrian System), erosion had produced a flat to gently rolling surface on these rocks. Isolated erosional knobs are also known to occur on this surface and many have been the targets of deep test drilling.

Cambrian System

Cambrian strata underlie the entire state; they range in thickness from about 1000 feet along the Mississippi River to more than 3500 feet in eastern Illinois. South of the Cottage Grove Fault System the thickness generally exceeds 3000 feet, and locally, in the Reelsfoot Rift, it exceeds 6000 feet (Schwalb, 1982).

The dominant lithology in the basal part of the Cambrian is sandstone with some interbedded shaly zones. This unit (Mt. Simon Formation) covers the Precambrian surface of the entire state except for a few isolated knobs of granite that are higher than this sandstone. Dolomite is the dominant lithology above the basal sandstone. Northward from the central part of Illinois the dolomite includes some intergranular sand and interbedded sandstones, and this sand becomes more dominant northward. In the same region of the state, the Eau Claire Formation is a shale and acts as a confining interval for the basal sandstone.

The Cambrian has several existing and potential horizons that can accept injected waste from Class I wells. These horizons are found in the basal sandstone and in highly permeable zones of the dolomite sequence (Eminence and Potosi Formations) in regions where these formations are not USDW. Four of the seven Class I sites inject wastes into the Cambrian System.

Basal Sandstone.   The Mt. Simon Sandstone consists of mostly angular, poorly sorted, fine- to coarse-grained sandstone and some thin, interbedded shales. The shales appear to represent about 5 percent of the lithology of this formation (Bergstom, 1968). The shales have increased continuity and thicken significantly toward the southern extremity of Lake Michigan (Buschbach, 1964). Permeable zones in this sandstone sequence are interbedded with nonpermeable intervals and typically represent less than half the total thickness of the Mt. Simon throughout many areas of the state. The sandstone ranges in thickness from less than 500 feet along the Mississippi River to more than 2700 feet in the northern part of eastern Illinois. In the south, thicknesses of at least 3000 to 4000 feet are expected in localized areas of the Reelfoot Rift. In the north, the fine- to medium-grained basal sandstone (Elmhurst Member) of the Eau Claire Formation is included in the basal sandstone. The thickness of this member ranges from 10 to 200 feet.

Eau Claire Formation.   This formation is a shale-dolomite sequence that grades from sandy shale in the north and west-central part of the state, to silty shale in the northeast and central part, to mostly carbonate in the south. Figure 2-5 shows the thickness and distribution of the Eau Claire. This unit is a major confining zone for waste disposal wells and natural gas reservoirs using the basal sandstone.

Ironton and Galesville Sandstones.   These formations consist of fine- to coarse-grained sandstone that ranges in thickness from 150 to 200 feet. In central Illinois they thin rapidly southward and grade into nonsandy dolomite of the Knox Megagroup. In most of the areas in which they occur these sandstones, particularly the Galesville, consistently yield large water supplies to wells that penetrate them. They offer little or no potential for the disposal of wastes in Class I wells.

Franconia Formation.   The Franconia Formation consists of glauconitic, clayey, dolomite-sandstone with some interbedded shale beds in the north. Toward the south its sand, silt, and glauconite content decreases, and it becomes predominantly a tight dolomite. The pure dolomite portion of this unit is included in the Knox Megagroup. Where this unit is sandy it may yield water to wells. In the central part of the state it acts as a tight basal confining zone for the overlying Eminence and Potosi disposal zones.

Eminence and Potosi Formations.   The Potosi Formation is a relatively pure dolomite ranging in thickness from 100 feet in the north to more than 600 feet in the south. The Eminence is similar in character but is more sandy in the north and is 100 feet thinner than the Potosi throughout the state. Sandstones in the Eminence in the northwest grade laterally into the Jordan Sandstone. Extensive systems of caverns and strong development of secondary porosity may exist in these units, particularly the Potosi, in many parts of Illinois. The cavern systems developed prior to the deposition of the St. Peter Sandstone. The distribution patterns of the cavern systems are not uniform and can be expected to be similar to those patterns developed in present-day karst terranes. These units contribute water to large-capacity water wells penetrating the more deeply buried sandstone aquifers. Disposal wells finished in these units south of the region where fresh water occurs have low static water levels, moderate to high injection capacity, and low injection pressures.

Hydrogeologic Characteristics of Cambrian System.   The Cambrian sandstones, sandy dolomites, and cavernous dolomites have significant potential for yielding water supplies. Figure 2-18 shows the distribution of public water supply wells obtaining water from deep bedrock sources. Many of the wells represented in this figure are finished in Cambrian units. Large yields are consistently available from the Ironton-Galesville Sandstones. Smaller yields can be developed from the sandy dolomites. Yields from dolomites tend to be highly variable depending on the degree of fracture and crevice development in the dolomite. The top of the Elmhurst-Mt. Simon aquifer is a source of supplemental water supply. Most well completions in the Cambrian are open to multiple units.

The extensive occurrence of USDW in the Cambrian units of northern Illinois reflects the broad distribution of relatively uniform hydrogeological characteristics of these units, particularly the moderate to high permeabilities exhibited by many of them. Figures 2-5, 2-6, and 2-7 show the southern limits of the basal USDW boundaries of 10,000 mg/L TDS (total dissolved solids) in the Mt. Simon Sandstone and in the significant aquifers lying above the Eau Claire Formation. Below and regionally downgradient from the USDW the mineral content of groundwater tends to increase rapidly. In the northern part of Illinois the mineral content in the Mt. Simon increases at least 2 1/2 orders of magnitude from its top to its base. At the base of the Mt. Simon there is an estimated three-fold increase in the mineral content of its formation water from northern Illinois to the deeper areas of the Illinois Basin lying to the south. Such changes in mineral content are observed in all the units having a regional distribution; however, few show the vertical contrast exhibited by the Mt. Simon.

Local and regional variations observed in the mineral content of groundwater reflect changes in the subsurface environment that may affect Class I disposal. For example, in the vicinity of Well C (point of intersection of cross sections A-A' and B-B' in Figure 2-2, and Figure 3-4), the Ironton-Galesville, the first significant aquifer above the Mt. Simon disposal interval, is situated in an isolated area of the regional flow system, where its formation water is not classified as a USDW. Another example of the effect of a rapid change in permeability on the mineral content of formation water is illustrated in the vicininty of Well E. In this area, permeability decreases as the sandstones

Rock Units and Their Hydrogeologic Roles

Southern Illinois

Geologic Column

SYS.	SER.	Formation Member	Thickness Feet	Group
QUAT.	PLEIS.	Glacial drift, loess, and alluvial deposits	0-300	
	PLI.	"Lafayette" Gravel	0-50	
TERTIARY	EOCENE	Wilcox Fm.	0-300	
	PALEO.	Porters Creek Clay	75-150	
CRETACEOUS	GULFIAN	Clayton Fm.	5-10	
		Owl Creek Fm.	0-10	
		McNairy Sand	125-500	
		Tuscaloosa Gravel	0-20	
PENNSYLVANIAN	VIRGILIAN	Greenup Ls.		McLeansboro
		Shumway Ls.		
		Mattoon Fm.	700+	
		Omega Ls.		
	MISSOURIAN	Millersville Ls.		
		Bond Fm.	100-350	
		Shoal Creek Ls.		
		No. 8 Coal		
		Modesto Fm.	200-500	
		Piasa Ls.		
		No. 7 Coal		
		No. 6 Coal		
		Carbondale Fm.	200-400	
		No. 5 Coal		

Hydrogeologic Description

Confining Bed/Aquifer: Quaternary — unconsolidated deposits; glacial pebbly clay (till), silt, clay, loess, sand and gravel; alluvial silt, sand, and gravel; major source of drinking water with larger yields from sands and gravels along present-day streams and in buried bedrock valleys; well yields are variable to more than 2,000 gpm; a few inches to more than 400 ft thick; tills and clays from uppermost confining interval.

Aquifer: Cretaceous-Tertiary — sands, clays, silts, and some gravels; aggregate maximum thickness of 900 ft; occurrence limited to southern tip of Illinois; McNairy and Tuscaloosa Formations are the most productive; local drinking water source with yields up to 1,000 gpm.

Confining Bed/Aquifer: Pennsylvanian — mainly shale, with some sandstone, siltstone, and coal; maximum thickness of 2,500 ft; forms the bedrock surface in most of the area; sandstone in upper few hundred feet constitutes a source of drinking water; commonly yields less than 10-15 gpm locally near outcrop area in southwest; yields of 50-100 gpm are possible; water is highly mineralized below depth of about 500 ft.

Northern Illinois

Geologic Column

SYS.	SER.	Formation Member	Thickness Feet	Group
QUATERNARY	PLEISTOCENE	Glacial drift, loess, and alluvial deposits	0-500	
CRE.	GLF.	Baylis Fm.	0-100	
PENNSYLVANIAN	MO.	Bond Fm.	200	McLeansboro
		LaSalle Ls.		
		No. 8 Coal		
		Modesto Fm.	140-220	
		Lonsdale Ls.		
		No. 7 Coal		
	DES MOINESIAN	No. 6 Coal		
		Carbondale Fm.	125-230	Kewanee
		No. 5 Coal		
		No. 2 Coal		
		Spoon Fm.	2-110	
		Seville Ls.		
	ATO	Bernadotte Ss. Abbott Fm.	2-85	McC.
	M.	Babylon Ss. Caseyville Fm	0-90	
MISSISSIPPIAN	VALMEYERAN	St. Louis Ls.	0-180	
		Salem Ls.	0-80	
		Sonora Ss.	0-40	
		Warsaw Sh.	40-200	
		Keokuk Ls.	50-100	
		Burlington Ls.	70-200	
	KIND.	Fern Glen Ls.	0-50	North Hill
		Sedalia Ls.	0-10	
		Starrs Cave Ls.	0-12	
		Prospect Hill Sts.	5-30	
		McCraney Ls.	5-50	
		Hannibal Sh.	15-125	
NIAN	UPPER	Louisiana Ls.	0-30	New Albany
		Saverton Sh.	0-120	
		Grassy Creek Sh.	0-100	

Hydrogeologic Description

Confining Bed/Aquifer: Quaternary — unconsolidated deposits; glacial pebbly clay (till), silt, clay, loess, sand and gravel; alluvial silt, sand, and gravel; covers most of Illinois; up to 600 ft thick; major freshwater source with largest yields along streams and in buried bedrock valley; tills and clays are the uppermost confining bed in the state.

Aquifer (minor): Cretaceous — clayey sand and sand, gravel at the base; limited occurrence in uplands of Adams and Pike counties; up to 100 ft thick; limited yields of freshwater to wells.

Confining Bed/Aquifer: Pennsylvanian — mainly shale with some sandstone, siltstone, limestone, and coal; covers south-central part of the region; maximum thickness approximately 700 ft; sandstones and some fractured limestones commonly yield less than 25 gpm; upper part constitutes principal source of small groundwater supplies where no source exists in glacial deposits.

Aquifer/Confining Bed: Valmeyeran — mainly limestone with shales, siltstones, and dolomites; underlies southern parts of region; maximum thickness less than 800 ft; where present near bedrock surface, constitutes a source of drinking water; yields are generally somewhat greater than those from the Pennsylvanian; mineral content increases below moderate depths of burial and becomes high in central-south part of region.

Confining Bed: New Albany — black, gray, and green shale; covers southern two-thirds of region.

Figure 2-3 Description of rock units and their hydrogeologic roles.

Left column

DES MOINESIAN

Unit	Thickness
No. 2 Coal	
DeKoven Coal	
Davis Coal	
Spoon Fm.	10-350
Curlew Ls.	
Murray Bluff Ss.	

Kewanee

ATOKAN

Unit	Thickness
Abbott Fm.	0-350
Grindstaff Ss.	

MORROWAN

Unit	Thickness
Pounds Ss.	
Caseyville Fm.	0-600
Battery Rock Ss.	
Lusk Sh.	

McCormick

CHESTERIAN

Unit	Thickness
Grove Church Sh.	0-65
Kinkaid Ls.	110-180
Degonia Ss.	40-100
Clore Fm.	50-110
Palestine Ss.	30-140
Menard Ls.	30-150
Waltersburg Fm.	35-80
Vienna Ls.	0-15
Tar Springs Ss.	30-150
Glen Dean Ls.	10-70
Hardinsburg Ss.	15-180
Haney Ls.	10-80
Fraileys Sh.	50-100
Beech Creek Ls.	2-25
Cypress Ss.	30-160
Ridenhower Fm.	30-75
Bethel Ss.	5-120
Downeys Bluff Ls.	5-30

Golconda

Alternating Sequence of Confining Beds/Aquifers: Chesterian — limestone-shale alternates with sandstone-shale; underlies much of the southern half of Illinois; thickens southward to more than 1,400 ft in southern part of Illinois Basin; some limestones and especially sandstones constitute sources of drinking water in outcrop areas along the perimeter of the Illinois Basin; commonly yields less than 25 gpm; at depth away from outcrop areas, water is highly mineralized.

Right column

DEVO. U/MID.

Unit	Thickness
Sweetland Creek Sh.	0-50
Sylamore Ss.	0-2
Cedar Valley Ls.	0-100
Wapsipinicon Ls.	0-80

SILURIAN — NIAGARAN

Unit	Thickness
Racine Dol.	0-500
Waukesha Dol.	0-30
Joliet Dol.	40-100

AL.

Unit	Thickness
Kankakee Dol.	20-60
Edgewood Dol.	0-80

Aquifer: Silurian-Devonian (Hunton Megagroup) — dolomite and some limestone; Devonian occurs only in southern part of region; Silurian underlies region except in north-central part; Silurian is the upper bedrock in northeastern and northwestern part; maximum thickness about 600 ft; limited yields from Devonian; Silurian yields range from limited to large, depending on degree of fracturing; mineral content is moderate to high in central and central-south part of region.

ORDOVICIAN — CINCIN. (Maquoketa)

Unit	Thickness
Neda Fm.	0-15
Brainard Sh.	0-100
Fort Atkinson Ls.	5-50
Scales Sh.	50-100

Confining Bed/Aquifer (minor): Maquoketa — shale with some interbedded dolomites underlies much of northern Illinois; average thickness of 200 ft; interbedded dolomites yield small quantities of water locally.

CHAMPLAINIAN (Galena)

Unit	Thickness
Dubuque Dol.	0-45
Wise Lake Dol.	50-80
Dunleith Dol.	100-140
Guttenberg Ls.	0-20
Spechts Ferry Sh.	0-10
Quimbys Mill Ls.	0-20
Nachusa Ls.	0-50

Aquifer: Galena-Platteville — predominantly dolomite with some shales; average thickness of 300 ft where top not eroded; covers northern Illinois except north-central; yields moderate quantities of water where overlain by drift; yields are reduced where overlain by Maquoketa, a drinking water source in northern Illinois.

(Platt.)

Unit	Thickness
Grand Detour Ls.	15-75
Mifflin Ls.	5-50
Pecatonica Dol.	10-60
Glenwood Fm.	0-150

(Ancell)

Unit	Thickness
St. Peter Ss.	5-600
Kress M.	

Aquifer: Glenwood-St. Peter (Ancell Group) — fine to medium grained sandstone with some shale in upper and lower parts; underlies much of northern Illinois except central part; commonly 200 ft thick; principal water yield is from middle part; an important source of drinking water in the region; becomes moderately mineralized in the southern part of region.

CANADIAN (Prairie du Chien)

Unit	Thickness
Shakopee Dol.	0-400
New Richmond Ss.	0-175
Oneota Dol.	100-300
Gunter Ss.	0-30

*****Aquifer (minor): Prairie du Chien** — dolomite with some sandstone; absent in north-central Illinois; yields are moderate to small; larger yields occur where glacial deposits overlie unit; maximum thickness is 1,000 ft in central Illinois; a drinking water source in west-central and northern third of Illinois.

Unit	Thickness
Eminence Dol.	15-150
Potosi Dol.	60-300

*****Aquifer: Eminence-Potosi** — dolomite and some sandy dolomite; maximum thickness exceeds 400 ft in the south; yields moderate to small quantities of water; drinking water source in west-central and northern third of the State.

System	Series	Formation	Thickness (ft)
MISSISSIPPIAN		Yankeetown Ss.	20-50
		Renault Ls.	10-50
		Aux Vases Ss.	10-80
		Ste. Genevieve Ls.	60-200
		St. Louis Ls.	150-500
	VALMEYERAN	Salem Ls.	100-400
		Ullin Ls.	70-800
		Fort Payne Fm.	0-500
		Borden Sts.-Springville Sh.	10-700
		Chouteau Ls.	0-50
		Hannibal-Saverton Sh.	1-50
DEVONIAN	UPPER	Grassy Creek Sh.	5-200
		Sweetland Creek Sh.	0-110
		Alto-Blocher Sh.	0-100
	MIDDLE	Lingle Ls.	20-120
		Grand Tower Ls.	0-200
		Dutch Creek Ss.	0-15
		Clear Creek Chert	0-600
		Backbone Ls.	30-150

(New Albany — spanning Upper Devonian shales)

Aquifer/Confining Bed: Valmeyeran — predominantly limestones with some sandstones, siltstones, shales, and dolomites; underlies most of central and southern Illinois; thin in west, more than 800 ft thick in north-central part of region, and more than 1,800 ft thick in southeastern Illinois; constitutes a drinking water source in outcrop areas in western part and southern margin of the state; variable yields, typically less than 30 gpm but locally up to 1,800 gpm; highly mineralized at depth away from outcrop area.

Confining Bed: New Albany — black, gray, and green shale; covers almost entire southern half of the state; over 300 ft thick.

System	Series	Formation	Thickness (ft)
CAMBRIAN	CROIXAN	Franconia Fm.	50-250
		Ironton Ss.	0-150
		Galesville Ss.	0-100
		Proviso Sts.	
		Eau Claire Fm.	250-600
		Lombard Dol.	
		Elmhurst Ss.	
		Mt. Simon Ss.	500-2800

*Aquifer/Confining Zone: Franconia — dolomite, shale, and interbedded sandstone with sandstone most prominent in north; thickness increases southward to maximum of 400 ft; yields moderate to small amounts of water; a source of drinking water in west-central and northern third of the state; near southern margin or region unit is tight and acts as confining bed.

*Aquifer: Ironton-Galesville — fine to coarse-grained sandstone, some dolomitic sandstone; generally exceeds 100 ft thick; thins southward in central Illinois and grades to dolomite; basal zone is most favorable water-producing zone; yields large quantities of water; major source of drinking water in bedrock; becomes moderately mineralized in central Illinois and highly mineralized at southern limit.

*Confining Bed: Eau Claire — shales, siltstones, dolomites, and dolomitic sandstones; underlies entire region; exceeds 700 ft thick in southeast part of region and exceeds 1,000 ft in southeastern Illinois.

*Aquifer: Elmhurst-Mt. Simon — sandstone with some interbedded shale; underlies entire state, locally not deposited over Pre-Cambrian highs; more than 2,500 ft thick in northeastern Illinois; thins southward to less than 500 ft in southern Illinois; sandstones range from fairly permeable to very tight; upper parts constitute a source of drinking water in northern one-fifth of Illinois; mineral content can increase one to two orders of magnitude across this unit from top to bottom.

PATTERNS

- Limestone
- Dolomite
- Anhydrite, Gypsum
- Breccia
- Sandstone, Sand
- Gravel, Granules
- Siltstone, Silt
- Shale, Clay
- Black Shale
- Coal
- Underclay
- Chert

				Unit	Thickness (ft)	Description
SILURIAN		LOWER		Grassy Knob Chert	120-250	
	NIAG-CAY.			Bailey Ls.	250-450	**Aquifer: Silurian-Devonian (Hunton Megagroup)** — predominantly limestone with dolomite, siltstone, shale, and chert; thickness of 200 ft in the west to more than 1,800 ft in the southeast part of the region; constitutes drinking water source from fractured limestones in outcrop areas; Devonian cherts are sources for small to moderate supplies in southern and western parts of the region; well yields range from moderate to maximum of 300 gpm; away from outcrop areas units are highly mineralized.
				Moccasin Springs Ls.	100-800	
				St. Clair Ls.	20-100	
		AL.		Sexton Creek Ls.	15-80	
				Edgewood Ls.	0-60	
				Girardeau Ls.	0-40	
ORDOVICIAN	CIN.		Maquoketa	Brainard Sh.	0-150	**Confining Bed: Maquoketa** — mainly shale, some limestone and sandstone; underlies almost all of southern Illinois; more than 300 ft thick along eastern margin of state.
				Fort Atkinson Ls.	0-50	
				Thebes Ss.		
				Scales Sh.	50-150	
	CHAMPLAINIAN		Dec. Kimms. Galena	Cape Ls.	0-20	
				Wise Lake Ls.	0-50	
				Dunleith Ls.	100-150	
				Guttenberg Ls.	0-20	**Aquifer/Confining Bed: Galena-Platteville** — dominantly limestone, some dolomite, shales and cherts; a possible source of drinking water where these units from upper bedrock along the western-southwestern boundary of Illinois; thickness increases southward to a maximum of about 725 ft in southeastern part of region; away from outcrop area this sequence contains highly mineralized water.
				Kings Lake Ls.	0-15	
				Spechts Ferry Sh.	0-15	
				Quimbys Mill Ls.	15-35	
			Plattin Subgroup / Platteville	Nachusa Ls.	40-75	
				Grand Detour Ls.	50-210	
				Mifflin Ls.	15-120	
				Pecatonica Ls.	0-140	
			Ancell	Joachim Dol.	60-385	**Aquifer/Confining Bed: Joachim-Dutchtown-St. Peter (Ancell Group)** — dolomite, limestone, sandstone with a few anhydrite or gypsum deposits; underlies southern half of Illinois; reaches maximum thickness of 700 ft in the southern tip of the region; St. Peter thins southward as carbonate units become thicker; constitutes a limited source of drinking water in extreme western Illinois.
				Dutchtown Ls.	0-200	
				St. Peter Ss.	65-300	

PRECAM.

⊗ ⊗ ⊗ Geodes, Drusy Quartz

· · · · · Oolite

Till

Igneous, Metamorphic

* Description also applies to southern region of the state.

Abbreviations:

Al.	Alexandrian
Cay.	Cayugan
Cin., Cincin.	Cincinnatian
Dec.	Decorah
Kimms.	Kimmswick
K., Kind.	Kinderhookian
Paleo.	Paleocene
Pli.	Pliocene
Precam.	Precambrian
Ser.	Series
Sys.	System
I.	Injection zone
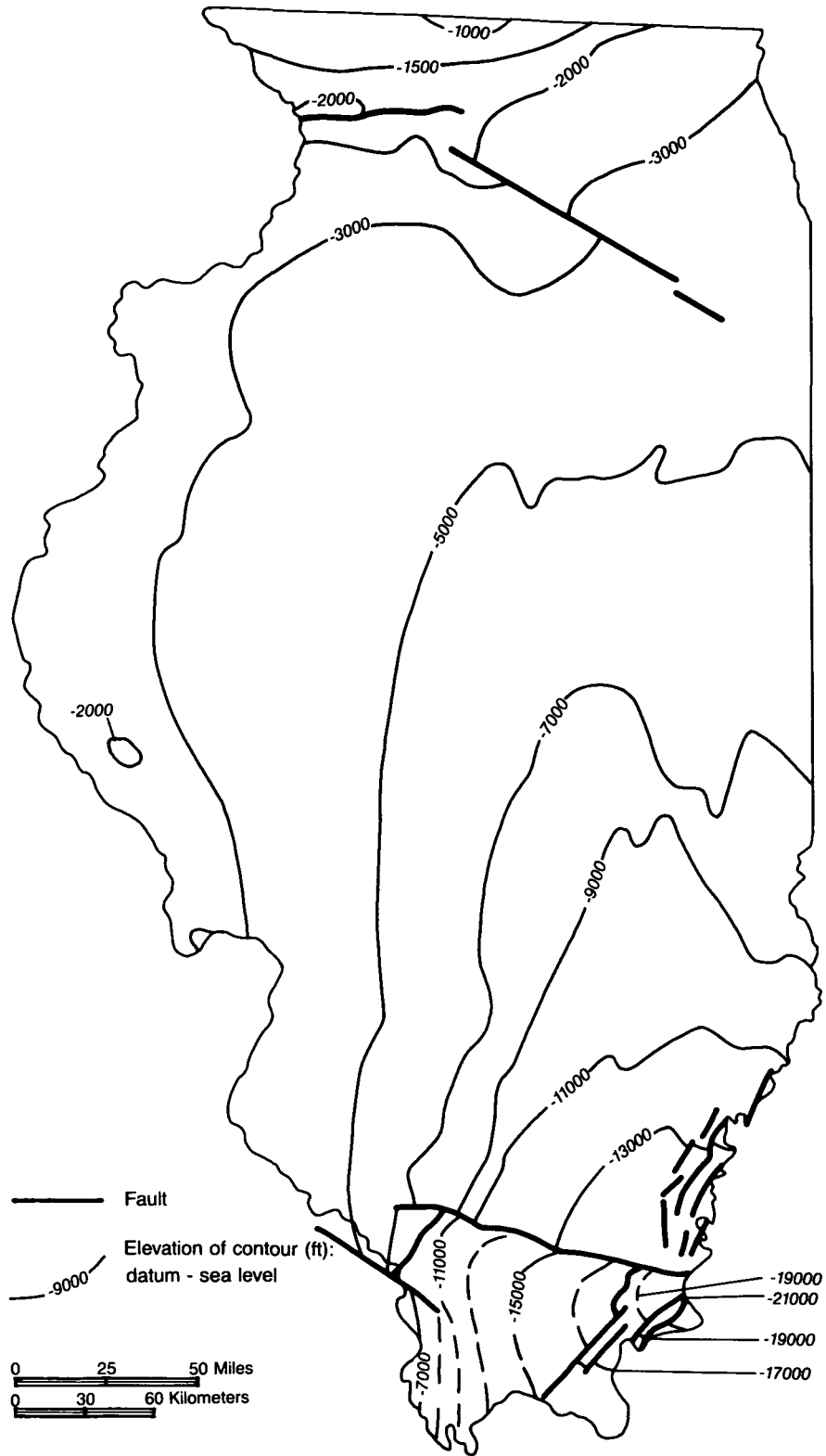
**Figure 2-4** Morphology of the top of the Precambrian (modified from Sargent and Buschbach, 1985).
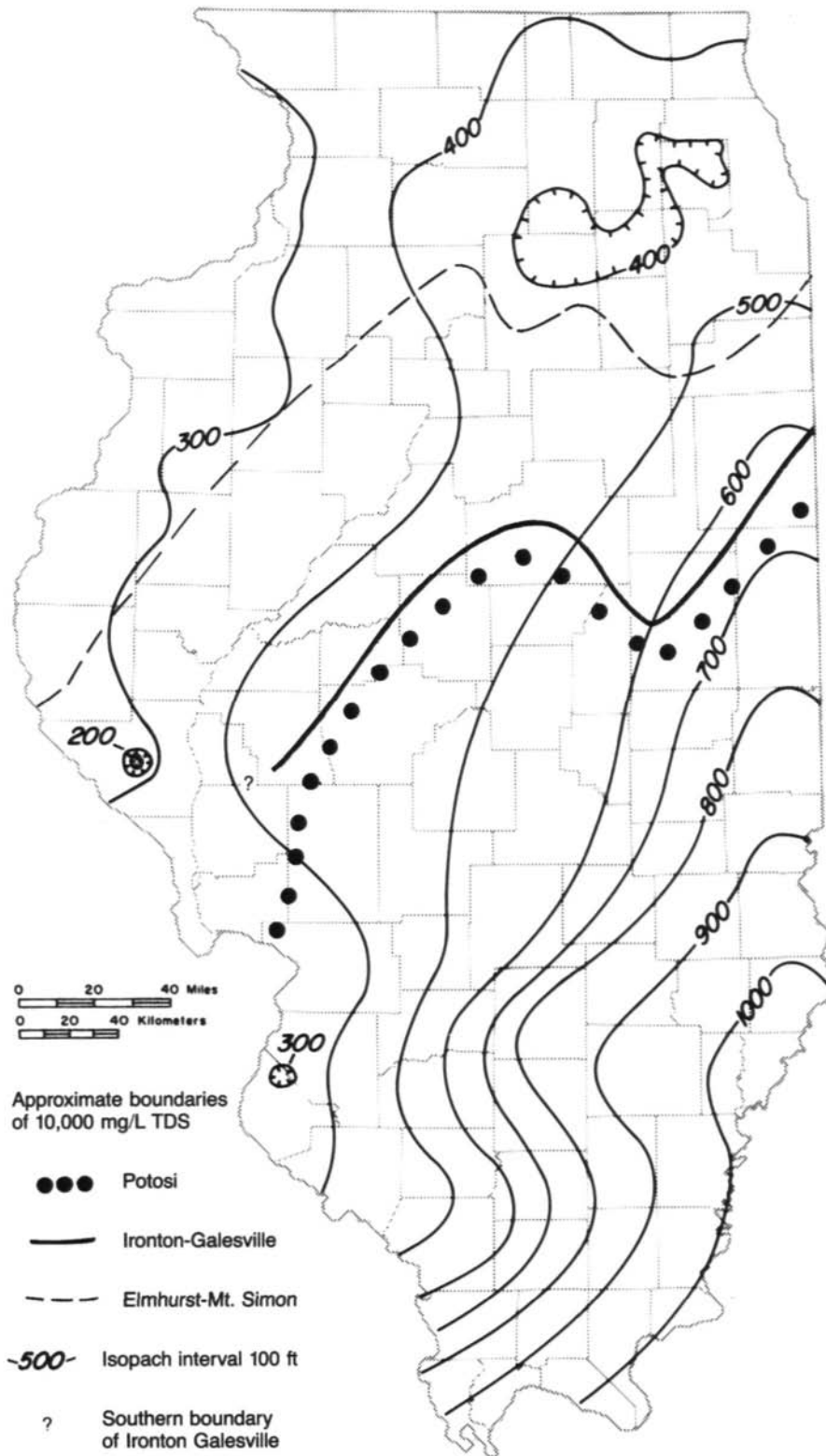
Figure 2-5 Thickness and distribution of the Eau Claire Formation (after Willman et al., 1975) and southern boundaries for <10,000 mg/LTDS water in water-yielding units of the Cambrian System.
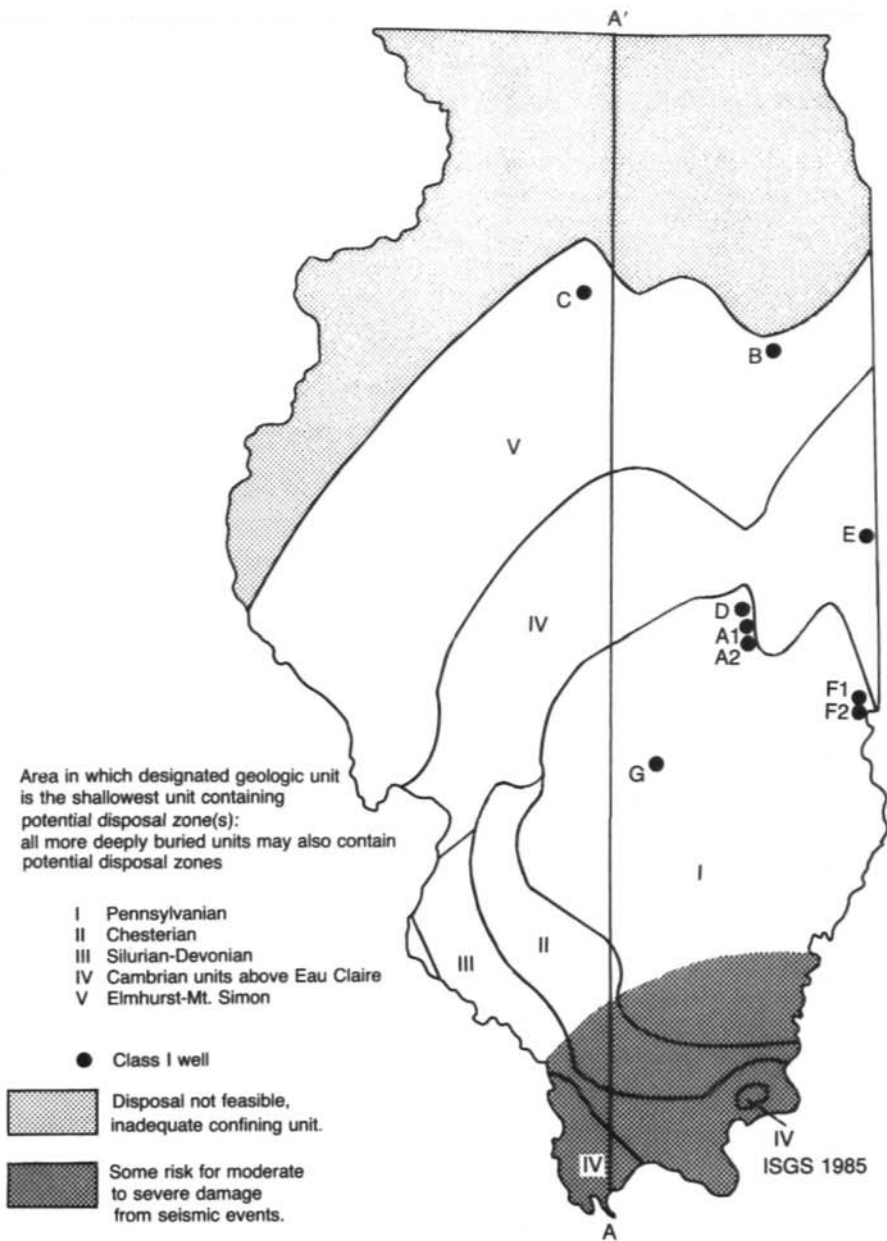
Figure 2-6 Uppermost geologic units with potential disposal zones for Class I wells.

of the Ironton-Galesville grade southward into dolomite (Knox Dolomite), causing a significant differential increase in mineral content of the formation water (Figure 3-3) and hydraulic head of these sandstones over mineral content and hydraulic head in the overlying Eminence-Potosi disposal zone. Several tens of miles to the north the mineral content and head values are similar for these two units.

Porosity and permeability values measured in gas storage reservoirs for the Mt. Simon range from 8 to 13 percent and 8 to 55 millidarcys, respectively. Average values are significantly lower toward the center of the basin where the Mt. Simon lies at great depth. This same pattern is also observed in the other Cambrian units. Measurements made in the Ironton and Galesville intervals in gas storage fields show that the average porosity and permeability values for the Ironton are low (6% to 10% and <0.1 to 128 millidarcys, respectively) and those for the Galesville are relatively high (17% to 20% and 200 to 650 millidarcys). The Franconia shows a range in average values of 3 to 11 percent porosity and <0.01 to 16 millidarcys permeability. Average porosity values for the Eau Claire range from 2 to 9 percent and average permeability values are <0.0002 to 0.9 millidarcys.

2-12

Boundary between USDW and
aquifers with groundwater
containing > 10,000 mg/L TDS
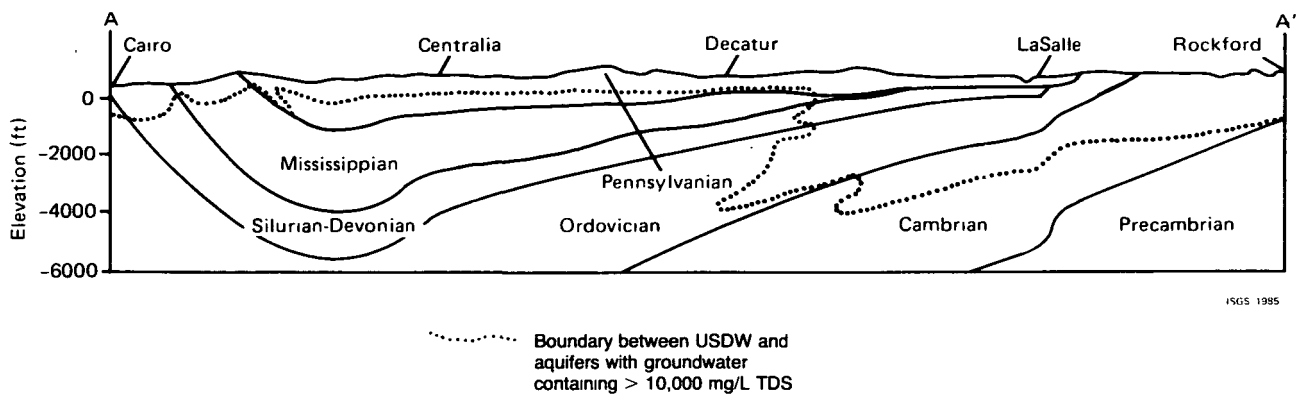
Figure 2-7 Basal boundary of USDW in north-south cross section from Rockford to Cairo (see Figure 2-6 for line of cross section).

Csallany (1966) reports average specific capacities in the Ironton-Galesville of 4.0 gpm/ft for water wells located in the heavily pumped area in eastern Kane County.

Ordovician System

Ordovician strata cover the entire state except along the Sandwich Fault, where erosion has removed them. These rocks have a thickness ranging from 700 feet in the north, where they are not affected by preglacial erosion, to more than 6000 feet near the Ohio River. The gradual thickening to the south is attributed to more rapid subsidence southward into the central part of the Illinois Basin and also to less erosional loss of accumulated sediment in the rapidly subsiding areas.

Dolomites and limestones, having some interbedded sandy zones, and four distinct sandstones represent the principal lithologies in the lower two of three series of this system. The sandstones are associated with the transgression of seas northward across erosional surfaces. The upper series consists of fine-grained clastics (mostly shale) and some dolomites. Units in this system were potential targets for disposal at several well sites but did not have adequate injection capacity.

Prairie du Chien Group. The Prairie du Chien Group of the Canadian Series consists of two dolomite-cherty dolomite formations and several sandstones. They thicken gradually southward from an erosional feather edge in the vicinity of the Sandwich Fault to a maximum of more than 2500 feet near the Ohio River. The basal sandstone is widespread but rarely exceeds a thickness of 20 feet. The New Richmond Sandstone lies between the dolomite formations in an area extending southwestward from the Sandwich Fault in La Salle County and bounded on the east by a line that can be drawn from Kankakee to St. Louis. The upper dolomite unit, the Shakopee Formation, accounts for most of the southward thickening of this group. The tight dolomites in this group are the confining interval for the Class I wells utilizing the Eminence-Potosi disposal zone. There is a very limited potential for disposal in this group.

Ancell and Galena-Platteville Groups. The units in the Champlainian Series consist of a basal sandstone-dolomite sequence (Ancell Group) and the overlying Galena- Platteville Dolomite Groups. The St. Peter Sandstone has a thickness range of 100 to 200 feet across the state, but where valleys were cut into the underlying dolomites prior to deposition it may be twice as thick. As the deposition of this fine-grained, well-sorted sandstone moved northward with a transgressing shoreline, shaly limestone of the Dutchtown Formation and subsequently sandy and clayey dolomite of the Joachim Formation accumulated in the south to a thickness approaching 600 feet near the Ohio River. Above these units the Platteville Group accumulated as a clayey dolomite ranging in thickness from less than 50 feet near the Mississippi River in west-central Illinois to more than 600 feet in the southeast. The Galena Dolomite Group has a thickness of 125 feet in the south and increases to more than 250 feet in northwestern Illinois. Figure 2-8 is a structural morphology map drawn on the top of the Galena, a well-defined structural surface in Illinois. The St. Peter has a somewhat limited potential for injection because of its low to moderate injection capacity.

Legend:

Approximate boundary of 10,000 mg/L TDS

- - - Galena

— · — St. Peter

Galena absent or top eroded

Fault, downthrown side indicated

D Desplaines Disturbance

G Glasford Disturbance

Elevation contour; contour interval 200 ft, 1000 ft in southern Illinois
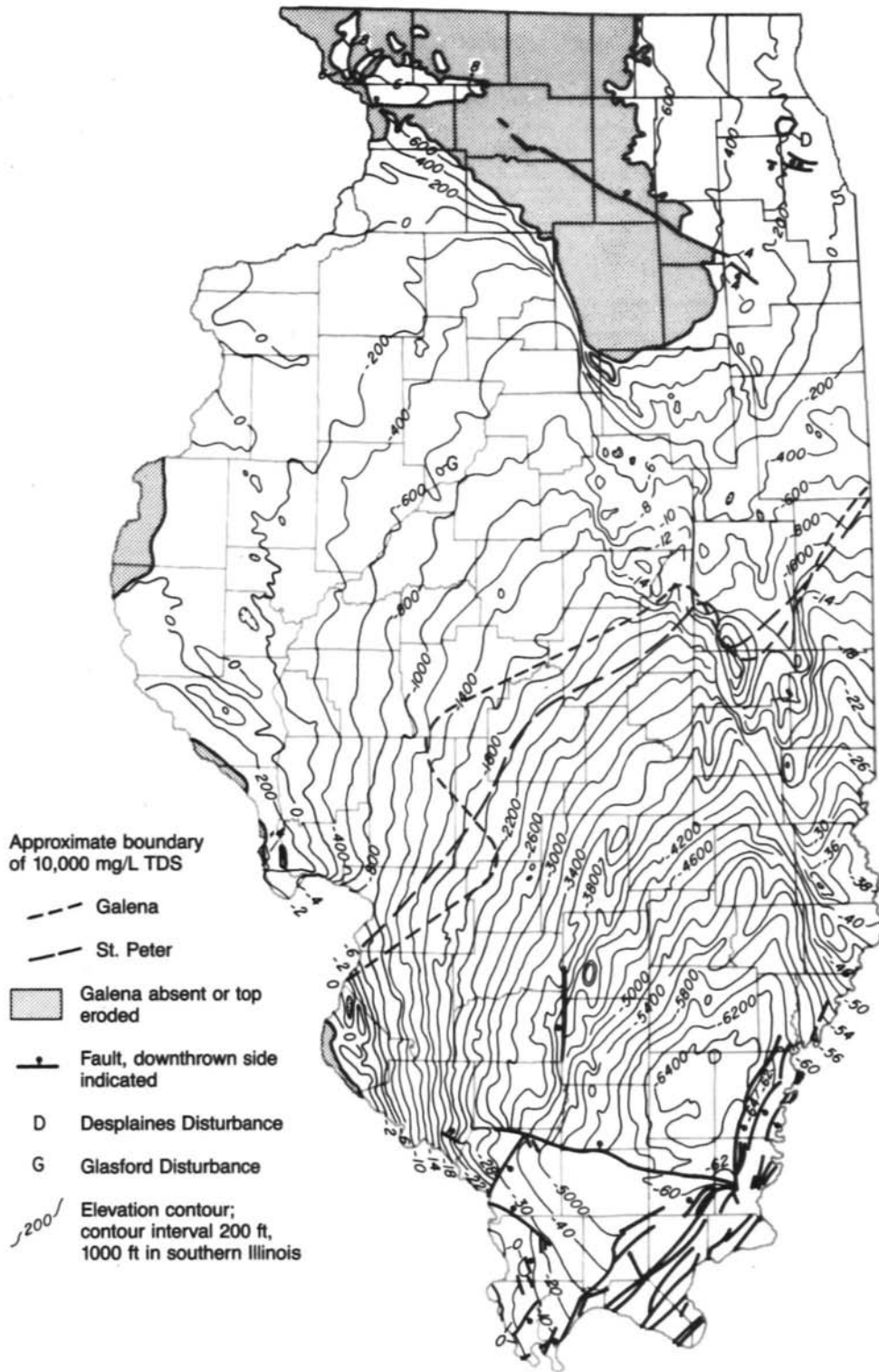
Figure 2-8 Morphology on the top of the Galena Group (Willman et al., 1975) and southern boundaries for 10,000 mg/L TDS in the Galena and St. Peter.

Maquoketa Group.   The Maquoketa Shale Group of the Cincinnatian Series consists of two shale units and an interbedded shaly limestone-dolomite. Figure 2-9 shows the thickness and distribution of this rock group in Illinois. This sequence of units has been identified as a major confining zone in the Illinois Basin.

Hydrogeologic Characteristics of Ordovician System.   At shallow depths all the units except the shales provide water supplies to wells penetrating them. In general, only the sandstones yield moderate to large supplies, typically less than 200 gpm/ft. In the northern third to half of the state, the Ordovician dolomites, the St. Peter, and the Cambrian units above the Eau Claire are combined into one large aquifer group (Visocky et al., 1985). This sequence of units acts as a mappable aquifer because there is adequate, though limited, permeability through the carbonate units in this aquifer group. To the south the permeability in all the Ordovician units decreases, and units with low permeabilities act as confining intervals.

The permeable character of the St. Peter Sandstone throughout the northern and central part of the state has allowed southward movement of fresh water for a considerable distance from recharge areas. High hydraulic heads that developed during glaciation appear to have displaced the brines southward, thus positioning fresh water in the St. Peter beneath very mineralized water in the shallower Devonian, Silurian, and Mississippian units. For example, in Macon County, water in Mississippian units is 30 times more mineralized than water in the St. Peter, which lies at twice the depth below the surface (Figure 2-7). The southernmost position for encountering water with less than 10,000 mg/L TDS in the St. Peter and the Galena is shown in Figure 2-8. Restricted groundwater circulation and possibly reduced permeability is reflected by the northwestward shift in the boundary for the Galena Group in the central part of the state. The position of the 10,000 mg/L TDS boundary for the Prairie du Chien Group lies somewhat further north.

Specific capacities for the St. Peter are reported to range from 1.5 gpm/ft in northwestern Illinois to less than 0.9 gpm/ft south of Chicago (Csallany, 1966). Specific capacities for the Galena-Platteville, where it is buried beneath the Maquoketa in northern Illinois, average about 0.2 gpm/ft.

Porosities in the dolomites in the southern half of Illinois are very low and generally lie below an average value of 10 percent. Permeabilities generally do not exceed 1 to 30 millidarcys in the more permeable horizons of the dolomites. Very low permeabilities exist for the tight, unfractured rock intervals. Porosities across vertical sections of the St. Peter are quite variable, but in the more permeable zones average values obtained from multiple wells at selected sites in the northern half of the state range from 12 to 17 percent. Permeabilities, likewise, are variable and average values have been reported to range from 25 to 250 millidarcys.

Silurian and Devonian Systems

The Silurian and Devonian Systems are discussed together because the limestone and dolomite units (Hunton Limestone Megagroup) of these systems are similar in character and act as a single hydrologic unit. The combined thicknesses of the two systems, including the overlying Devonian and Mississippian age New Albany Group, range from an erosional featheredge along the Mississippi River and northern Illinois to more than 2100 feet in Massac County. The Hunton Megagroup has a maximum thickness of 1800 feet in the south (Figure 2-10). Dolomites predominate in the north and limestones in the south.

Hunton Megagroup.   The Silurian portion of the Hunton increases in thickness eastward from an erosional margin along the Mississippi River to more than 700 feet in east-central Illinois. The Niagaran Series, the principal unit of the Silurian, consists of three dominant carbonate facies: (1) shaly dolomite in the south; (2) intermediate-purity carbonate in the north-central and northeast; and (3) relatively high-purity carbonate in the northwest. Reefs occur in all the series, and in the south many reefs are oil-bearing.

The Devonian System is represented in the Hunton by the Lower and Middle Devonian Series. The Lower Devonian consists of siliceous limestone, dolomite, and chert deposited in the southern third of the state; it thickens southward to a maximum of more than 1200 feet in Massac County. The Middle Devonian, which consists of relatively pure limestones and dolomites, covers much of the southern two-thirds of Illinois. This Series is thin in the central and southwest regions and
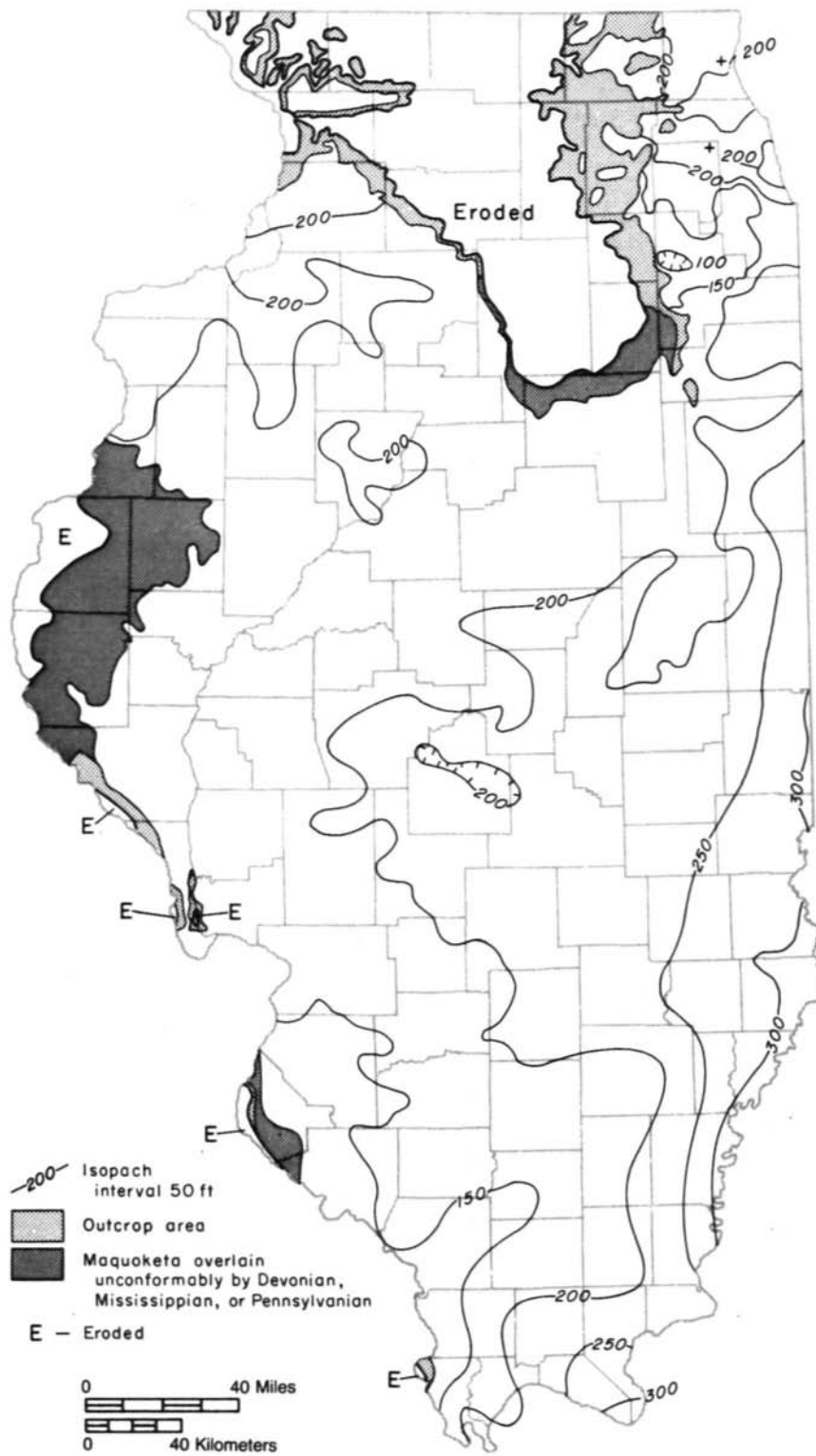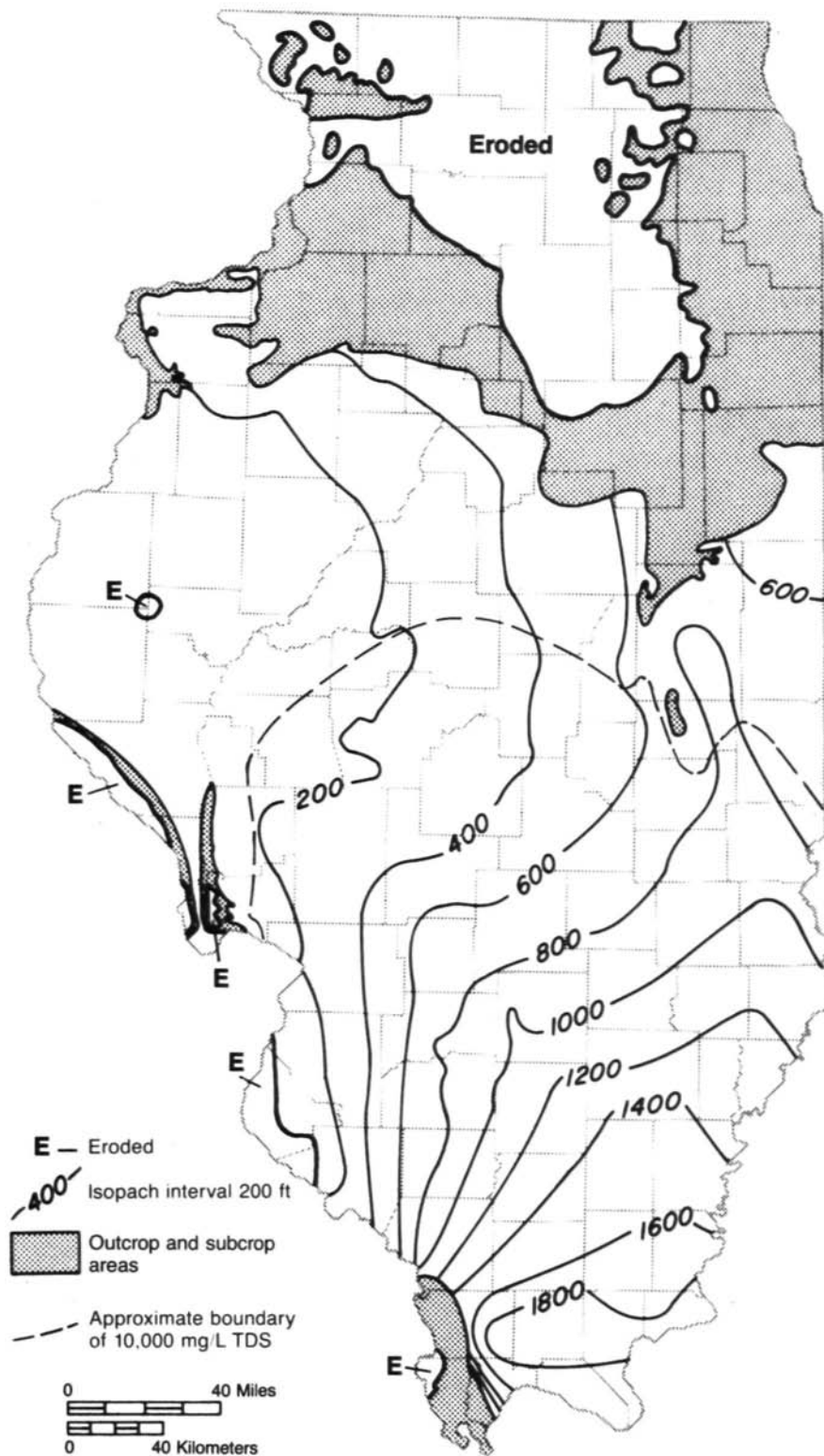
Figure 2-9 Thickness and distribution of the Maquoketa Shale Group (Willman et at., 1975).

Figure 2-10 Thickness and distribution of the Hunton Megagroup (after Willman et al., 1975), and boundary for 10,000 mg/L TDS in the Hunton.

Figure 2-11 Thickness and distribution of the New Albany Shale Group (Bergstrom et al., 1980).

thickens gradually toward the southeast to more than 400 feet in Gallatin County. The Devonian was not deposited in the vicinity of the Sangamon Arch (Whiting and Stevenson, 1965). One Class I well injects into limestones in this system.

New Albany Group.   Sedimentation during late Devonian and early Mississippian time involved the widespread accumulation of black, gray, and green shales with some limestones and siltstones. The thickness and distribution of the units in this group, which is a major confining interval, are shown in Figure 2-11.

Hydrogeologic Characteristics of Silurian and Devonian Systems.   Fresh water is found in the units of the Hunton Megagroup throughout the northern third of the state, along the La Salle Anticlinal Belt in east-central Illinois, at Hicks Dome in Hardin County, and in small areas at the margins of the Illinois Basin where these units lie near the surface. Yields are small to moderate and tend to decrease with increased depth of burial. Figure 2-10 shows the position at which the 10,000 mg/L TDS boundary can be expected. On the Illinois basin side of this boundary there is a rapid increase in mineral content toward the center of the basin. The mineral content increases from 20,000 to 130,000 mg/L TDS across Macon County. A maximum of 150,000 mg/L is reported in White County (Meents, 1952); however, Graf et al. (1966) determined a value of 216,100 mg/L for water from a deep Devonian test in the same area. In northern Macon County the water in the Hunton is up to ten times more mineralized than groundwater in the more deeply buried St. Peter Sandstone. The Maquoketa Shale Group is the confining unit separating these two aquifers.

Large variations in the degree of fracturing and solution development of fractures can be expected in these units, and these variations account for the wide range in yields to water wells. Specific capacity values may range from a fraction of a gallon per minute per foot of drawdown to more than several hundred gpm/ft. Specific capacities tend to be higher in Silurian than in Devonian units. Data from oil-producing areas indicate that porosities are low and permeabilities range from low to moderate for all carbonate reservoirs in these systems. Mast (1967) reports mean porosities and permeabilities of 13 percent and 40 millidarcys, respectively, for Ordovician (Galena), Silurian, and Devonian carbonate reservoirs in Illinois oil fields. Porosity values ranging from 12 percent to 19.5 percent and permeability values ranging from 50 to 300 millidarcys are reported by Ford et al. (1981) for 269 wells finished in Devonian carbonate reservoirs.

Mississippian System

This system covers the southern two-thirds of the state and crops out near the margin of the Illinois Basin along the Mississippi, Illinois, and Ohio Rivers and in a narrow band from Champaign through Iroquois Counties. Pennsylvanian units overlie this system on an erosional surface that has considerable relief and marks a significant truncation of Mississippian units in the northern part of the basin. A maximum thickness of about 3300 feet occurs in Williamson and Saline Counties (Figure 2-12). Thinning to the north is a product of both erosional truncation and depositional thinning of many units.

The middle part (Valmeyeran Series) and the upper part (Chesterian Series) of the Mississippian System are represented by a complex set of limestone, siltstone, sandstone, and shale units that accumulated in shallow to moderately deep seas. An upland area situated to the northeast supplied the clastic sediments found in these units. Shales and siltstones in the lower part (Kinderhookian Series) are discussed under the Silurian-Devonian System. The thin limestone at the top of the Kinderhookian (Chouteau Limestone) has a wide distribution across the basin. Carbonate and sandstone units at and near the surface offer a limited potential for water supply. However, in the Illinois Basin there is significant oil production from these units. Two Class I wells utilize this system for disposal. A third well was proposed for construction in mid-1987 to replace one of these two wells.

Valmeyeran Series.   The Valmeyeran Series has a basal deposit (Borden Siltstone) of deltaic, fine-grained clastics and some localized sandstones that developed southwestward across Illinois from central Indiana. Contemporaneously, limestone accumulated to the north (Burlington and Keokuk Limestones) and to the south (Fort Payne chert and Ullin Limestone) of this delta. These units are overlain by widespread limestones (Salem, St. Louis, and Ste. Genevieve Limestones) that exhibit numerous lateral gradations in lithology. The top of the Valmeyeran is capped by a thin but widespread sandstone (Aux Vases Sandstone) that marks the base of significant cyclical sedimentation. Valmeyeran units have a maximum aggregate thickness in the southeast and thin
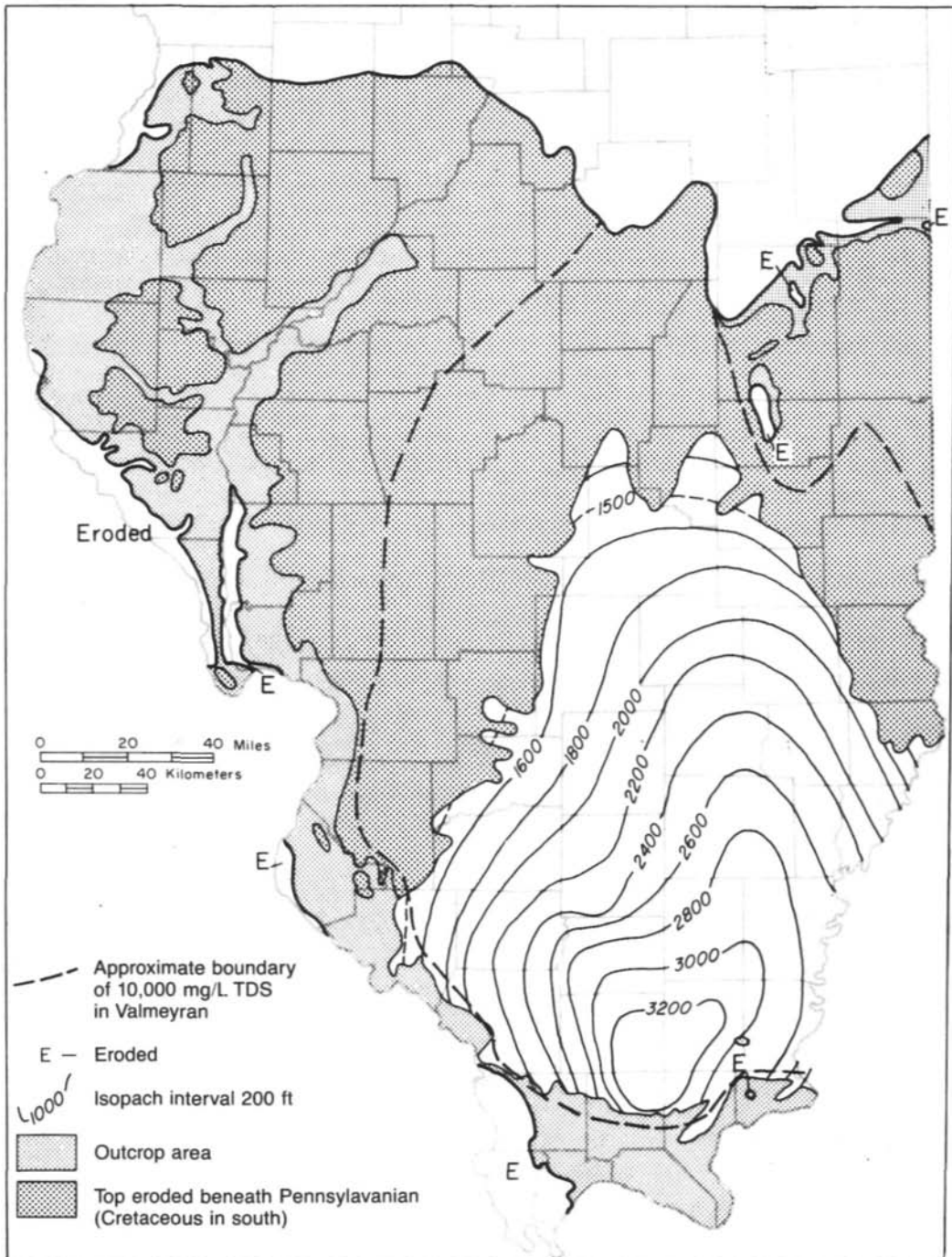
Figure 2-12 Thickness and distribution of the Mississippian System (Willman et al., 1975), and the boundary for 10,000 mg/L TDS in the Valmeyeran.

depositionally to 600 feet in the north and the west before pre-Pennsylvanian erosional truncation reduces the thickness of this series to a feather edge (Figure 2-12). The Salem Limestone receives waste injection from two Class I wells. There is extensive petroleum production and disposal of oil field brine in Valmeyeran units.

Chesterian Series.   The Chesterian Series consists of multiple cyclic sequences of shale-lime stone and shale-sandstone formations. These formations accumulated during cyclic changes in relative sea level. Clastic sediments were transported into the state by a southwest-trending river system and deposited in delta, nearshore, and offshore environments as the delta shifted constantly

2-20

along an oscillating northwesterly trending shoreline. The shale-limestone units accumulated in the offshore and to some extent nearshore marine environments. The rock types in this series consist of approximately 50 percent shale, 25 percent limestone, and 25 percent sandstone. Figure 2-13 shows the thickness and distribution pattern of the series and also reflects the topographic relief of pre-Pennsylvanian erosional valleys that developed in the top of the Chesterian. The columnar section included in this figure shows the interrelationships and lithologies of the formations.

Petroleum production and oil field brine disposal activity take place in the sandstones having the higher permeabilities. Production also occurs in some of the limestone units. The more important sandstone aquifers in the Chesterian include the Palestine, Waltersburg, Tar Springs, Hardinsburg, and Bethel Sandstones.

Hydrogeologic Characteristics of Mississippian System.   Mineralization of groundwater in the Valmeyeran and Chesterian units of the Mississippian System ranges from low in the outcrop areas to a maximum of 100,000 to 160,000 mg/L TDS in the Illinois Basin. Groundwater with low TDS occurs only in and near the outcrop areas except in the broad area between and adjacent to the Illinois and Mississippi Rivers. Detailed maps showing the heavy brine concentrations in the principal aquifers (oil pay zones) have been published by Meents et al. (1952). Figures 2-12 and 2-13 show the estimated position at which 10,000 mg/L groundwater is encountered in the Valmeyeran and Chesterian, respectively.

Water supply development in the Chesterian is limited essentially to the outcropping areas of this series and locally may extend a few miles downdip from the outer margin of the Pennsylvanian units. Sandstones and fractured limestones have provided very small to moderate (<1 gpm to >70 gpm) yields to wells. Specific capacities for wells finished in sandstones have a reported range of 0.08 to 1.1 gpm/ft and a median value of 0.3 gpm/ft (Csallany, 1966). Brine wells finished in the Tar Springs and Bethel Sandstones that were used as a water source for water flooding operations in the oil fields have reported yields of 12 to 52 gpm, with large drawdowns (Pryor et al., 1957).
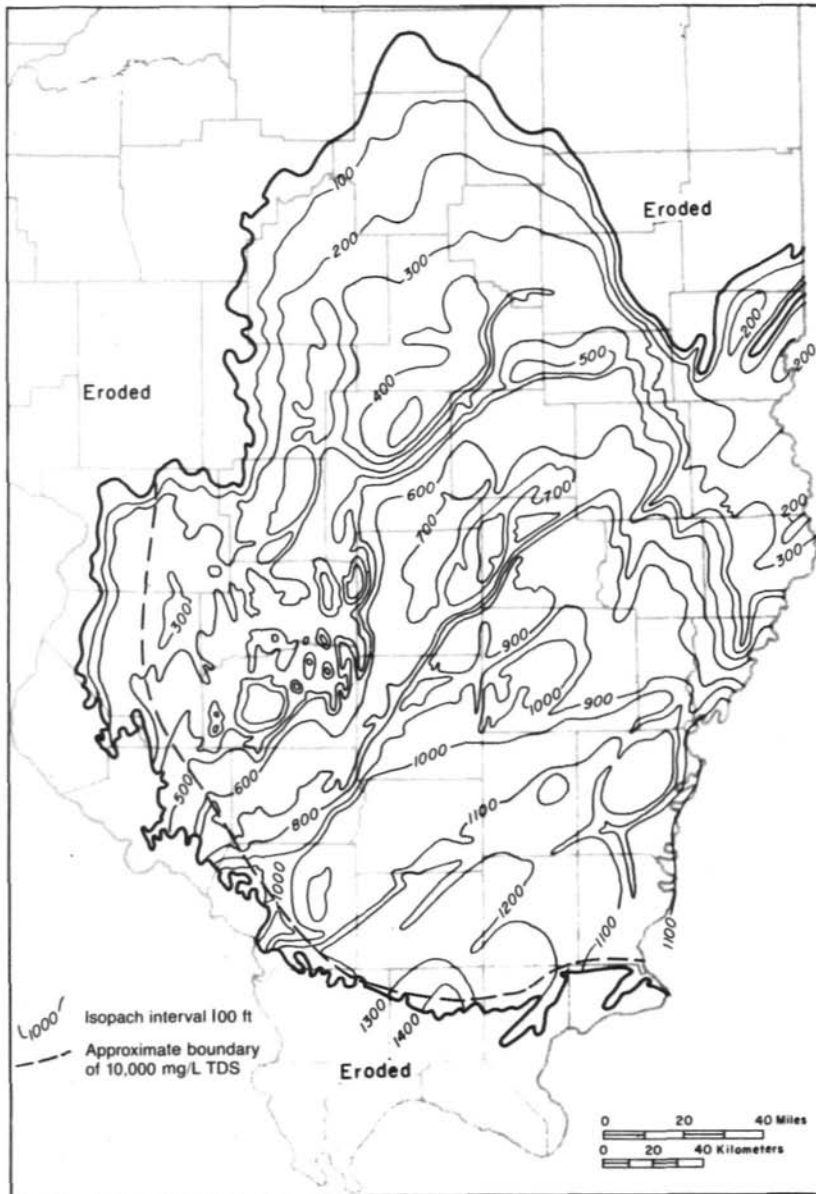
Water supply development has been more extensive in the Valmeyeran than in the Chesterian. Yields typically range from a few gpm to more than several hundred gpm from fractured limestones. Maximum water well yields of 25 to 75 gpm have also been reported for a sandstone (Aux Vases Formation) in this series. Median specific capacities for water wells range from 0.12 gpm/ft for the limestones in the upper Valmeyeran to 1.02 gpm/ft for the Burlington-Keokuk Limestone. The capacity of the more deeply buried, brine-filled units is expected to be smaller than that reported for wells yielding potable water.

Data from oil producing and oil field brine disposal horizons in both series show moderate to relatively low porosities and relatively low permeabilities. Porosities average 16 to 18 percent (Whiting et al., 1964) and range from 10 to 24 percent (Ford et al., 1981). Permeabilities for oil-producing Chesterian sandstones 10 to 20 feet thick range from 68 to 231 millidarcys (Whiting, 1964). Ford et al. (1981) summarized ranges of 11 to 480 millidarcys for Chesterian sandstones and 11 to 3000 millidarcys for Valmeyeran carbonates used for oil field brine disposal. Mast (1967) reported an average permeability of 206 millidarcys for Valmeyeran limestones. Injection rates reported for limestone reservoirs under water flood operations tend to be larger than those for sandstone reservoirs (VanDenBerg et al., 1966).

Pennsylvanian System

About two-thirds of the bedrock surface in the state consists of rocks of the Pennsylvanian System; most are covered with glacial deposits. The relatively flat-lying units are subdivided into seven formations and three broad groups (Figure 2-1). A maximum thickness of about 2500 feet is attained in Wayne County. More than 50 cyclic sequences having at least 500 identifiable units with distinct lithological characteristics have been mapped. This cyclic sedimentation represents a continuation of fluctuating sea levels that occurred in the Chesterian. The Herrin Coal (Coal No. 6) is a widely mapped marker unit in the Pennsylvanian (Willman et al., 1975).

More than 90 percent of the lithologies consist of clastic sediments. Shales and clays are the dominant lithologies and account for 25 to 70 percent of the thickness of the seven formations. Sandstones are dominant in only the two lower formations; in the other formations they contribute

Figure 2-13 Thickness and distribution of the Chesterian Series (after Willman et al., 1975), and the boundary for 10,000 mg/L TDS; columnar section shows formations.

less than 25 percent to formation thicknesses. Limestones and coals, which are most dominant in the Bond and Carbondale Formations respectively, represent <1 to 10 percent of the aggregate thickness of the upper five formations.

Sandstones offer the only significant source of permeability in this system; however, thin units and low permeabilities limit the potential for development of water supply and waste disposal. No Class I wells are finished in the Pennsylvanian. This system is used by the oil industry for water supply and brine disposal in many areas of the state. The coarser-grained sandstones are typically located in the south and southwest or are associated with channel facies deposits. Most channel deposits are narrow and have a sinuous, discontinuous pattern of occurrence. Sheet facies sandstones are fairly widespread, but tend to be thin, have a fine-grained texture, and grade laterally into siltstone or sandy shale.

The potable water zone is limited to the upper several hundred feet except in local areas and near the outcrop of the thick, permeable, basal sandstones in the south. These sandstones contain potable water to depths of 600 to more than 900 feet in a band 8 to 15 miles wide downdip from the southern-southwestern margin of this system. The base of the USDW in the Pennsylvanian typically lies at a depth of 400 to more than 1000 feet (see cross section in Figure 2-7). The areal distribution of units with heavily mineralized groundwater that lies below the USDW is shown in Figure 2-6.

The abundance of shale and clay units with low permeability provides thick confinement intervals for permeable sandstones within this system. The low permeability of the fine-grained clastics is demonstrated by the lack of fresh water penetration through the top of the system and into interbedded sandstones at shallow depth.

Yields to water wells in the Pennsylvanian range from very small to about 150 gpm. Yields in excess of about 25 gpm are not common except in the areas with thick sandstones in the south and southwest, where yields of 40 to 75 gpm are frequently reported. Specific capacities for selected groups of wells were shown by Csallany (1966) and Pryor et al. (1957) to range from 0.02 to 6 gpm/ft, with a median range of 0.32 to 0.43 gpm/ft. Porosity and permeability measured from core samples and wells associated with oil and gas production range from 9 to 25 percent and 10 to 1000 millidarcys, respectively. Porosities within most oil-producing sandstones are relatively uniform, averaging 17 to 20 percent (Whiting et al., 1964). In these sandstones permeability tends to range between 100 and 400 millidarcys and decreases as depth of burial increases.

Nonindurated Units

Throughout most of Illinois the bedrock surface is covered with nonindurated sediments of the Cretaceous, Tertiary, and Quaternary Systems. Sand and gravel deposits present in these sediments are a principal source of fresh water for domestic, agricultural, industrial, and public water supplies. Detailed geologic information for these systems is provided by Willman et al. (1975), Frye et al. (1970), Kolata et al. (1981), and Berg and Kempton (1984).

Cretaceous and Tertiary Systems.   Clastic rocks of the Cretaceous System have a maximum thickness of about 500 feet along the Ohio River and thin rapidly northward to a featheredge. In scattered areas of Adams and Pike Counties, deposits similar in character to glacial units reach thicknesses of 100 feet. Sands and some silts, clays, and gravels are the principal lithologies. In the south, the Cretaceous units are covered by Tertiary sands and silty clays. The Tertiary has a maximum thickness of 400 feet in the vicinity of Cairo and also thins rapidly to the north. Figure 2-1 shows the distribution of these units.

Quaternary System.   Extensive deposits of glacial drift, loess, alluvium, and residual soil of the Quaternary System cover the bedrock virtually everywhere in Illinois. The Glacial Map of Illinois (Willman and Frye, 1970) and the Quaternary Deposits Map (Lineback, 1979) show the distribution and character of the surficial deposits of the state. Thicknesses range from zero to about 600 feet (Figure 2-14) (Piskin and Bergstrom, 1975). These deposits are composed primarily of glacial units whose thickness is strongly affected by a system of valleys on the bedrock surface (Figures 2-14 and 2-15).
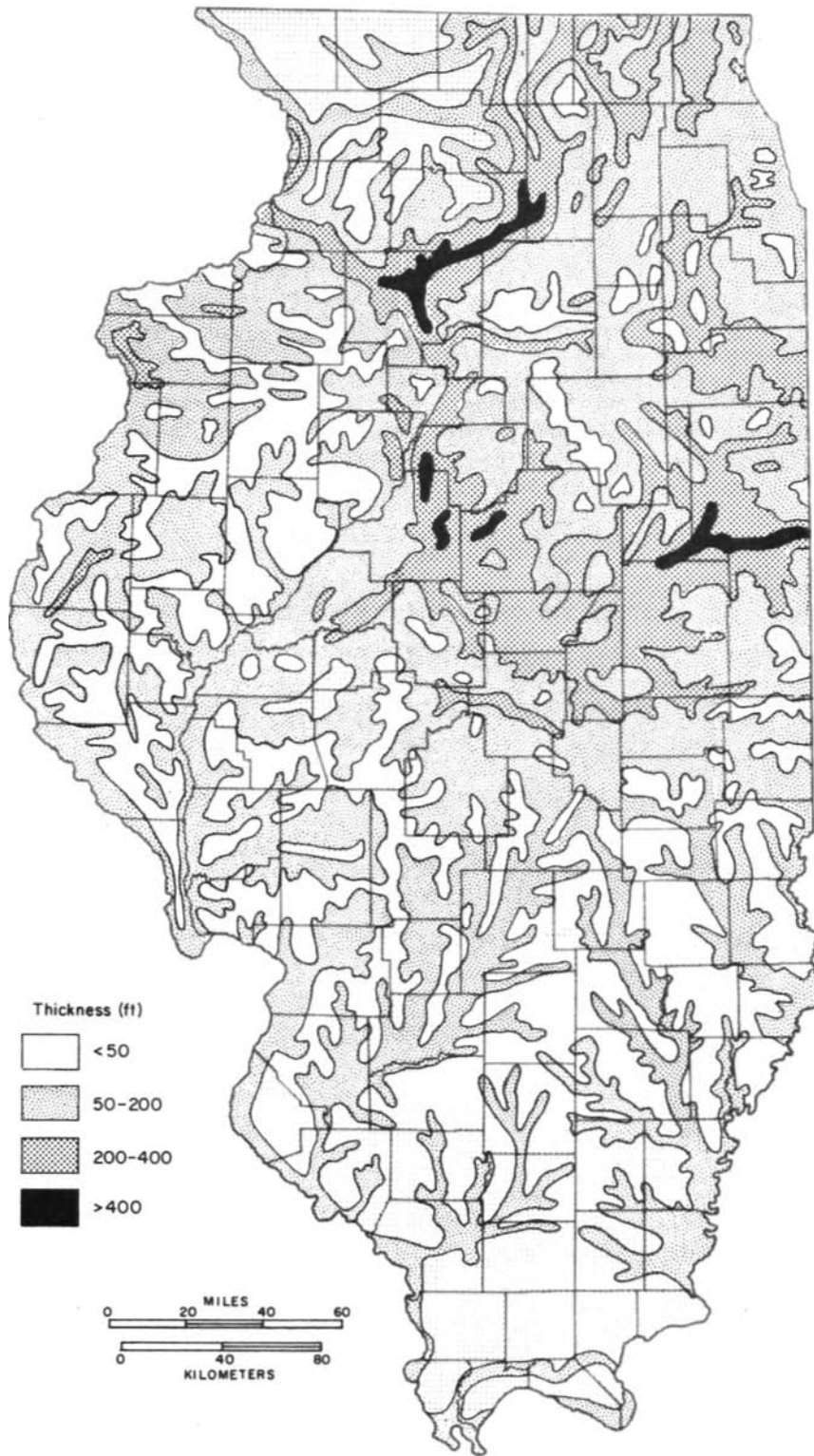
Figure 2-14 Thickness of Quaternary deposits (after Piskin and Bergstrom, 1967; Willman and Frye, 1970).
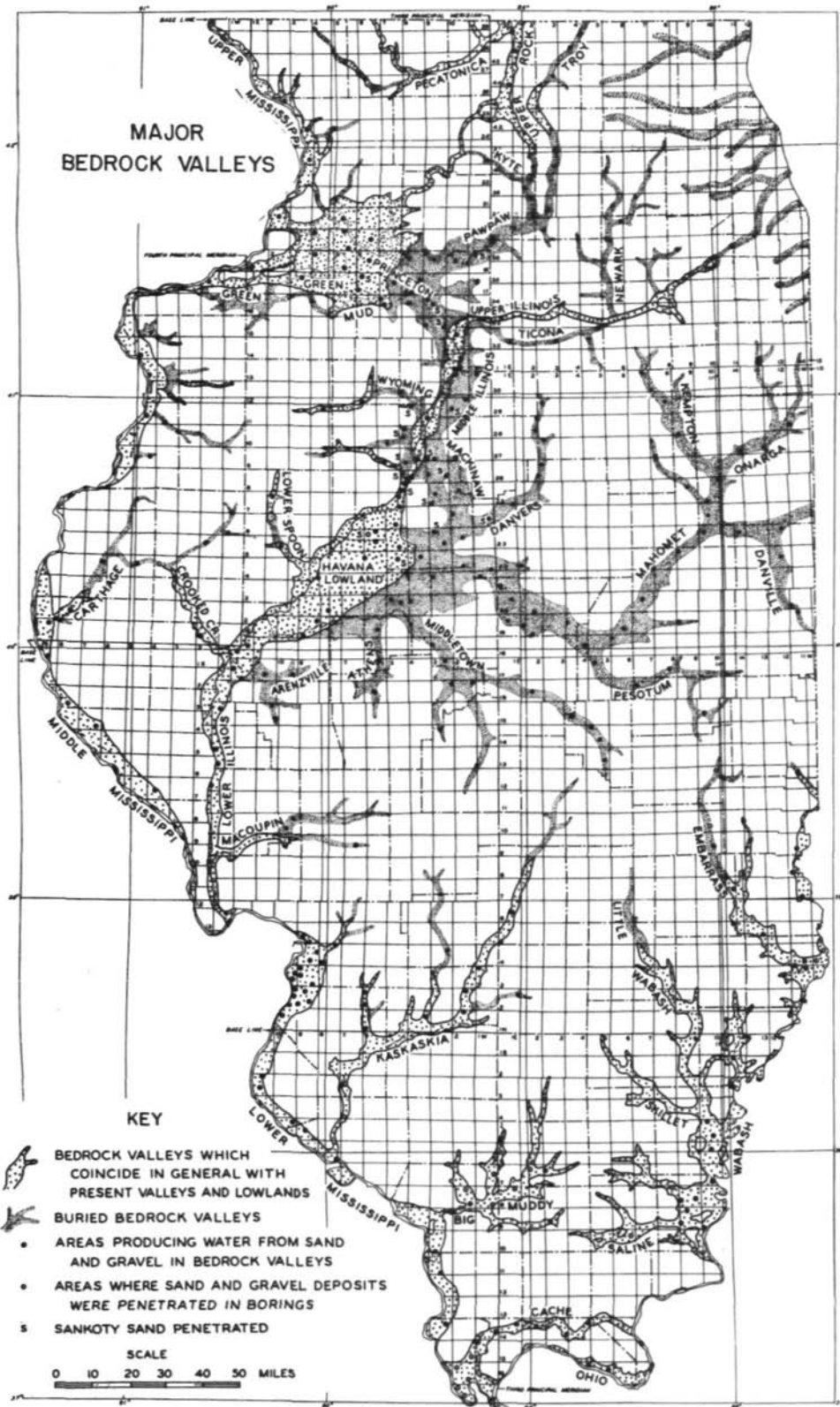
Figure 2-15 Major bedrock valleys (Horberg, 1950).

Geologic Units Having Potential Waste Disposal Zones

Potential injection zones and their associated confining units occur within a number of broadly defined geologic units. The permeable zones may form either a small or large portion of each unit, as can the confining intervals; however, confining intervals tend to have larger aggregate thicknesses. Table 2-1 lists units that may provide suitable injection zones in selected areas of the state. The associated confining unit for each disposal unit is also shown. The areal distribution for potential disposal units can be estimated from the information given on the map in Figure 2-6. Each area on the map represents the uppermost unit that may contain a potential disposal zone(s). All geologic units buried at greater depth than the mapped unit may also have potential disposal zones. Figure 2-3 provides a summary of geologic and hydrogeologic information for the units in each rock system.

Table 2-1   Geologic units with significant potential for disposal zones, and primary confining intervals.

SYSTEM	SERIES/GROUP	FORMATION	Potential Injection Interval	Confining Interval
PENNSYLVANIAN			M	
MISSISSIPPIAN	Chesterian		M	
	Valmeyeran		P	
DEVONIAN	New Albany Group			
	Hunton Megagroup		P	
SILURIAN				
ORDOVICIAN	Maquoketa Group			
	Galena-Platteville Groups			
	Ancell Group	St. Peter	M	
	Prairie du Chien Group		M	
CAMBRIAN	Knox Megagroup	Eminence Potosi	P	
		Franconia		
		Ironton-Galesville	M	
		Eau Claire		
		Mt. Simon	P	
PRECAMBRIAN				

ISGS 87

sandstone	shale and siltstone	P Principal disposal interval
limestone and dolomite	igneous and metamorphic	M Minor disposal interval

2-26

GEOLOGIC CHARACTERISTICS CRITICAL TO SITING/OPERATING INJECTION WELLS

Subsurface waste disposal via Class I wells involves the entire geologic environment in the vicinity of the disposal well. The vertical extent of this influence ranges from the surface environment, which underlies the surface facilities required to operate a disposal system, to the basal confining unit underlying the geologic unit that receives the injected wastestream. All geologic units lying between these boundaries, but most particularly the primary confining unit that overlies the injection zone, must be thoroughly evaluated to ensure lifetime integrity of the disposal well and adequate confinement of the proposed wastestream within the disposal zone and its confining units. The lateral extent of influence is determined by many factors that control both the radial movement of waste and the radial distribution of the pressure front from the well bore. The area of the disposal zone and its confining units affected by an increase in pressure is much larger than the area invaded by the wastes. The extent of the area in the disposal zone influenced by the disposal operation, the nature of the influence, and the magnitude of the influence must also be evaluated relative to other existing or potential uses of the disposal zone, its confining units, and all other geologic units lying above or below the area of influence.

The geologic characteristics important to siting and operating Class I injection wells, determining the area influenced by well operation, and evaluating the impacts of well operation within the area of influence can be categorized as (1) those directly controlled by the subsurface environments and (2) those that limit the use of the subsurface environment for disposal.

Factors Controlling Selection of Disposal Zones

The main goal in selecting a disposal zone at a specific site is isolation of the injected wastestream from all overlying drinking water sources, mineral and fuel resources, and those portions of the environment used for most human activities. Each site has unique characteristics that must be evaluated to determine the suitability for injection and potential impacts of injection.

Geologic Factors   The lithologies associated with the disposal zone system can be divided into two main categories based on the capacity to allow or restrain the flow of fluids: (1) the porous, permeable rocks and (2) the tight, relatively impermeable rocks. The porous and permeable rocks that serve as aquifers, reservoirs, and disposal zones are mostly sandstones and permeable carbonates (limestone and dolomite). The rocks with low permeabilities that are used as confining intervals consist of fine-grained clastics (shale and siltstone), unfractured, tight carbonates, and unfractured metamorphic and igneous rocks. Injection is possible in all lithologies but is not practical in most lithologies with low permeabilities because injection rates and storage capacities are low and hydraulic fracturing or cavern excavation may be required. Lithologic characteristics important to the waste injection system include grain size, grain-size distribution, grain cementing agent and degree of cementation, porosity, permeability, and unit thickness. The degree of uniformity of these characteristics (in the disposal zone portion of the well bore and extending radially from the well to the maximum extent of influence of the well) is also important. In Illinois, the porous carbonates can be expected to have the best disposal potential; however, these rocks have less predictable reservoir characteristics than do the permeable sandstones.

Knowledge of the structural and geologic framework of a specific site and its relationship to the regional geologic setting is a prerequisite to understanding the geologic processes that have controlled the deposition of the rock sequence and that will directly control the injection and containment behavior of the proposed disposal system. Rock units deposited in a broad sedimentary basin provide optimum conditions for waste disposal because relatively uniform geologic characteristics are generally found throughout a wide area. Structural features such as minor folds and flexures do occur in all sedimentary basins but have relatively minor effect on disposal potential. Faulted and strongly folded rocks may possess some permeable dislocations and open fractures through which fluids under a hydraulic gradient could move. Such features are not desirable in primary confining units because the capacity of these rock units to confine wastes could be compromised. Fractures and small dislocations in the rock of the disposal interval generally do not adversely affect disposal capacity, but they generally produce some degree of anisotropy in flow conditions (in other words, flow conditions may vary with direction). Review of geologic records, examination and testing of drill cuttings and core, evaluation of selected geophysical logs, and hydraulic testing of the well can help determine the degree of fracture development in rock units.

The depth to the shallowest potential disposal zone is determined by the combined thickness of the rocks containing all overlying USDW and the primary confining unit(s) of the shallowest potential disposal zone. As the depth of burial for disposal zones increases, rock units tend to show a decrease in porosity and permeability and an increase in the temperature, degree of cementation, and level of groundwater mineralization. Generally, below depths of 8000 to 10,000 feet the porosity and permeability of the sandstones are expected to be too low for significant disposal potential. However, selected carbonates in which fractures have developed by solution may locally have a greater potential for accepting injected waste at these depths than sandstones have. The shallowest depths for potential disposal zones occur in the Pennsylvanian in the south-central part of the state. Although numerous shallow units may qualify for disposal, many do not have sufficient injection capacity.

The geometric dimensions of each disposal zone and its overlying and underlying confining units must be adequate to accept and contain the injected wastestream. The thickness of a disposal zone may range from a few tens of feet to several thousand feet, but generally the range is from 100 to 500 feet. The upper and lower boundaries of the disposal zone must be established and are generally located at the contacts with the confining beds. The horizontal dimensions should be adequate to handle the injected waste for the duration of the proposed well life. Likewise, the confining unit thickness and lateral extent must be adequate to prohibit the transport of formation water, wastewater, and hazardous or toxic substances through the confining interval for the duration of active injection and extending into the future until the bottom hole pressure in the injection zone reaches the preinjection pressure and the injected waste components can be classified as nonhazardous.

Geologic conditions in the vicinity of the well determine the configuration of the area influenced by injection. Careful measurement of the lithologic character, porosity, permeability, and mineralogy of the rocks encountered in the well bore and the lateral determination (or extrapolation) of these features throughout the area influenced by the injection operation are vital to predicting the rate and direction of transport of the waste in the injection zone and the confining intervals. Oil and gas exploration and gas storage operations have generated site data on these parameters at many locations in the Illinois Basin, and well records from these projects are on file at the Illinois State Geological Survey. Illinois Commerce Commission hearing documents for gas storage projects include much geologic test data. These files and records show that many of the characteristics of geologic units in the Illinois Basin, particularly in the lower Paleozoic units, are relatively uniform over wide areas. Since Illinois is essentially covered by one broad sedimentary basin, some units extend over many thousands of square miles.

Hydrogeologic Factors   Fluid flow in earth materials is controlled by certain physical properties of the pore fluid and the media in which flow occurs. These properties include the density and viscosity of the fluid, the permeability and porosity of the media, and the compressibility of both fluid and media. Describing the flow pattern that is expected to develop with time requires knowledge of the spatial character of these properties and the capacity of the disposal and confining units to place injected fluid into "compressible" storage. The area of influence for any disposal operation is dependent on the previously described properties and, in addition, the bottom-hole injection pressure applied to the injected wastestream.

The density and viscosity of formation and wastestream fluids are determined when compatibility tests are conducted. The values of these test results can be adjusted to disposal zone conditions if formation temperature and bottom-hole pressure on the disposal zone fluid are known. During injection the temperature in the disposal zone opposite the well bore is constantly changing in response to the variable temperature of the injected wastestream and the heat generated by chemical reactions of the waste with constituents of the disposal zone.

Porosity is a measure of the void spaces (i.e., pores, cavities, and open fractures) relative to a unit volume of rock and is expressed as a percentage. Permeability is a measure of the capacity of the rock to transmit a fluid through the pores and fractures and is measured in a unit called the millidarcy. The size of the pores and their interconnecting channels and the degree of interconnection of pores affect flow characteristics. Effective porosity, which may in some cases be several times lower than the total porosity, provides a measure of the porosity actively involved in the fluid flow. Effective porosity and permeability control the injection rate and the pressure required to obtain

this injection rate. Both effective porosity and permeability are important in determining the thickness of the confining unit needed to retain the waste in the disposal system for the life span of the hazardous component(s) in the waste. Effective porosity is also an important factor in determining the average velocity of the waste moving in the disposal zone as the waste spreads radially from the well bore.

The degree to which the formation fluid and the rock matrix can be compressed by the injection pressure determines the volume of waste water that can be accommodated in the injection zone and thus determines the area of influence associated with the injection operation. The injection zone must be extensive and relatively uniform in character to accommodate the area of influence. Heterogeneities in porosity and vertical and horizontal variations in permeability caused by changes in lithology, faults, degree of cementation, degree of solution of crevices, and other factors affect the rate at which fluid can be placed in storage.

Fluid compressibility is affected by the temperature and pressure of the disposal zone. As the depth of burial increases in the subsurface the water becomes less compressible per unit increase in pressure, but there is a small increase in compressibility as the temperature rises. The presence of a gas phase in the fluid of the disposal zone produces a large storage capacity as pressure is increased, but gas also blocks fluid movement through pores.

Rock matrix compressibility is related to the type of rock, degree of compaction, cementation status, and diagenetic history. As depth of burial increases, the degree of compressibility declines (Krumbein and Sloss, 1953). Geerstma (1957) identifies compressibility in rocks attributable to the matrix, the pores of the rock, and the bulk of the rock.

The rate at which the waste front moves radially from the well bore with time depends upon the amount of fluid going into storage and the lateral displacement of fluid away from the well. The increase in storage capacity of the disposal zone per incremental change in pressure is related to the porosity of the rock and the compressibility factors of the formation water and the rock matrix. Formations with higher permeabilities can dissipate the pressure buildup more quickly than units with low permeability; thus, formations with higher permeabilities have less residual pressure buildup in the disposal zone due to injection activities than is observed in units with lower permeabilities. This relationship between injection pressure and injection zone hydraulic properties is well illustrated in a study of the feasibility of desalting water from the Mt. Simon aquifer, reported by the Illinois Water Survey (Illinois State Water Survey and Hittman Associates, 1973).

Calculation of the position of the waste front with respect to the well bore assumes there is no significant mixing of the waste fluid with formation water because of dispersion or overrun of waste and formation fluid by a density/gravity separation. Since a significant portion of the volume of fluid injected into the disposal zone goes into compressive storage, the waste front expands more slowly than it would with only pistonlike displacement of formation water by the injected waste. Differential rates of movement of some of the components in the waste can be expected because of interactions between these components and the formation matrix. The nonuniform character of the expanding waste front and pressure front in a thick disposal zone has been demonstrated in a model study conducted by Heidari and Cartwright (1981) using data from Well C.

The piezometric surface of potential injection zones in Illinois (measured in wells completely filled with fresh water) can be expected to range from several hundred feet below to nearly 200 feet above the land surface. Injection produces an increase in the bottom-hole pressure of injection zones by an amount that is determined by injection rate, waste density, and the capacity of the disposal zone to accept the injected fluid. Regulatory practice sets the maximum allowable increase in bottom-hole pressure at 0.65 of the preinjection bottom-hole pressure at the top of the injection zone. Injection that raises the bottom-hole pressure to this pressure or higher in Illinois may initiate fracture development on the surface of the well bore. Increasing the injection pressure (by increasing the horsepower of the pump) would propagate the initiated fracture deeper into the rock surrounding the well bore. The amount of pressure in excess of preinjection bottom-hole pressure needed to initiate fracturing can be determined by running a pressure-monitored injection capacity test. Such tests are expected to show that many formations in Illinois will have fracture gradients greater than 0.65, the maximum limit accepted in the regulatory practices of the Illinois UIC Class I program.

Fracture gradients for deeply buried formations in various geologic settings around the earth may range from much less than 0.4 in overpressured regions to more than 1.5 for high-strength rock units with very low piezometric levels. A fracture gradient is the bottom-hole pressure required to be applied above the preinjection pressure to initiate fracture development on the surface of the well bore at a specified depth. Many confining zones appear to require somewhat greater pressure to initiate fracture development than that required to fracture rock in injection zones. Several carbonate disposal zones (particularly the Eminence-Potosi Dolomite) at selected sites in Illinois have the capacity to accept very large injection volumes (>500 gpm) under low pressure or gravity flow into the well. Where such conditions exist a very large injection rate would be required to determine the fracture gradient.

Many formulas used to calculate the hydraulic properties of the disposal system assume that permeability and porosity values are uniform throughout the disposal formation; that is, that they are independent of the location (homogeneous) and the direction (isotropic) in which the measurement is made. Real-world injection zones are layered, and horizontal variabilities are common as a result of small variations in the depositional environment or forces acting on the rock since deposition took place. The degree of nonhomogeneity and anisotropy in these parameters in the disposal zone and in the confining beds can affect the disposal operation and the flow pattern of waste injected into the disposal zone. Since some degree of variability can be expected in all hydrogeologic factors, the magnitude of the variability in these factors should be figured into predictions of the performance of the waste disposal system and calculation of the area of review.

Geochemical Factors. Prior to injection of fluids from an outside source, groundwater in an aquifer can be expected to have a fair degree of chemical equilibrium with the rock matrix forming the aquifer. There is slow, ongoing interaction between ionic components in the water and minerals on or near the common surface of the pores and the mineral grains. Study of both the water in the pores and the minerals forming the pore surfaces in the aquifer can provide information on current and past chemical activity associated with the rock matrix and pore fluids. In deep flow systems such as those used by disposal wells in Illinois, fluid movements are expected to be slow, and chemical equilibrium should be approached for most chemical consituents that are present. The introduction of a waste fluid into a disposal horizon within the deep flow system will upset the established chemical equilibrium. The degree of compatibility between the injected waste and formation water and rock matrix minerals will determine the nature and extent of adverse, neutral, or beneficial reactions that will take place in an attempt to reestablish chemical equilibrium.

The complex chemical and microbiological processes in the subsurface environment can affect the capacity of each potential disposal zone to accept and retain the injected waste and the potential for reducing the degree of hazardousness or toxicity of these wastes. Any examination of these processes in the laboratory must duplicate all subsurface conditions to adequately predict the compatibility of the waste with the subsurface environment and the fate of the waste in that environment. Once the framework in which chemical and biological reactions operate is established, the effects of the various reactions on the fate of the waste in the disposal environment and the integrity of the disposal system can be determined. This is a difficult task to accomplish in the laboratory. Prior to the mid-1970s, most compatibility evaluations were short-term bench tests run under standard laboratory pressure and temperature conditions; such tests provided information on the degree of incompatibility that would hinder the injection potential of an injection zone but did not factor in the complex interactions occurring in the disposal zone.

Factors Limiting Deep Well Disposal

USDW. All water-yielding units containing groundwater with less than 10,000 mg/L TDS have been reserved as a drinking water source by the Safe Drinking Water Act of 1974. Subsequent amendments have established regulations for waste disposal activities to prohibit contamination or adverse alteration of the quality of the USDW. Two categories of water exist in the USDW of Illinois: (1) aquifers containing potable fresh water (<2500 mg/L TDS) that are or potentially could be used directly as drinking water sources for humans and livestock, and (2) aquifers having more heavily mineralized water (2500 to 10,000 mg/L TDS, or brackish water) that could be readily treated to drinking water standards. Some livestock that have been acclimated to drinking heavily mineralized water can use water with a total dissolved solids content somewhat greater than 2500 mg/L.

USDW typically exhibit a gradual increase in mineral content downward from the surface and horizontally toward an adjacent sedimentary basin (downgradient direction). Near the basal boundary of USDW, the rate of change in mineral content increases significantly. This more rapid rate of change continues downward until the mineral content exceeds 20,000 to more than 40,000 mg/L TDS or laterally until the mineral content exceeds 60,000 to more than 120,000 mg/L TDS. The rate of change declines at still higher TDS values. The pattern of the rate of change in mineral content of USDW and the adjacent zones of saline water is similar to that observed in coastal aquifers in which fresh water is in contact with intruding sea water, or on a small oceanic island in which a fresh water lens is in contact with sea water.

The distribution patterns of USDW in Illinois are determined by the lithology, thickness, burial depth, areal extent, permeability, and geographic location of geologic units capable of yielding drinking water. Figures 2-16, 2-17, and 2-18 show the distribution of public water supply wells in three categories of geologic units containing USDW: (1) unconsolidated deposits aquifers, (2) shallow (<600 feet) bedrock aquifers, and (3) deep (>600 feet) bedrock aquifers (Shafer, 1985). Private wells finished in Illinois aquifers tend to be concentrated at the shallower depths. The depth intervals occupied by the primary (<2500 mg/L TDS) and secondary (>2500 mg/L) fresh water aquifers at each Class I well site are shown in the geologic columns in Figures 3-3, 3-4, and 3-5.

Groundwater is the source of water for 35 percent of the population of Illinois; average daily consumption was estimated in 1984 (Kirk et al., 1985) to be 475 mgd. Fresh groundwater is also used extensively for power generation, cooling, and irrigation.

Figure 2-3 provides descriptions of the principal rock units capable of yielding groundwater for drinking water purposes and brief summaries of the hydrogeologic roles of the principal sedimentary units in the state. Note that fresh water occurrence in the Pennsylvanian units is limited to the upper few hundred feet of bedrock except in the southern part of the state. In the south, thick permeable sandstones at the base of the Pennsylvanian contain fresh water that extends downdip as far as 15 miles from the outcropping of the units and to depths exceeding 900 feet. The deepest occurrence of fresh water is in the upper part of the Mt. Simon Sandstone in northern Illinois (test hole H, Figure 3- 5).

Figure 2-7 is a cross section that shows the approximate position of the base of the USDW. The relatively thick, extensive aquifers with moderate to large permeabilities have downgradient tongues of fresher water under units with highly mineralized water in the central and extreme southern parts of the state. Aquifers in the glacial deposits of the Pleistocene Series and in the semiconsolidated silt, sand, and gravel units of the Cretaceous and Tertiary Systems all contain fresh groundwater.

Adequacy of Confining Units.   The confining unit, the principal means by which waste is retained in the disposal system, must be thoroughly evaluated to determine its capacity for long-term retention of the injected waste, displaced formation water, and the elevated pressure head generated by the injection operation.

Injection requires raising the hydraulic head of the fluid in the well bore above the static pressure head on the fluid in the rock surrounding the exposed well bore. As injection proceeds, the elevated pressure from injection rapidly radiates laterally through the injection zone. Confinement is required above and below the injection zone to restrict the waste and the pressurized formation water to this zone. The thickness of the confining units required to accomplish this task over a designated period of time will be determined by the permeability of each confining unit, the pressure gradient acting across the unit, the length of life of the disposal operation, and the amount of time required for the elevated pressure in the injection system caused by injection activities to dissipate after injection ceases.

Procedures are available to calculate the pressure gradient across the primary confining unit and the penetration rate of waste components (solutes) through the confining unit at specific time intervals following initiation of injection. Basic data obtained by collecting available data from all subsurface sources and conducting an adequate geophysical logging and testing program on the overlying confining zone during well construction are required for such calculations.
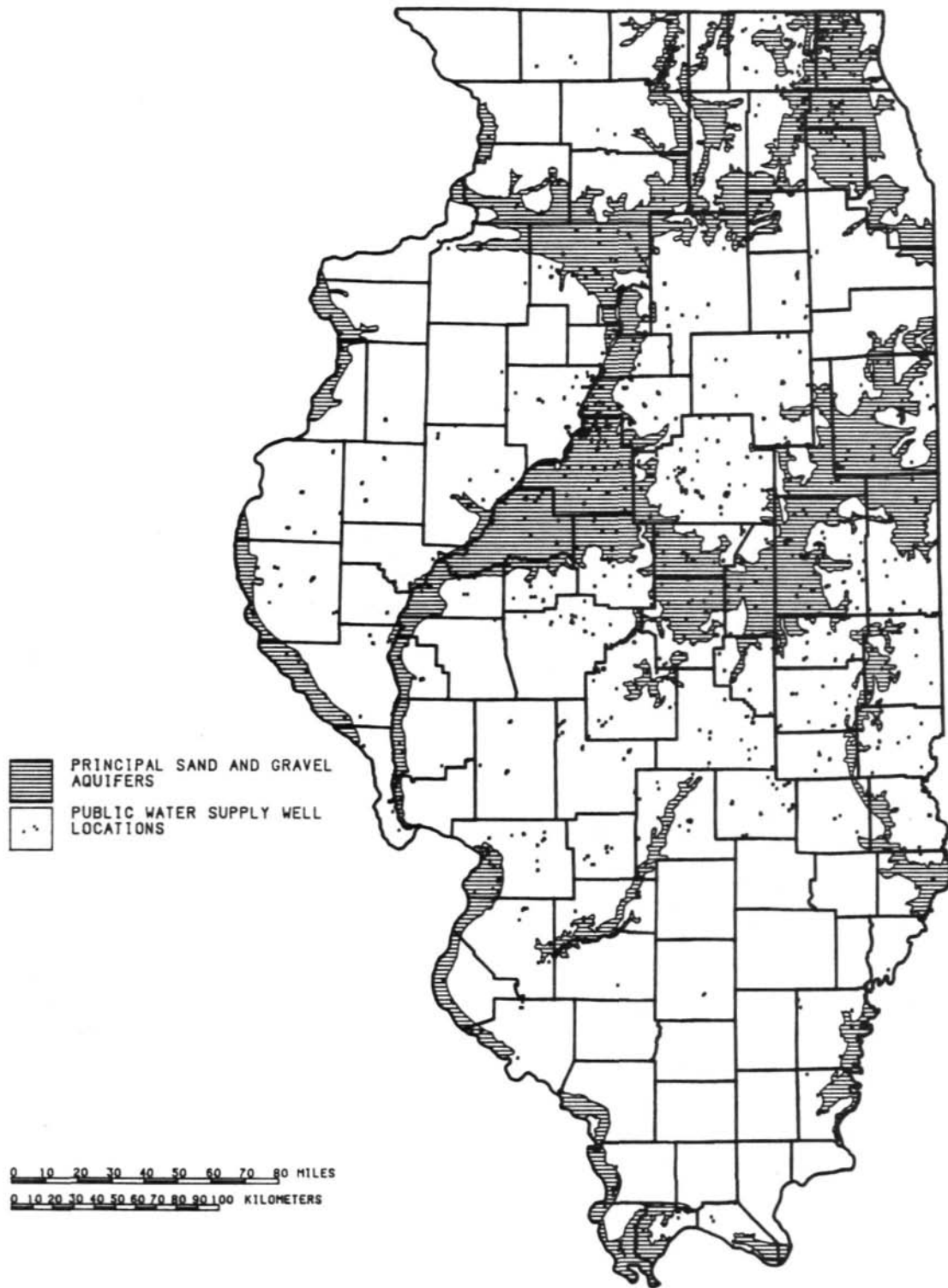
PRINCIPAL SAND AND GRAVEL AQUIFERS

PUBLIC WATER SUPPLY WELL LOCATIONS

0 10 20 30 40 50 60 70 80 MILES

0 10 20 30 40 50 60 70 80 90 100 KILOMETERS

Figure 2-16 Public water supply wells open to sand and gravel aquifers (Shafer, 1985).
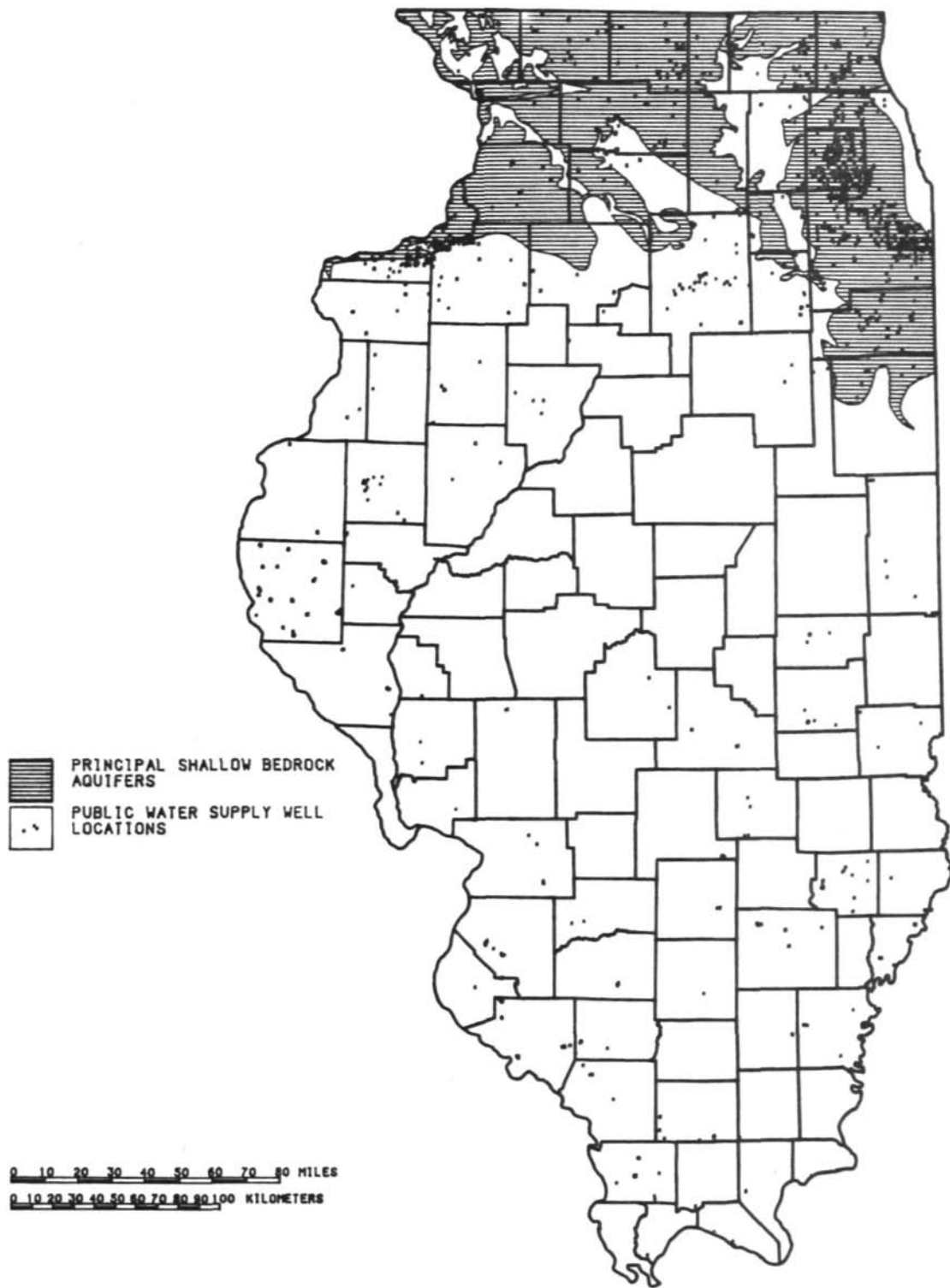
Figure 2-17 Public water supply wells open to shallow bedrock aquifers (Shafer, 1985).
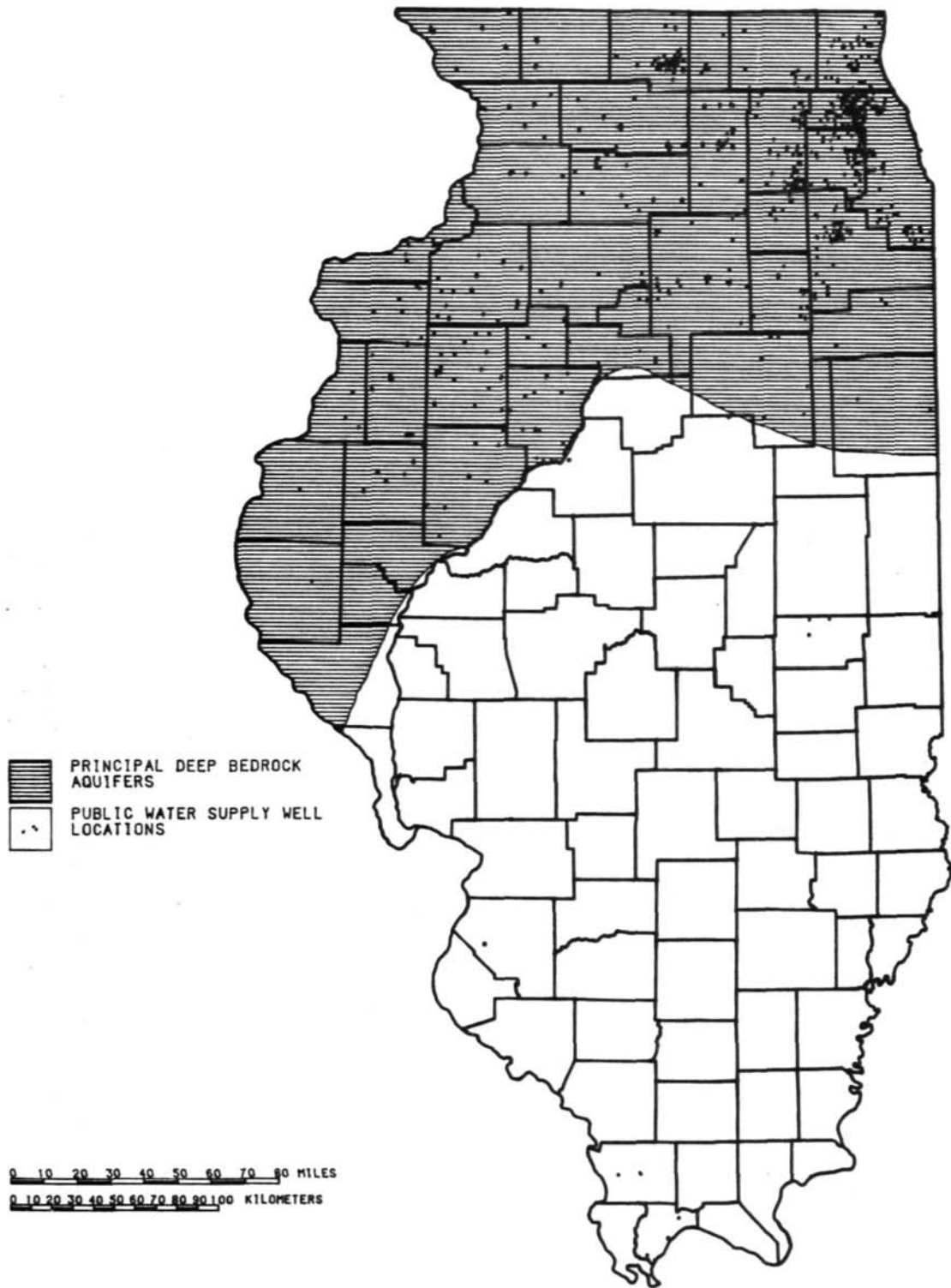
Figure 2-18 Public water supply wells open to deep bedrock aquifers (Shafer, 1985).

Shales, unfractured carbonates with low primary and secondary porosities, and many unfractured and unweathered igneous and metamorphic rocks qualify as confining units. Shales are generally the most desirable lithology; however, in the Illinois Basin the very thick, low-permeability carbonates can serve equally well as confining units.

Seismicity. Earthquakes are infrequent events in Illinois, and most of those recorded have been of low to moderate magnitude and intensity (Figure 2-19). The largest earthquake events recorded near Illinois have occurred in the New Madrid, Missouri area during 1811-1812. Since earthquake waves traveling through earth materials can affect deep well disposal systems, the magnitude and intensity of these events may have a direct bearing on deep well disposal activities. The frequency and intensity of earthquake events in Illinois are of particular concern where the intensity is sufficiently large to cause damage to waste disposal wells or possibly alter the hydrogeologic properties of the disposal zone rocks.

An earthquake is a rapid release of stress that has built up in earth materials. The energy released sends out a radiating pattern of waves. The magnitude of an earthquake is a measure of ground motion at a point of interest. Richter (1935) devised a logarithmic scale that relates ground movement to the amount of energy released. An increase in a whole number on the Richter Scale represents a 10-fold increase in energy release.

The intensity of an earthquake is a measure of the amount of shaking, the damage to property, and the deformation of the earth that is felt or observed at a specific location. Since earthquake energy does not move out uniformly in a radial pattern from the epicenter, the configuration of intensity patterns around epicenters reflects the nature of wave generation at the epicenter and the effects of wave propagation through earth materials and man-made structures. Hard rock transmits energy more efficiently than soft or loose rock materials, so hard rock is shaken less severely. For this reason, deep well sites should not be located on soft, loose surficial materials, such as those under portions of many floodplains. These materials are slow transmitters of seismic energy and thus tend to enhance intensity values. Enhanced intensity values could subject surface facilities and the parts of wells sited in areas with soft alluvial deposits to an increased possibility of damage. Many industries in Illinois that could be potential candidates for deep well injection are built in alluvial-filled valleys.

Energy transmission takes place through several types of wave motions. Any rock body or structure receiving the waves can transmit the energy by reflecting, transmitting, or absorbing it. Absorption of the energy occurs when the transmission rate through the body is slower than the rate at which it is received. Any body that absorbs energy will shake violently. Energy may also build up amplitude if the earthquake waves are resonant with the natural frequencies of vibration of the rock body or man-made structure through which the waves pass. An excessive buildup of amplitude in the body may cause failure to occur.

The Modified Mercalli Intensity Scale (see Table 2-2) is one of many intensity scales devised to measure earthquake intensity. Most earthquakes in Illinois have generated intensities of VII or less. The November 9, 1968 event in Hamilton County in southeastern Illinois has been the largest earthquake event of the present century: it had a registered magnitude of 5.5 and an estimated intensity of VII (Heigold, 1968; Stauder and Nuttli, 1970; Gordon et al., 1970). Lower-intensity events have occurred in Lee County in 1972, St. Clair and Richland Counties in 1974, and Richland County in 1987 (Heigold 1972 and 1987). The New Madrid earthquake of 1811 had an estimated intensity of at least IX in the Ohio valley area of Illinois, an intensity that resulted in a significant level of damage in the southernmost part of the state. This event had an estimated magnitude of 7.2 on the Richter Scale.

The seismic risk map of Illinois (Figure 2-20, adapted from Algermissen, 1969) divides the state into three regions on the basis of areal damage expectance (minor, moderate, major) from potential earthquakes. Region 3 is defined as having a significant potential for severe damage from earth-quakes centered in the region or more likely from earthquakes with epicenters located in the New Madrid area southwest of Illinois.

Well construction criteria for any well sited in or near Region 3 should be evaluated to ensure that the design criteria are based on the design earthquake for the siting area. A design earthquake is
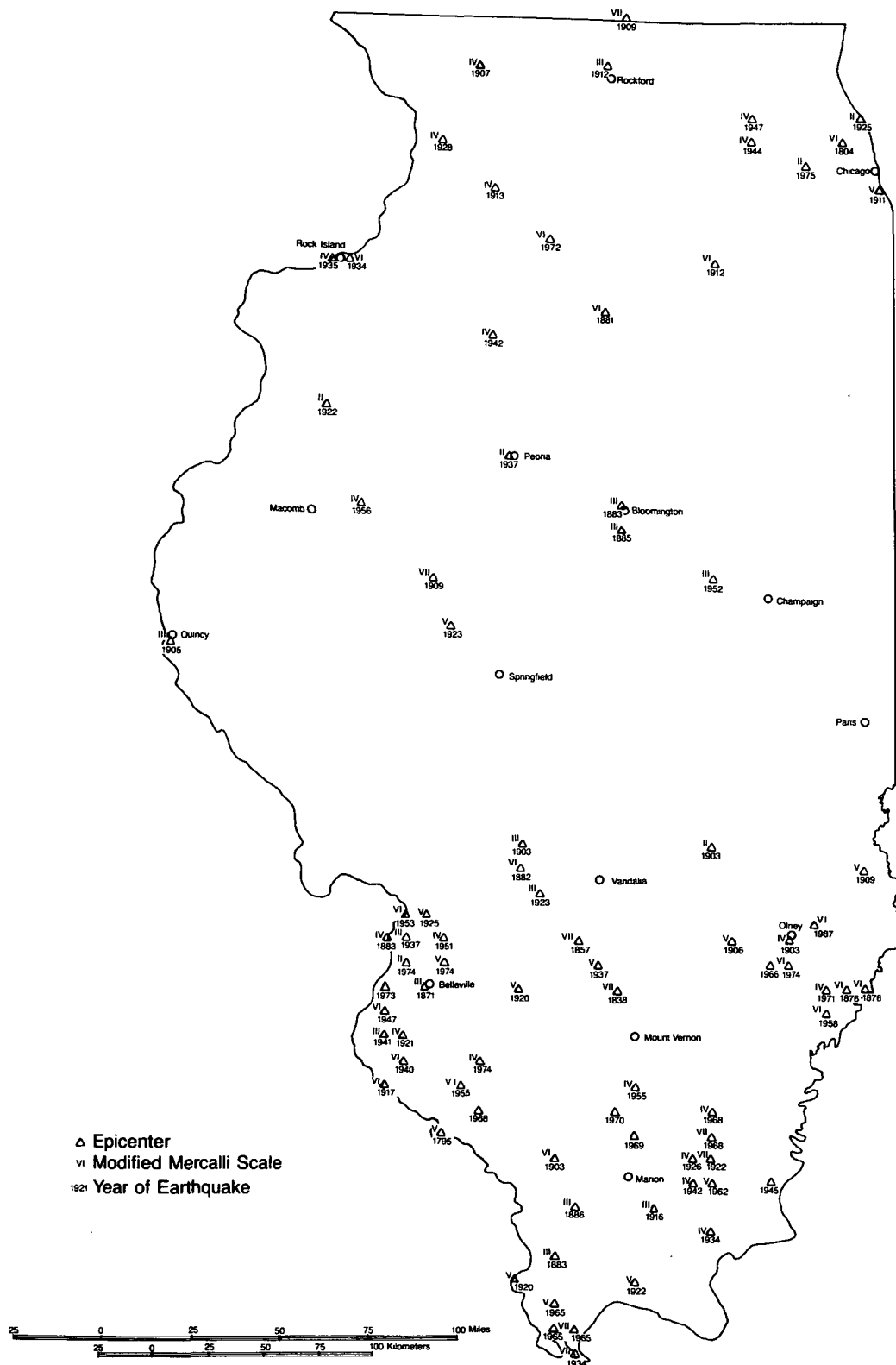
Figure 2-19 Earthquake epicenters (modified from Stover et al., 1979).

Table 2-2. Modified Mercalli scale for measuring earthquake intensity.

Scale degree	Effects on persons	Effects on structures	Other effects	Rossi-Forel equivalent	Equivalent shallow magnitude
I	Not felt except by few under favorable circumstances.			I	
II	Felt by few at rest.		Delicately suspended objects swing.	I-II	**2.5**
III	Felt noticeably indoors. Standing cars may rock.		Duration estimated.	III	
IV	Felt generally indoors. People awakened.		Cars rocked. Windows, etc., rattled.	IV-V	**3.5**
V	Felt generally.	Some plaster falls.	Dishes, windows broken. Pendulum clocks stop.	V-VI	
VI	Felt by all. Many frightened.	Chimneys, plaster damaged.	Furniture moved. Objects upset.	VI-VII	
VII	Everyone runs outdoors. Felt in moving cars.	Moderate damage.		VIII	**5.5**
VIII	General alarm.	Very destructive and general damage to weak structures. Little damage to well built structures.	Monuments, walls down. Furniture overturned. Sand and mud ejected. Changes in well-water levels.	VIII-IX	**6**
IX	Panic.	Total destruction of weak structures. Considerable damage to well built structures.	Foundations damaged. Underground pipes broken. Ground fissured and cracked.	IX	
X	Panic.	Masonry and frame structures commonly destroyed. Only best buildings survive. Foundations ruined.	Ground badly cracked. Rails bent. Water slopped over banks.	X	
XI	Panic.	Few buildings. survive.	Broad fissures. Fault scarps. Underground pipes out of service.	X	**8.0**
XII	Panic.	Total destruction.	Acceleration exceeds gravity. Waves seen in ground. Lines of sight and level distorted. Objects thrown in air.	X	**8.5**

Heigold, 1972, after Wood and Neumann, 1931; Richter, 1958.

the largest magnitude earthquake that can be expected to occur in the vicinity of the well site. Nuttli (1973, 1978) describes the assessment procedure for determining design earthquakes in the central United States. A structural analysis of the well design criteria and the rocks penetrated by the well will determine whether the proposed well design and the disposal zone would continue to be in compliance with the UIC regulations during and after an earthquake equal to or smaller than the design earthquake.

Earthquakes in Illinois and adjacent regions, except those associated with the New Madrid seismic zone, typically have had intensity values of I to VII (Figure 2-19). Most future earthquakes originating in Illinois and adjacent regions are expected to have a low frequency rate and intensity values ranging from I to VII (Heigold, 1985). Intensities in this range are not associated with serious damage to man-made structures.

Figure 2-20 Seismic risk map (after Algermissen, 1969).

Earthquakes associated with the New Madrid seismic zone occur more frequently than earthquakes originating in Illinois. New Madrid-related events with magnitudes less than 4.5 occur annually or more frequently; however, destructive events with magnitudes in excess of 5.7 on the Richter Scale occur very infrequently. The damage associated with the infrequent, large-magnitude events accounts for most of the risk potential assigned to Region 3 in Figure 2-20.

The response of the waste disposal well system to severe, damaging seismic events requires further study with respect to maintaining mechanical integrity of the well and integrity of the confining zones. Information generated by such a study could provide a basis for (1) minimum well design

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criteria tied to the geographic location and site geology for wells located near seismically active areas; (2) possible limitations needed in well operations to maintain the integrity of the confining zones for sites located in moderate to severe seismic risk areas; and (3) delineation of geographic areas in which disposal practice should be limited or prohibited.

Mineral and Fuel Resources and Subsurface Storage.   Significant subsurface mineral and fuel resources are found in many of the sedimentary rock units qualified to receive injected wastes. Oil and some gas have been exploited in many of the permeable units lying above the St. Peter Sandstone. Oil production is mainly associated with Mississippian age deposits; however, significant production has been developed in other units. The region of production is confined to the Illinois Basin, as shown in Figure 2-21. Numerous exploration and production wells have been drilled in and adjacent to the oil and gas fields shown in this figure, and these wells have yielded a wealth of information about subsurface conditions. However, any wells penetrating the disposal system units within the area of review provide an avenue for fluid escape, and must be properly plugged and abandoned.

Coal deposits in the Pennsylvanian System are more widespread than oil and gas resources. Frequently, multiple coal deposits exist at a specific location, but only a few of these are thick enough to be mined. Most coal mining has been done at relatively shallow depths and in rock units in which the groundwater has less than 10,000 mg/L TDS. Figure 2-22 shows the distribution of areas mined out by major coal operations. Recently developed deep mines in the southeast are not shown on this map. Significant reserves of thick coal deposits have not been tapped in many areas of Illinois.

Gas is stored underground at many locations in Illinois where there is adequate caprock to confine the stored gas and a subsurface structure with sufficient closure in deep aquifers to ensure containment of the gas bubble around the injection and withdrawal wells. This activity is described in detail by Buschbach and Bond (1974).

Porous rock is used for compressed air energy storage (CAES); the same criteria for adequate caprock and structural closure applies to compressed air storage as to natural gas storage. Such storage has been demonstrated recently to be feasible at a test project site in Pike County. This type of storage is also feasible in caverns excavated in the rock at depths up to several thousand feet below the surface. Storage of liquified natural gas in excavated caverns is practiced in Illinois, and storm water is stored in tunnels excavated beneath Chicago. Development and use of other types of subsurface storage at shallow and moderate depths is likely to increase (e.g., the SSC Project proposed adjacent to Fermilab in northern Illinois) (Kempton et al., 1985).

Future wells injecting waste in deep subsurface formations must not adversely affect the significant subsurface mineral, fuel, and priority storage space resources of the state. Conversely, future resources must not be developed in the area of influence of active disposal wells and abandoned wells in which there is a residual remnant of the injection pressure or hazardous waste components in the underlying disposal zone.

Land Surface Environment.   The surface environment does not affect either the operational character of the well nor the deep subsurface disposal environment; however, any leakage or spillage of waste at the wellhead or from equipment used in conjunction with the well could affect shallow groundwater resources. Site-specific descriptions of the surface deposits, nearby public water supply sources, and the effects of potential spillage on the surface/near surface environment are discussed in Chapter 3. Waste leakage from piping, the manufacturing process area, storage tanks, and surface lagoons is covered under RCRA regulations for each of the deep well disposal sites.

Special attention must be given to well design in regions where there is a moderate to severe risk of damage by seismic events, particularly in large alluvial valleys or in areas with soft, unstable, unconsolidated surficial deposits. Such deposits are poor transmitters of seismic energy and thus shake more violently than the underlying bedrock or adjacent uplands that are covered by firm glacial deposits over bedrock.
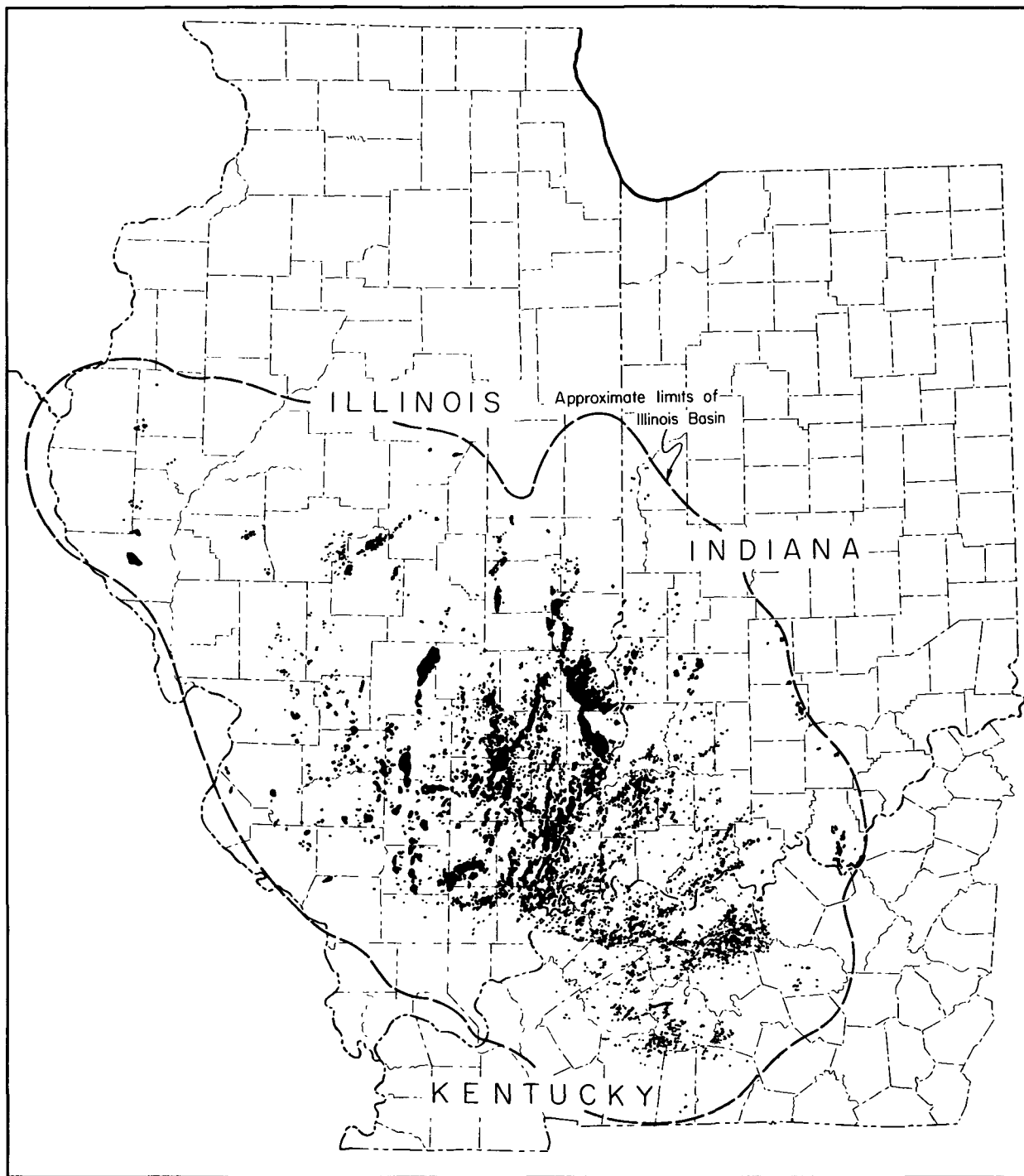
Figure 2-21 Oil and gas fields within the bedrock units of the Illinois Basin (from Illinois and Indiana & Kentucky Geological Societies, 1968).

In addition to the geologic factors that control the siting of deep disposal wells, there are also geographic considerations. These include proximity to population centers, availability of adequate transportation facilities, and surface siting preferences of industries generating large volumes of liquid wastes that are difficult to treat and properly dispose of. Commercial disposal well facilities, which process wastes from many sources, can be sited more selectively for optimal geographic location than can disposal facilities located at the plant site of the waste generator. Illinois currently has no commercial Class I disposal well facilities.
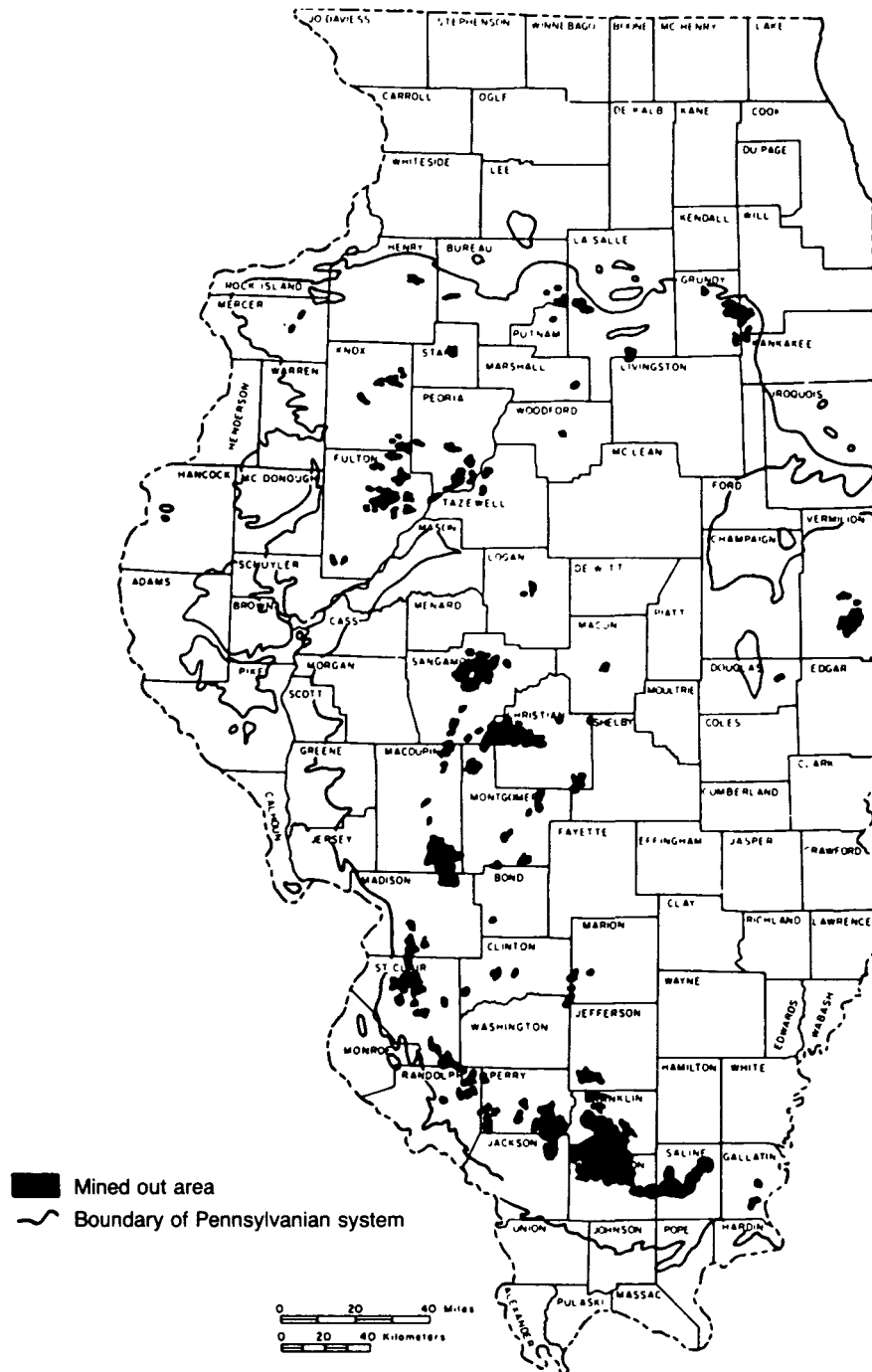
2-40

Figure 2-22 Large coal mining operations.

The most extensive use of subsurface space (except for areas in which mineral and fuel production/ storage has occurred or resources of commercial value have been identified) appears to be for deep well disposal in saline formations. However, deep well disposal makes use of only a very small fraction of the total available unused subsurface storage space. There is no restriction on the use of subsurface storage space for disposal beyond obtaining operating and drilling permits, meeting the regulatory requirements of these permits, and not adversely affecting drinking water or mineral and fuel resources with a commercial value.

Disposal of fluids into saline water-bearing formations of Illinois by injection wells does not appear to require leasing the properties overlying all portions of the area of the injection zone penetrated by the injected fluid. The size of the area of waste penetration associated with Class I injection in Illinois is relatively small; however, at the end of the typical design life (generally 20 years for Class I wells) the radial expansion of the waste front from the well bore may extend this area beyond the lease or surface property boundaries held by the well operator.

RISKS OF DISPOSAL IN THE SUBSURFACE GEOLOGIC ENVIRONMENT

A fundamental requirement for every Class I disposal system is confinement of waste in the disposal zone. Any injected waste or formation water pushed out of the disposal zone by the injection pressure gradient buildup represents a potential risk to overlying USDW. The degree of risk associated with the potential loss of confinement integrity can be assessed by evaluating (1) the features in the geologic environment that could act as avenues of escape for injection zone fluids and (2) the nature of the flow system through which these fluids must travel to reach the USDW. Features that could act as avenues for escape include: faults, joints, and fractures transecting the primary confining interval; flow through rocks of the confining interval; improperly plugged wells penetrating the rocks used for disposal; poor annular cement in the disposal well; induced fracturing resulting from well completion procedures or excessive injection pressures; and excessive lateral migration of low-density waste from disposal sites adjacent to the fresh water/saline boundary of the disposal zone.

The risk associated with breaching the integrity of the well can be reduced by selection of proper materials, good construction and testing procedures, adequate mechanical integrity testing during the life of the well, and good operational management of the well. The use of construction materials compatible with the waste and all geologic materials penetrated by the well will minimize loss of integrity by corrosion.

If a chemical reaction leads to reduced injection potential in the disposal zone, an increase in injection pressure will be required to maintain flow rate. Elevated injection pressures are permissible up to the limit fixed in the permit (a limit set at 0.65 times the static preinjection bottom-hole pressure at the top of the injection zone or a value calculated from a tested fracture gradient pressure at the same position); however, as the pressure in the injection zone increases a larger driving force (hydraulic gradient) is exerted across the confining units. Although the permit allows injection at pressures up to the maximum limit, the opportunity for loss of fluid through the confining unit increases as the injection pressure in the injection zone increases.

The production of a gas phase in the disposal zone must be avoided. Gas that rises into the tubing and displaces the fluid column will place excess pressure on the upper portion of the well. Proper management of the well operation will eliminate gas phase development in wells receiving strong acidic wastes that are disposed of in carbonate units (see discussion in Chapters 3 and 6). In addition, special precautions are required when the wellhead of acid wells is removed for maintenance or testing. The risk for gas lift blowouts can be reduced with the use of blow-out preventers and a continuous flush with fresh water.

Acid wastes injected into carbonate disposal zones could, after a considerable period of time, remove enough rock in the disposal zone by solution to initiate subsidence at the base of the overlying confining unit. An evaluation of this situation should be undertaken to determine the pattern of solution development, the amount of solution required before subsidence begins, and the maximum allowable subsidence permitted before confining unit integrity is placed at a significant level of risk.

Final testing of all Class I wells that are to be plugged and abandoned is recommended to identify any problems with well integrity, particularly in the cement behind the casing. All deficiencies must be corrected to ensure retention of the waste in the disposal zone and to prohibit interformation flow between aquifers lying above the primary confining units.

Seismicity represents an unknown factor to deep well disposal that must be given careful consideration. The frequency and potential magnitude of seismic events can be estimated with reasonable accuracy from historical records and from an evaluation of the shallow and deep geologic environments. Well design should take into consideration factors that will allow the construction of a well capable of maintaining integrity during a design earthquake. Placing limits on siting, design, and operational features of wells proposed for areas with a significant potential for severe damage is recommended.

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3 ILLINOIS DISPOSAL FACILITIES: WELLS, WASTES, AND PROBLEMS

This chapter reviews specifications of the wells used for disposal, operational problems encountered at underground injection facilities in Illinois, types and characteristics of wastes, and potential for contamination of shallow aquifers present beneath disposal sites.

GENERAL INFORMATION ABOUT DISPOSAL WELLS

The waste injection wells are located in the eastern and central part of Illinois (see Figure 3-1). In addition to these Class I wells, an observation well adjacent to Well F2 in Clark County is also shown on this figure. Figures 3-2 through 3-5 provide general information and specifications for the waste disposal wells. The well profiles show the status of these wells through mid-1986. Recent modifications and workovers have changed the specifications of two wells (A2 and C) that have been converted from a packerless to packered design. Modification of a third well (A1) is proposed. These modifications represent a change in well design from open-pressurized annulus to packer-pressurized annulus.

Figure 3-2 describes symbols and patterns used on the well profiles and on the geologic columns at the left of each well profile. A more detailed statewide geologic column and a hydrogeologic description of the units is given in Figure 2-3.

The Safe Drinking Water Act has reserved all groundwater resources with a total dissolved solids (TDS) content of less than 10,000 mg/L for existing and potential drinking water use. Two categories of aquifers are identified: primary fresh water aquifers (<2500 mg/L TDS) and secondary fresh water aquifers (2500 to 10,000 mg/L TDS). The disposal zone at each well site except at Site B has at least one saline aquifer lying between the primary confining interval and the deepest USDW.

All wells are equipped with double casing through the fresh water zone. The long string is landed at the top of each injection zone. The intermediate string is landed below the deepest occurrence of groundwater with <10,000 mg/L TDS except in the two oldest wells. In these wells it was landed below the deepest zone containing water with less than 5000 mg/L TDS, per regulations established by the State Sanitary Board prior to construction of these wells. Shortly after construction of the well at Site A, the regulations were amended to raise the mineral quality limit of groundwater reserved for drinking water purposes to 10,000 mg/L TDS. This limit was later adopted under the Federal Safe Drinking Water Act. The two oldest Class I wells are on standby use status. Well F1 has not recently received waste and is being prepared for plugging and abandonment in the summer of 1987. Well A1 continues to inject waste on a limited basis. Several of the wells have a section of corrosion-resistant casing immediately above the disposal zone to protect the well from reaction with strongly acidic wastes. Acid-resistant epoxy resin cements have been used in the annulus outside the corrosion-resistant casing. At most of the wells a short section of surface casing has been placed opposite local aquifers used as sources of drinking water.

Cement was placed in the annulus outside each casing string to provide an adequate seal against migration of fluids behind the casings. Cement was circulated back to the surface for each casing except for the long string at Site E and both long strings at Site B. In Well E, the cement failed to rise more than 900 feet above the base of the intermediate string. In Well B, the construction plans did not call for circulation of cement back to the surface on the two annuli. Cement bond logs run in the wells during construction and later testing have indicated adequate cement bond in all the wells. The well profile figures show either normal or acid-resistant cements used in disposal well construction. Those wells in which cement did not return to the surface have water in the annulus above the cement. Kerosene is typically floating on the water at the wellhead for freeze protection during the winter season. The annulus between the two long strings in Well G was not cemented but is filled with corrosion-inhibited water and is held under pressure.
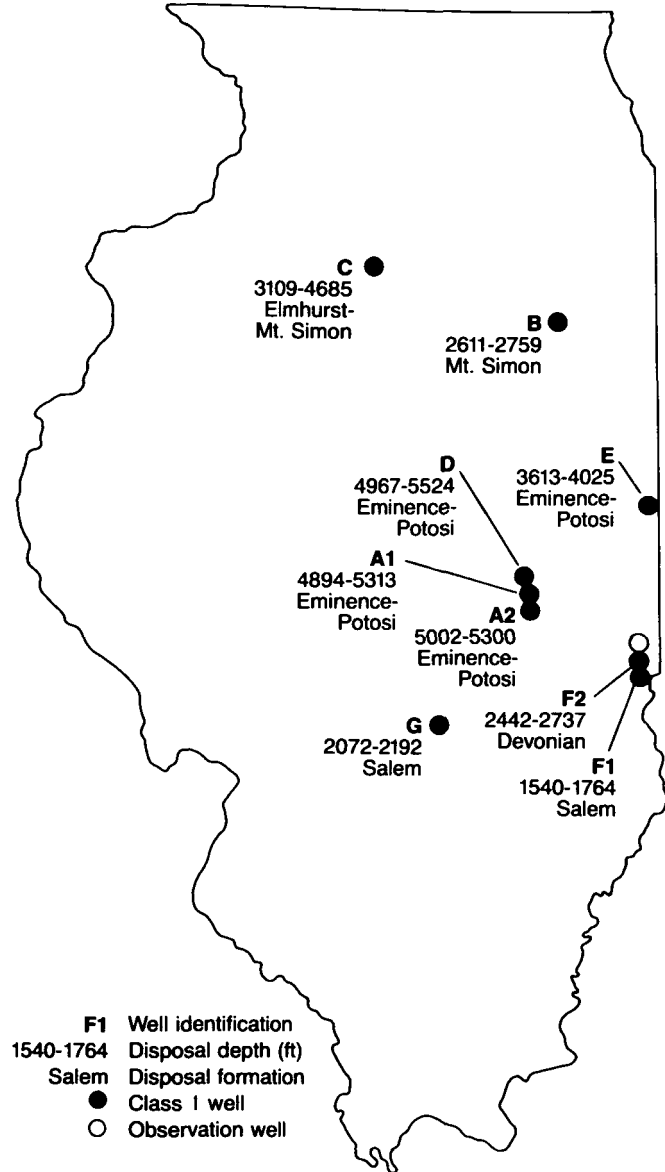
Figure 3-1 Location of Class I wells and identification of disposal intervals (see p. I-3 for key to letter designation of each well site).

The well at Site E was reworked in 1973 and completed with acid-resistant cement between the 5 1/2-inch casing and the 7-inch casing. Acid-resistant 4 1/2-inch casing 112 feet long was attached to the lower end of the 5 1/2-inch casing string. The two wells at Site A also have acid-resistant casing attached to the base of the long string, and these sections of the casing are sealed in the borehole with acid-resistant cement. Packer recompletions were scheduled for 1987 for both wells. Recently the well at Site C was recompleted with a new long string casing (including a basal section of Hastelloy), and a packer.

Each well is fitted with a wellhead assembly that includes valves and monitoring component ports for the annulus and injection tubing. Waste samples may be collected for chemical analysis at a port in the wellhead or in the piping between the injection pump and waste storage tank(s). Most wells lie in close proximity to the waste storage facilities; however, one well lies more than 1000 feet away (Site G).

OPERATIONAL PROBLEMS ENCOUNTERED AT ILLINOIS UIC FACILITIES

Site A

Prior to 1975.   Between August 1966 and April 1975, well maintenance was performed twice a year on Well A1, including removal of tubing, hydrostatic testing of tubing and replacement of joints that failed the test, and running cement bond and casing thickness logs on the steel casing in the well. On several occasions, tubing joints needed replacement because of cracks or leakage; this damage was probably caused by the frequent dismantling and reassembly of the more delicate non-steel tubing with power and hand tools, and hydrostatic test pressures of up to 1000 psi (IEPA files).

In July 1972, parted tubing was discovered after a loss of annulus pressure. A casing inspection log showed no change in casing thickness as a result of this incident (IEPA files, 1972).

April 1973 Incident.   On April 9, 1973, well instrumentation showed sudden changes in flow rate and annulus pressure. Flow to the well increased with a corresponding decrease in annulus pressure, indicative of possible tubing parting. The well was removed from service 6 hours later. Inspection of the tubing revealed minor damage to all couplings, possibly from being tightened too much after the previous inspection; however, the causes of the flow rate and pressure changes were never determined (IEPA files, 1973).

Because this incident was unforeseen, there was no time to lower the water level in the pre-injection settling pond at Site A prior to shutdown of the well. As a result, a low-pH (about 2.0) wastewater discharge to surface waters began on April 10. Soda ash and liquid caustic were added to the discharge for pH neutralization. The discharge ceased on April 16. No fish kills were reported to the IEPA (IEPA files, 1973).

April 1975 Incident.   On April 25, 1975, the completion of a routine workover was delayed by a parting of the bottom five joints of tubing in the well. The IEPA was very concerned that the water level of the settling ponds was approaching a critical height for dike stability; a decision was made to use a diked tank farm area for temporary storage of waste to avoid another discharge to surface waters. The well was placed back in service on May 2, and no discharge from plant property occurred (IEPA files, 1975).
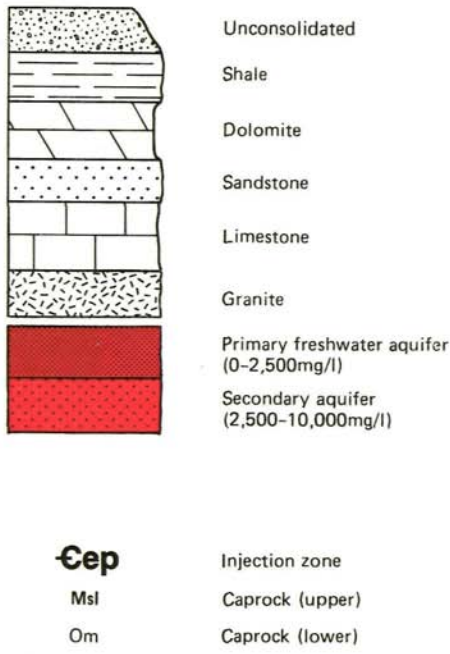
August 1975 Blowout.   Since 1966, Site A had been permitted to dispose of up to 31.5 percent hydrochloric acid (HCl) wastes. Only HCl that could not be sold was disposed of through the well. As the market for HCl was favorable at the time, disposal of concentrated acid was intermittent.

Several weeks prior to the blowout, the capacity of Well A1 to take fluid steadily decreased. A buildup of solids in the tubing was suspected. On August 20, 1975, a heavy calcium chloride brine was pumped down the tubing at a high rate to dislodge the buildup. A loss of annulus pressure resulted, indicating possible parted tubing. A well service unit was called to remedy the situation.

On August 21, annulus and tubing pressures increased suddenly to about 450 psi and expelled the upper joint of the tubing through the casing head. The well blew three times. Fresh water was left running into the open casing overnight (at 50 gpm) to keep the well under control and to dilute any possible buildup of acid inside the casing. Meanwhile, the well service unit had recovered all but 317 feet of tubing from the well. Casing inspection, 3D velocity, and caliper logs run on August 23 showed that the casing appeared to be in as-run condition. A fresh-water stream of about 25 gpm kept the casing full at the surface.

On August 24, a larger well service unit was rigged up in an attempt to retrieve the remaining 317 feet of injection tubing. At 8:05 p.m., with the first four joints of the fishing string in the well, a backflow began. The pH of the backflow was 1.3; the pH decreased to 0.5 by 9:00 a.m. on August 25. The well backflowed at an estimated 250 to 300 gpm until 6:00 p.m. on August 26, when a blowout preventer was installed and the well was put under control. (It was not standard practice at the time to install a blowout preventer before well maintenance or workovers; the blowout preventer was called for on August 25 and arrived at the site at 9:00 a.m. on August 26.)
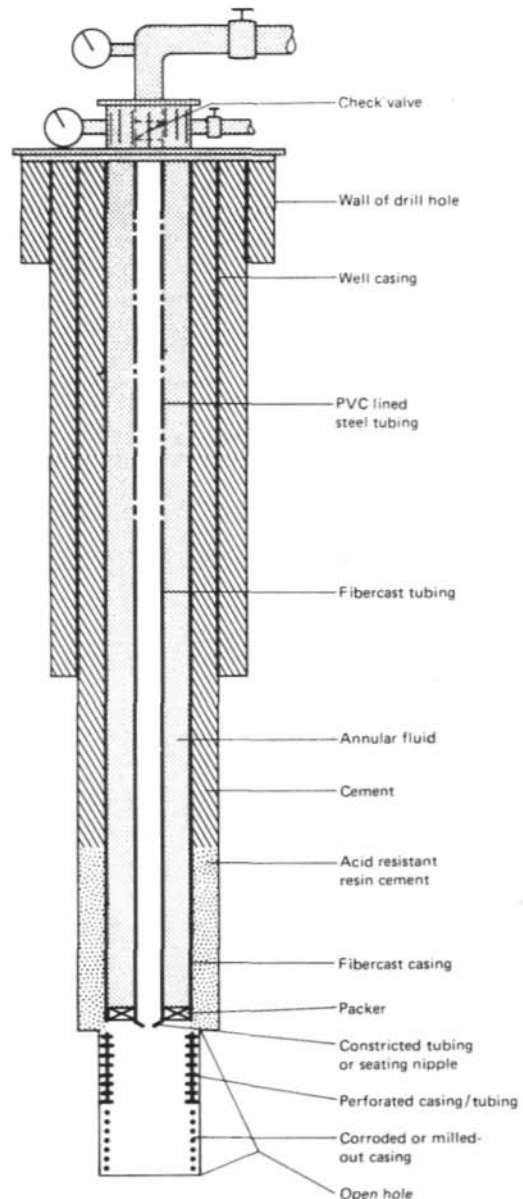
Q   Quaternary
P   Pennsylvanian
M   Mississippian
   Mc   Chester Sandstone
   Msl   St. Louis Limestone
   Msa   Salem Limestone
D   Devonian
   Dna   New Albany Shale
S   Silurian
O   Ordovician
   Om   Maquoketa Shale
   Ogp   Galena-Platteville Dolomite
   Osp   St. Peter Sandstone
   Opdc   Prairie du Chien Dolomite
Є   Cambrian
   Єep   Eminence-Potosi Dolomite
   Єf   Franconia Formation
   Єig   Ironton-Galesville Sandstone
   Єec   Eau Claire Formation
   Єms   Mt. Simon Formation
Pre-Є   Precambrian

Unconsolidated

Shale

Dolomite

Sandstone

Limestone

Granite

Primary freshwater aquifer
(0–2,500mg/l)

Secondary aquifer
(2,500–10,000mg/l)

Єep   Injection zone

Msl   Caprock (upper)

Om   Caprock (lower)

Well I.D.	Location Drilled depth (ft) Total finished depth (ft)	Date Construction Initial injection	Injection formation Geologic age **Injection interval (ft)**	Confining zone **Upper** Lower	Static water level (ft)
A1	Douglas Co 5,318 5,318	3/66–4/66 8/66	Eminence, Potosi Cambrian **4,894–5,313**	**Prairie du Chien** Franconia	160
A2	Douglas Co 5,300 5,300	9/75–1/76 2/76	Eminence, Potosi Cambrian **5,002–5,300**	**Prairie du Chien** Franconia	160
B	Kankakee Co 2,774 2,749	1974 1/75	Mt. Simon Cambrian **2,611–2,759**	**Eau Claire** Precambrian	
C	Putnam Co 4,868 4,685	7/66–8/66 4/68	Elmhurst- Mt. Simon Cambrian **3,067–4,685**	**Eau Claire** Precambrian	
D	Douglas Co 5,524 5,524	5/70–8/70 9/70	Eminence-Potosi Cambrian **4,967–5,524**	**Prairie du Chien** Franconia	160
E	Vermilion Co 6,684 4,025	6/72–10/72 3/73	Potosi Cambrian **3,613–4,025**	**Prairie du Chien** Franconia	160
F1	Clark Co 2,634 1,764	Completed 5/65 9/65	Salem Mississippian **1,540–1,764**	**Pennsylvanian Shales** New Albany	180
F2	Clark Co 6,007 2,737	11/71–12/71 3/72	Devonian Devonian **2,442–2,737**	**New Albany** Maquoketa	140
G	Fayette Co 2,256 2,217	9/74–10/74 10/74	Salem Mississippian **2,072–2,192**	**St. Louis** New Albany	150
H	Du Page Co 4,043 ———	1/67 ———	Proposed lower Mt. Simon Cambrian		———

Figure 3-2   General information on waste disposal wells and explanation of schematics
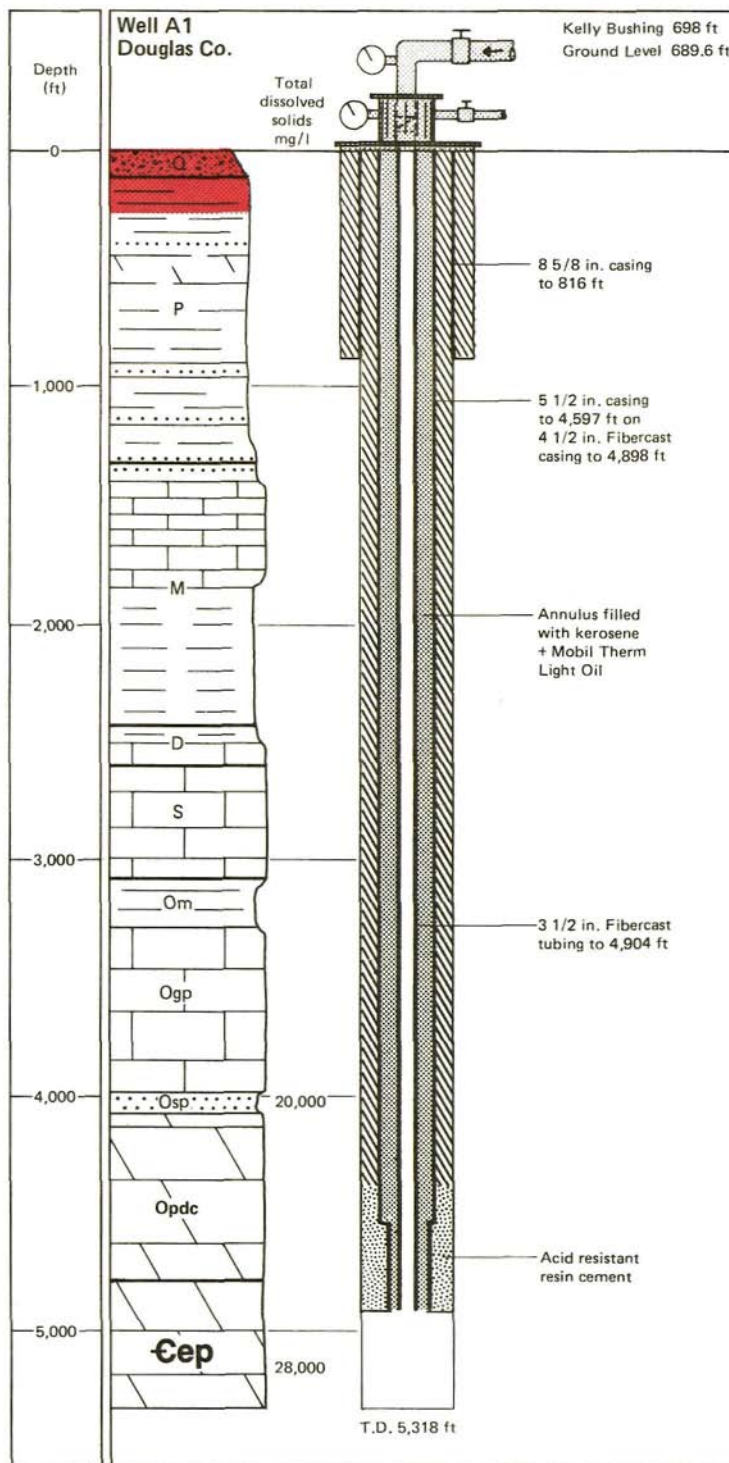
Tubing replaced in 1971. Temporary backflow problem in 1975 due to CO_2 effervescence; acid concentration reduced to alleviate problem. Well was placed on standby status in 1976.

No known problems since well began operation.

Well originally drilled for natural gas storage in 1965. Reworked for waste disposal in 1974. Tubing replaced with fiberglass in 1982.

In 1975, a short length of coated steel in Fibercast tubing string corroded, causing lower 100 ft of tubing to fall to bottom of open hole. (Contact with waste caused 42 ft of casing to corrode away.)

Tubing replaced in 1971. Tubing liner failure in 1975 caused corrosion to lower 50 ft of casing.

Initial injection zone 5,144–6,684 ft in 1973. Well failure resulted in identification of a better disposal zone with adequate caprock. Well reworked and plugged below 4,025 in 1973. Tubing replaced in 1977, 1981.

Initial injection into Devonian Ls (2,390–2,634 ft). Hole collapse caused waste to flow into Salem Ls. Well was placed on standby status in 1972, and reworked for Salem Ls injection zone. Present tubing stuck in hole. Tube lining failed 1977, temporarily clogging hole.

Hole plugged back to 2,737 ft due to lack of adequate disposal zone at greater depth. Observation well installed 1/3 mile north to fulfill permit requirement in 1973.

Originally drilled as a saltwater-disposal well in 1968. Reworked as a waste-disposal well in 1974. Reworked again in 1975–76; second annulus added, and injection tubing replaced. Tubing replaced again in 1982. In 1982 surface leakage required replacement of surface piping.

Could not demonstrate adequate caprock. In 1969, well was plugged back to 2,130 ft and left open as freshwater supply well.

Check valve

Wall of drill hole

Well casing

PVC lined steel tubing

Fibercast tubing

Annular fluid

Cement

Acid resistant resin cement

Fibercast casing

Packer

Constricted tubing or seating nipple

Perforated casing/tubing

Corroded or milled-out casing

Open hole

ISGS 1985

ADDENDUM
June 1987

A1 Proposed for rebuilding with packer in late 1987.

A2 Rebuilt with packer completion in 1987; packer set in fibercast casing at 4,900.7 ft.

C Rebuilt in 1986 with packer completion; set at 3094 ft in hastelloy section of new casing string landed at 3,109 ft; epoxy resin cement used behind hastelloy.

D Tubing replaced in 1986 following linerfailure.

E Anode system modified and positioned in fiber-cast casing in 1986.

F1 Plugging and abandonment scheduled for 1987.

G Plugging and abandonment proposed when well 2 becomes operational in 1987.

Figure 3-3 Schematic diagrams of wells A1, A2, B

Well A2
Douglas Co.

Kelly Bushing 705 ft
Ground Level 690 ft

Total dissolved solids mg/l

Q

P
(undif.)

M

D

S

Om

Ogp

Osp

Opdc

€ep

12,460

19,253

21,000
34,224

16 in. casing to 280 ft

10 3/4 in. casing to 3,164 ft

Annulus filled with kerosene + Mobil Therm Light Oil

7 5/8 in. casing to 4,691 ft on 7 5/8 in. Fibercast casing to 5,002 ft

4 1/2 in. Fibercast tubing to 5,008 ft

Acid resistant resin cement

T.D. 5,300 ft

Well B
Kankakee Co.

Kelly Bushing 684.8 ft
Ground Level 669.8 ft

Total dissolved solids ppm

Q
Om
Ogp

Osp

Opdc

€ep

€ig

€ec

€ms

1,357

1,761

2,254

19,055

20 in. casing to 82 ft

13 3/8 in. casing to 887 ft

Annuli filled with mud

9 5/8 in. casing to 1,458 ft

Annulus filled with inhibited water

7 in. casing to 2,611 ft

4 1/2 in. casing to 2,611 ft

2 3/8 in. fiberglass tubing to 2,598 ft
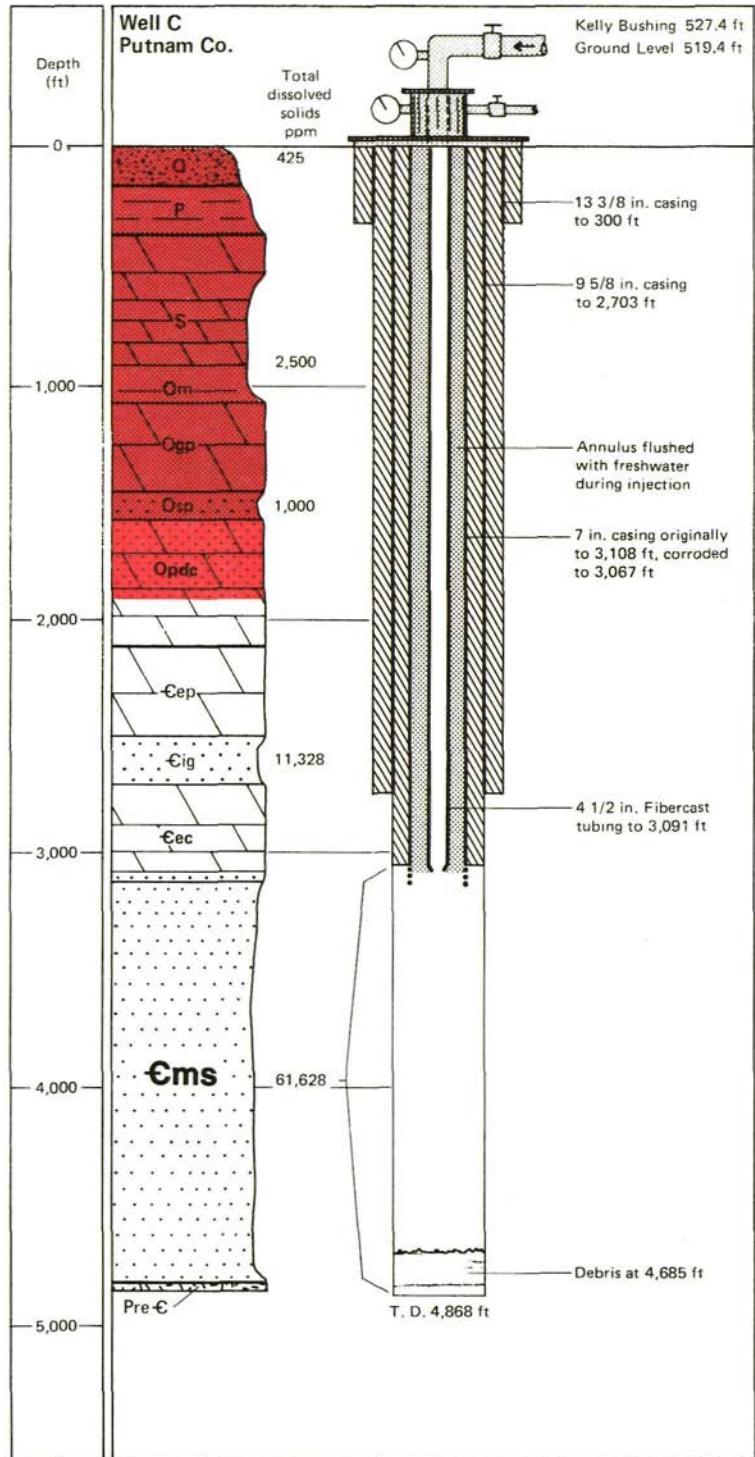
Packer at 2,611 ft
Packer at 2,595 ft

T.D. 2,774 ft

ISGS 1985

Figure 3-4 Schematic diagrams of wells C, D, E

Well D
Douglas Co.

Kelly Bushing 698 ft
Ground Level 693 ft

Total dissolved solids ppm

Q

P

M

D

S ·· 10,000

Om

Ogp

Osp

Opdc

Ɛep

Lost circulation

13 3/8 in. casing to 210 ft

Annulus filled with inhibited water

9 5/8 in. casing to 2,798 ft

7 in. casing to 5,015 ft, corroded to 4,967 ft

4 1/2 in. PVC lined tubing to 4,933 ft, with 2 7/8 in. stinger to 4,967 ft

Oil periodically implaced under packer

Packer at 4,933 ft

T.D. 5,524 ft

Well E
Vermilion Co.

Kelly Bushing 661.8 ft
Ground Level 647.8 ft

Total dissolved solids mg/l

Q
P

M

D

S

Om

Ogp

Osp   14,900

Opdc

Ɛep   34,600

Ɛf

Ɛig   112,000

Ɛec

Ɛms   207,800

172,000

13 3/8 in. casing to 224 ft

9 5/8 in. casing to 2,773 ft

Annulus filled with water and kerosene

7 in. casing to 5,144 ft, milled out from 3,613 to 4,154 ft

Acid resistant resin cement

5 1/2 in. casing to 3,551 ft, set on 4 1/2 in. Fibercast casing to 3,163 ft

Annulus filled with kerosene

2 7/8 in. Fibercast tubing to 3,540 ft, on 2 3/8 in. Fibercast tubing to 3,655 ft

Cement plug from 4,025 to 4,154 ft, resting on mud, debris, and cement

T.D. 6,684 ft   ISGS 1985

3-9

Figure 3-5 Schematic diagrams of wells F1, F2, G, H

Well G
Fayette Co.

Total dissolved solids ppm

Kelly Bushing 615.3 ft
Ground Level 601.3 ft

Q

P

≈10,000

Msl

≈110,000

Msa

115,190
102,295

10 3/4 in. casing to 583 ft

7 in. casing to 2,255 ft, perforated from 2,072 to 2,192 ft

5 in. casing to 2,062 ft

Annuli filled with inhibited water

2 1/2 in. Fibercast tubing to 2,032 ft

Packer at 2,028 ft

Packer at 2,056 ft

Bottom of hole at 2,256 ft; plugged back to 2,217 ft

Site H
Du Page Co.

Kelly Bushing 741 ft

Total dissolved solids ppm

O
S
Om
Ogp

Osp

Єep

Єig

Єec

600

4,304

Єms

37,035

94,940

Pre-Є

When the well was under control, a pump truck displaced the casing with 125 barrels (5250 gal.) of fresh water. After the pumping, the well was on a strong vacuum (static level below land surface). Fresh water was left running in the well overnight. On September 2, the remainder of the tubing was pushed out of the casing into the open hole. Casing inspection, 3D velocity, and caliper logs were rerun; the casing still appeared to be in as-run condition. "Holes" noted on the caliper log at 951 and 4074 feet were identified respectively as a casing cementing perforation and a DV tool. Both anomalies have been present since original well cementing operations and have been noted in other logging operations (IEPA files, 1975).

By September 7, the casing had been pressure-tested at 200 psi, new tubing had been installed, and the well put back into service. It was concluded that previous incidents of loss of well capacity ascribed to tubing deposits may have been caused by pressure buildups similar to the one that caused the blowout. The concentration of HCl allowed to flow to the well was immediately reduced to about 5 weight percent at Site A.

Fish Kill. Efforts to prevent discharge from the plant property during the August 1975 blowout were not successful. Liquid caustic was added to the low-pH fluids leaving the plant property for pH neutralization. At some point in time, too large a slug of liquid caustic was released, which affected waters farther downstream than those contaminated by the pH neutralized discharge. A fish kill was reported by a district fishery biologist on September 3. A pH of up to 13 was recorded. An estimated 3849 minnows were killed in a 3-mile stretch of stream (IEPA files 1975).

Site B

The Class I injection well at Site B was originally drilled in 1965 as a Mt. Simon injection/withdrawal well for the site operator's gas storage field. The well was reworked in 1974 for disposal (into the Mt. Simon) of a natural gas scrubbing operation waste. Testing of the well in 1982 showed it to have mechanical integrity. The well itself has experienced no failures. On two occasions, however, injections into the well were not in compliance with regulations.

1976 Incident. Site B began testing surface equipment for injection in 1975. Prior to injection, the waste was filtered with a 5-micron filter to remove suspended solids. Soon after the start of operations, it was discovered that within short periods of time the 5-micron filter would clog and operations would have to be stopped. A decision was made to install prefilters at Site B ahead of the 5-micron filter and to delay the deep-well operation.

An inspection by IEPA field personnel in March 1976 revealed that Site B had begun injecting waste into the Potosi Formation via an unpermitted well near the Class I well, even though the Potosi was a USDW, containing waters of some 3200 mg/L TDS. The Site B operator claimed at the time that the alternate Potosi injection was specified in an IEPA operating permit issued earlier. The manager of the IEPA's Hydrology Unit did not learn of this unpermitted injection until November, at which time he began an investigation into the matter. In November 1976 the Site B operator stated that an approval letter for the Potosi injection had been obtained from the IEPA in late 1975. The IEPA, having no record of a permit for this injection, treated it as noncompliance and ordered it ceased. This was done in December. An estimated 10,920,000 gallons of waste water had been injected into the Potosi (IEPA files, 1976).

It was also learned in November 1976 that at Site B the Mt. Simon had been hydrofractured to increase injectivity because of its low permeability; the Site B operator was requested to demonstrate that the integrity of the Eau Claire confining zone had not been affected. Subsequent monitoring of water quality in Galesville wells revealed no significant differences from water quality analyses submitted earlier. According to the Site B operator, gas injected into the Mt. Simon with a tracer was not detected in the Galesville, suggesting that the integrity of the Eau Claire was preserved (IEPA files, 1976, 1977, 1985).

1982 Incident. In March 1982, with the pre-injection storage pond empty, the injection tubing was pulled from the well in order to service the packer. The packer separated during pulling and was pushed to the bottom of the open hole section when fishing operations proved unsuccessful. While the replacement packer was being prepared for use, accumulated water in the storage pond was filtered and injected into the well casing between April 7 and 11, after which the new packer and injection tubing were run into the well (IEPA files, 1982).

Site C

Site C was granted a permit by the Sanitary Water Board (forerunner of the IEPA) in June 1966 to construct and operate a deep well injection facility; well operation began in April, 1968.

1975 Incident. In a permit renewal letter issued by the IEPA on Feburary 19, 1975, a special condition was imposed requiring that within the following 90 days a "testing program" would be conducted to determine the condition of the injection tubing and casing in the well. This had not been done since the well's completion in 1967.

> In May 1975, the 4 1/2-inch Fibercast tubing was pulled for inspection. It was discovered that the plastic-coated steel tubing support, located at about 3068 feet, had deteriorated, resulting in a failure of the hanger. The bottom part of the hanger and 100 feet of 4 1/2-inch Fibercast tubing had parted and had fallen to the bottom of the open hole. With the loss of the 100 feet of the 4 1/2-inch Fibercast tubing, it is assumed that waste pickle liquor came in contact with the bottom of the 7-inch O.D. (outside diameter) casing, resulting in corrosion of the casing to its present length at 3066 feet. The original length of this casing was 3108 feet; 42 feet was lost by corrosion after the failure, according to a subsequent casing inspection survey. The 4 1/2- inch Fibercast injection tubing was rerun and set open ended at 3091 feet (approximately 25 feet below the end of the 7-inch O.D. casing) (IEPA files, 1984).

The plastic-coated steel tubing support was the only steel component in the tubing string. When its plastic coating failed, the steel was corroded by the waste pickle liquor, resulting in the loss of all the Fibercast casing below it. Continued injection of waste pickle liquor corroded all but a small piece of threaded steel collar at the top of the hanger. It is possible that the dynamic fluid flush of the annulus precluded any detection of the failure. It is not known when the failure occurred. However, the effectiveness of the flush was attested to by the small remnant of steel collar attached to the bottom joint of Fibercast tubing.

1976 Incident. During a routine start up of the well on January 12, 1976, it was noted that injection pressure on the annulus increased sharply, as was expected, but that pressures held steady at 30 to 50 psi rather than the usual 250 to 300 psi. The operator noticed that the cellar in which the well head is located was flooding with water and shut the well down. A broken pipe on the annulus water line was discovered and repaired. Injection was attempted again, but the pressure did not come up to normal, and injection was stopped once again. A third attempt was made while the cellar was being pumped out. A worker noticed that the injection piping running to the wellhead was sagging, and that the 4-foot section of tubing on which the tubing hanger was attached had been pulled out of the overhead pipe flange. The worker also noticed that the 4-foot section had no weight on it. The entire injection string had parted and fallen to the bottom of the hole. The threads holding the tubing hanger were defective, and the threads holding the tubing column had failed.

Site C reported that no waste acid had reached the well during the three attempted start-ups. The water in the cellar was not acidic, even though the well backflowed 200 to 300 gallons. Since some 12,000 gallons of fresh water had been injected into the well at the end of the previous injection, it was believed that no waste had come into contact with the steel casing during the backflow (IEPA files, 1976).

The IEPA was then informed of the failure. A well-service unit located the top of the tubing at 1617 feet and retrieved it. The first 10 or so feet pulled harder, indicating that the tubing had penetrated soft fill at the bottom of the well. Water displaced into the pit by the fishing tool was not acidic (IEPA files, 1976).

The well-service consultant believed that no testing of the tubing was necessary beyond visual inspection. He thought the slow velocity of the fall through the fluid-filled well bore, the breaking of the fall by contact with the casing and borehole, and the final landing into soft fill would preclude the possibility of damage. The IEPA and ISGS believed that a 1617-foot fall of tubing weighing some 4792 pounds in water could have caused damage and recommended that the tubing be

checked. An ISGS memo to the IEPA recommended that testing be done to determine the integrity of the injection tubing prior to granting an operating permit for the well (IEPA files, 1976).

Since the Site C operator did not pressure test the tubing before placing the well into full operation on January 19, 1976, the IEPA requested in a letter of January 23, 1976, an immediate shut down of the well and pressure testing of the tubing. The agency noted that "in their experience cracks in Fibercast tubing were typically not visible to the naked eye" (IEPA files, 1976).

Permission was given by the IEPA to pressure test the tubing string in the well at Site C; testing was done on January 30. The test began at 7:30 a.m. with a pressure of 250 psig; at 9:23 a.m., pressure had dropped to 159 psig, 63.0 percent of the starting pressure. Steady pressure drops were observed throughout the test, the greatest being a 1.36 psi/min drop between 8:06 and 8:39 a.m. Part of this leakage occurred through the lubricator. The IEPA concluded that leakage in the tubing was "negligible, if any. Well may be safely put back into operation in accordance with the terms and conditions of its State operating permit" (IEPA files, 1976). On Feburary 13, 1976, Site C was granted a renewal of its permit to operate the well.

Site D

The Site D waste disposal well was originally drilled and permitted for the disposal of some 130,000,000 gallons of waste gypsum water that had accumulated in surface impoundments. After the 130,000,000 gallons of waste water was disposed of, the well was to be shut in (pending the development of other possible candidate wastestreams for underground disposal) or permanently plugged and abandoned.

1970 Incident. Shortly after the well was put into service in September 1970, a release of annulus pressure was observed, requiring pulling of the 2 1/2-inch tubing and packer. Severe corrosion was found on several tubing couplings (IEPA files, 1970), and one joint of tubing exhibited a hole approximately 3/4-inch wide by 1 1/2-inches long (IEPA files, 1985). A small groove in the plastic tubing liner produced by a wire line during swabbing development of the well had exposed carbon steel (part of the tubing) to attack by the acidic wastewater. The well was returned to service in March 1971 with a new packer and a new 4-inch PVC-lined tubing string.

Injection of Fluids Other Than Permitted Wastes. Site D was originally permitted to operate the deep well for the disposal of waste gypsum water. When Site D submitted an application for permit renewal in June 1973, the description of the wastestream to be injected included rainfall accumulation on the gypsum piles, ion exchange resin regeneration waste, cooling and boiler blowdown water, occasional accumulations of water containing water-soluble organic material (primarily ethyl alcohol), and sample residues from the quality control laboratory containing organics (primarily ethyl alcohol and diethyl ether) and mercury compounds (IEPA files, 1973).

When questioned about the additional components to be added to the wastestream, the Site D operator responded that since 1972 about 100 gallons per minute of water from an ion exchange regeneration system in a new alcohol operation had been added to the gypsum water pond. The operator also reported that rather than allow used mercury-containing analytical reagents to flow into the sewers, they had begun collecting them, and that as of October 1973 approximately 4 gallons of analytical wastes had been added to the gypsum pond water (IEPA files, 1973). The cooling tower blowdown, boiler blowdown, or ion exchange regeneration waste from the power plant had not yet been injected at Site D. On January 24, 1974, the IEPA issued a permit to Site D to operate the disposal well for the disposal of the five wastestream sources named in the permit application, despite the fact that unpermitted and unreported wastes had been included in the injected wastestream for at least the preceding 22 months.

1974 Incident. In October 1974, pressure monitoring gauges began to show a slowly declining annulus pressure. Operations were halted, and a small water flow (5 gpm or less) was begun into the annulus to maintain a positive pressure (a packer leak was suspected) and to ensure that waste fluid would not enter the annulus. The problem worsened, however, and the well was taken out of service on November 13. Logs run on December 2 indicated that there was a hole in the injection tubing at about 4912 feet and that the tubing and casing were badly corroded below 4907 feet. On December 10 the Site D operator reported that "two tracer logs have been run but no final

conclusion has been reached. We have confirmed that there is some communication between the annulus and tubing at the packer level but there is no leakage above this level" (IEPA files, 1974). The well remained out of service until January 10, 1975. The IEPA did not receive a copy of the logs until the end of March.

On February 4, 1975, the Site D operator reported that "based on our studies, as well as the recommendation of our deep well consultant, the well was put back in operation on January 10, 1975. While it appears that some communication may exist between the annulus and the tubing at the packer level, this will not endanger the system" (IEPA files, 1975). By this time, however, a flow of 50 gpm into the annulus was necessary to maintain annulus pressure. Also, the annulus pressure was half the injection pressure. The IEPA allowed the injection to continue.

At a meeting held on March 31, 1975, between the IEPA, the site operator, and the Illinois Surveys, it was disclosed that the December 1974 radioactive tracer (RAT) survey indicated that fluids injected into the annulus were lost somewhere in the system and that one or more holes possibly existed in the tubing and/or casing. Site D's consultant felt that the problem was either a hole in the tubing or a leaking packer (IEPA files, 1975).

The well was shut down for repairs on April 12, after having operated 24 hours per day for all but one day since January 11. A 1/4-inch x 2-inch hole was found in the tubing at 4920 feet when it was pulled from the well. A vertilog run on April 17 showed severe casing corrosion below 4956 feet. A pressure test of the casing the following day showed no casing leaks above this depth. A caliper log run on April 21 showed severe casing corrosion below 4958 feet. It was not certain whether any casing was left below 4968 feet (the original casing depth was 5015 feet). On April 29, a new packer was set at 4933 feet. After new 4 1/2-inch, PVC-lined carbon steel tubing was run the well was sucessfully pressure tested and returned to service on May 8 (IEPA files, 1975).

1975 Incident.   On July 7, 1975, the annular flow meter showed that fluid was being added to the annulus (at the wellhead) at a rate of 11 gpm, indicating a possible hole in the tubing. Injection continued until July 11, by which time the annular flow had increased to about 25 gpm. During this time, the annulus was kept under a higher pressure than the tubing. A RAT survey performed on July 14 showed a hole in the injection tubing at 4903 feet. When the tubing was pulled on July 16, several small holes were found in a collar just above the packer. Indications were that an O-ring had not made a good seal against the ends of the tubing. About two dozen other joints of tubing exhibited corrosion due to bad seals with O-rings. Several of the collars were corroded almost to the point of failure. New tubing joints were installed and joined manually to ensure proper sealing and compression of seal rings against the ends of the tubing (IEPA files, 1975).

Site E

Site E began operation of a deep disposal well in April 1973. The facility was originally permitted to dispose of a predominantly hydrochloric acid waste into the Mt. Simon Formation. The well was constructed without a packer. The annulus had a constant fresh-water flush to keep the acid waste out of the annulus and away from the steel well casing. A set of lead anodes was positioned on the outside of the injection tubing near the bottom of the long string to monitor the conductivity of the fluid in the annulus. If any acid having higher conductivity backflowed into the annulus between the tubing and the casing, alarms would sound to alert plant personnel.

1973 Incident and Well Recompletion.   On July 24, 1973, a high-conductivity reading by the monitoring anodes sounded the alarms, indicating a possible injection tubing failure. Since the tubing had just been visually inspected and pressure tested only days before, the Site E operator discounted the probability of tubing failure. The variable, abnormal conductivity was ascribed to turbulence in the annulus caused by a new large-capacity injection pump that was being used for the first time. A decision was made to investigate, but not shut the well down (IEPA files, 1973). On July 27, "evidence" of hydrogen gas generation was noted (IEPA files, 1973). Variable high conductivity conditions prevailed through August, accompanied by pressure buildups caused by hydrogen gas in the tubing upon shutdown of the well. The conductivity alarms were ignored, and the pressures after shutdown simply bled off. In early September 1973, a decision was made to shut the well down to investigate the problem (IEPA files, 1973). On September 11 and 12, the well was killed by injection of some 15,090 gallons of 21 Baume muriatic acid inhibited with Rodine

XL1060 (to reduce corrosion of steel by the acid) into the well. Pressures built up, and both tubing and annulus ejected hydrogen gas and inhibited fluid, which were bled to a residue pond (IEPA files, 1973).

Removal of the tubing was begun on September 13. A parting in the tubing was found at the 30th joint (600 feet). Fishing operations commenced; a new steel tool left in the hole and retrieved almost 4 days later was severely corroded, indicating the presence of acid in the hole. Salt water (9.8 lb/gal) was injected to displace any acid, and fishing operations for tubing and conductivity cable removal continued until October 2, when the fishing tool came out of the hole with small pieces of metal, indicating casing damage. A caliper log run on October 3 showed severe casing damage from 613 to 3650 feet, with no casing below that point. An audio collar log run the same day indicated some casing below 3705 feet. Given the large volume of hydrogen that evolved during depressurization, the well operator concluded that the inhibitor had not worked, and that the muriatic acid had damaged the casing (IEPA files, 1973).

A RAT survey run on October 7 indicated that fluid was leaving the hole at 3732 feet, moving into the Potosi Formation (IEPA files, 1973). The Mt. Simon disposal zone, having a higher hydrostatic head, was backflowing acid waste and formation water into the Potosi Formation. Backflow explained the severe corrosion of the tool left in the well and possibly the destruction of the lower part of the casing. By October 8, construction had begun at Site E on a temporary earthen holding basin for storage of accumulating plant operation waste, at the suggestion of the IEPA (IEPA files, 1973). The lagoon would have a 25-day capacity; it was estimated that 20 days would be needed to rework the disposal well.

More logs were run on October 13-14. A casing inspection log showed extensive corrosion of the casing wall from 613 to 2650 feet; casing thickness reached a minimum of just less than 1/8-inch (about 0.115-inch) between 1462 and 1488 feet, in contrast to 3/8-inch before the incident. The casing was gone below 3644 feet. Pressure testing of the 7-inch casing at 200 psig indicated that there were no holes in the casing above 3565 feet (IEPA files, 1973).

On October 17, the Site E operator submitted an application to the IEPA to recomplete the well in the Potosi Formation (3620 to 3928 feet deep). It was observed that the Potosi would take fluid easily without requiring pressure and circulation of fluids to the surface. Workover operations continued while the application was being reviewed by the IEPA. The workover and recompletion were finished successfully on November 27 (IEPA files, 1973).

The well was recompleted without a packer because it was believed that a packer could not be set in the well without significant damage to the acid-resistant Fibercast casing section at the base of the new 5 1/2-inch long string and the Fibercast tubing. However, the fresh water annulus flush was replaced with a pressurized static fluid seal of light oil. An anode conductivity system was again employed, with the two anodes located at 3538 and 3541 feet (inside the 5 1/2-inch steel casing).

1976 Incident.   No further problems were encountered at Site E until December 1976, during the usual semiannual mechanical integrity tests. Prior to testing, the well was flushed with 3000 gallons of fresh water to remove acid. The kerosene in the annulus was backflowed into the storage tank; during the withdrawal, pressure in the annulus increased some 39 psi, which was believed to be due to CO_2 gas (IEPA files, 1976). Pressure was killed by adding about 24,000 gallons of fresh water to the annulus over an 18-hour period.

> The pulling of the injection tubing commenced on December 7. After 1050 feet of tubing was out of the hole, CO_2 gas blew out of the casing annulus and went as high as 50 feet in the air blowing water and some kerosene. Water was immediately started down the tubing at a rate of 30 gpm. The well was allowed to blow CO_2 gas and water out of the casing annulus for approximately 12 hours while fresh water was being put down the tubing. As it was determined that a larger volume of water was needed down the tubing, a fire hose was connected to a fire hydrant and a rate of 200 gpm was attained down the tubing. After some 10 minutes of injection down the tubing at the higher rate the well was brought under control.

Water was allowed to flow down the casing annulus at a rate of 30 gpm during the next 6 hours. On the morning of December 8 both the tubing and casing were on a vacuum and all tubing and cable were pulled out of the well (IEPA files, 1976).

At that time, it was not a standard practice to install a blowout preventer before well workovers.

A RAT survey was performed on the casing on December 8 to determine if there were any casing leaks. The survey indicated a constant flow rate downhole with no casing leaks. The tracer material was seen leaving the well immediately below the bottom of the 4 1/2-inch casing (IEPA files, 1976). Having no tubing or kerosene in the well provided a good opportunity to show that injected fluid was leaving the wellbore and entering the disposal zone, not moving up behind the casing.

Site F

Site F began operation of its first waste disposal well in September 1965. Well F1 was drilled to 2634 feet, although the loss of some 30 to 35 feet of tools in the bottom of the hole made the "effective" depth about 2600 feet. The hole was cased with a 4 1/2- inch, Seran-lined steel long string to 2390 feet, except for a 224-foot section set between 1540 and 1764 feet (opposite the Salem Formation), which was cased with an unlined "Securaloy" (aluminum) casing. The Securaloy section could be dissolved by the Site F operator at a future date in order to open up the Salem Formation for injection. Until November 1970, the well had no tubing; waste fluids were injected through the 4 1/2-inch casing (IEPA files, 1970).

1969 Incidents. In mid-February 1969 a bridge caused by formation caving was discovered in the well at 1596 feet. During cleaning attempts the well caved badly; after three days, the well was cleaned out to 1884 feet, and a caliper survey was run to 1752 feet. The survey indicated that the Securaloy section of the casing was substantially dissolved. The sections between 1710 to 1748 feet, 1620 to 1650 feet, and 1542 to 1582 feet were shot with three jets per foot to provide injection into the Salem Formation. After the top series of shots, the well was found bridged to 1540 feet. The well was cleaned out to 1646 feet, and injection was resumed. According to the operator, "the upper 40 feet of the Salem Limestone may have been receiving the waste for as long as two years" (IEPA files, 1984).

On August 28, 1969, the "well was backflowing when the pump was shut down" (IEPA files, 1970). An attempt to run a temperature log to determine points of fluid entry into the well revealed a "solid bridge" at 1527 feet. The well was acidized with 15 percent HCI, after which the bridge was found at 1526 feet. Injection was resumed on August 29 at a lower pressure (40 psi), and the well took the fluid; pressure dropped to a 26-inch vacuum (inches of Hg) by September 2.

1970 Workover. In September 1970, the Site F operator submitted plans to the IEPA to rework the well. Plans called for the well to be cleaned out to total depth, followed by installation of a tubing string and resumption of injection into the original Devonian disposal zone. Work began at the end of October, at which time the static water level in the well was at land surface as a result of the blockage (IEPA files, 1970).

The bridge was encountered at 1524 feet. Drilling through the bridge was made difficult by several 'light' sections in which loose metal scraps (pieces of Securaloy or debris from the February 1969 shooting of the well) were believed to be binding the drill pipe. Cuttings recovered at the surface indicated "gyp, shale, and very fine metallic cuttings. Also obtained other debris not identified" (IEPA files, 1970). By November 3, the bridge was drilled to 2393.5 feet. Scrap metal continued to bind the pipe. At 2393.5 feet, circulation was lost along with vertical movement and rotation of the drill string. The drill pipe could only be moved upward 22 feet and then became permanently stuck. Pumpage of water at very low pressures with no circulation indicated that the drill string had managed to break through the bottom of the bridge into the Devonian (IEPA files, 1970).

On November 5, the drill string was cut off at 2025 feet. The next day, 1743 feet of injection tubing were run into the well. Four of the seven bottom tubing joints were perforated. No packer or annular fluid was added to the well. Injection resumed on November 6; although injection was primarily into the Salem Formation, the Devonian did accept part of the injected fluid via the lost part of the drill string connecting the two injection zones (IEPA files, 1970).

Well F2 Drilling. In December 1971, the drilling of Well F2 was completed. This well was intended for disposal of not only the wastes being injected into Well No. 1 at the time, but also all plant process area and other plant property runoff being discharged to a nearby creek; this would eliminate all of Site F's discharges to surface waters. The well was drilled to a depth of 6000 feet, and reached the lower Franconia Formation (Cambrian System). The disposal interval was intended to be the lower Oneota, Emminence, Potosi, and Franconia Formations. However, an injectivity test conducted at the end of December 1971 showed that these formations had poor fluid disposal capabilities. As a result, the well was plugged back to 2737 feet, about 11 feet above the bottom of the Devonian. Cement plugs were set at 2737 to 2990 feet (across the Silurian interval) and at 4095 to 4208 feet (across the St. Peter interval) (IEPA files, 1972).

The permit to operate Well F2 was granted by the IEPA on March 10, 1972. One condition of the permit was that Well F1 be properly reworked to inject exclusively into the Salem Formation and then be used only as a standby well. By June 19, a cement plug had been placed from 1764 to 2007 feet (from the bottom of the open hole to the top of the lost drill pipe) to seal off the well below the Salem Formation. A packer was installed in the well, with the annulus filled with inhibited fresh water. Another condition of the permit was that within 1 year a properly cased monitoring well be drilled through the Devonian at the northern edge of the Site F property in order to observe water quality and formation pressures with time. The monitoring well was completed on February 24, 1973, about 1740 feet north of Well F2 (IEPA files, 1972). Well F2 has operated since March 1972 with no operational problems.

1977 Incident. A well test performed on Well F1 in February 1977 revealed that the injection tubing was plugged because of the collapse of its liner. The tubing was cleared on February 4. Both annulus and tubing failed pressure tests conducted on February 5. In April 1977 another annulus pressure test failed; the tubing was stuck in the hole and could not be removed (possibly due to collapse of the casing liner). A RAT survey showed no leaks in the injection tubing. The well was open only to 1712 feet. An injection capacity test conducted in December 1977 led the Site F operator to conclude that Well F1 was "suitable and ready for use as a standby well" (IEPA files, 1977).

1981 Testing of Well F1. Site F's consultant conducted another RAT survey in Well No. 1 on October 16, 1981. Sloughing tubing liner presented problems in running test instruments into the tubing. Obstructions were cleared by the well service unit prior to running the survey. According to the consultant, the survey "clearly showed that 100 percent of the fresh water injected was entering the injection zone" (IEPA files, 1984). However, he also stated that "the continued 'standby' status of this well to meet a possible emergency need in the event of an outage of Well No. 2 is considered unreliable, since the carbon steel part of the injection tubing would be exposed to the wastestream" (IEPA files, 1984) as a result of the poor condition of the sloughing tubing liner.

Denial of Well F1 Permit. Waste injection through Well F1 has been rare since 1972. No waste has been injected into the well since March 1982. Under the new regulations that became effective when Illinois received primacy, the site operator submitted an application to the IEPA to drill a new well to replace Well F1. At the same time, an application for the repermitting of Well F1 was submitted to allow continuation of its permitted status as an emergency backup well until such time as Well F3 could be drilled and permitted. Site F received a final denial to operate Well F1, effective December 3, 1985, but has received a final permit to construct and operate Well F3 (IEPA files, 1986). Well F1 is scheduled for testing in mid-1987 prior to plugging and abandonment procedures.

Waste Holding Ponds. Waste disposal into Well F2 was permitted in two phases. Phase I, permitted on March 10, 1972, was for disposal into Well F2 of the high-saline Chlordane waste formerly disposed of in Well F1. Phase II, permitted on October 23, 1972, was for the installation and operation of holding ponds, filters, and pumps for injection of all plant effluent formerly discharged to surface waters of the state. This was accomplished in mid-1973 (IEPA files, 1972, 1973).

Throughout the 1970s, however, Site F had problems with unplanned discharges to surface waters. In response to an Illinois Pollution Control Board order of April 5, 1973, Site F now injects all land runoff from its process area and certain designated adjacent areas in addition to the wastes generated on-site. On several occasions in the 1970s, accumulation of water in the waste holding ponds during periods of heavy rainfall exceeded the capacity of the deep disposal wells to keep the pond levels down. On these occasions, wastewater was discharged to surface waters in order to prevent breakage of berm walls due to high water levels in the ponds (IEPA files).

Site G

The Class I injection well at Site G was originally drilled and completed in 1968 for injection of water removed from the Silurian natural gas storage reservoir. It was reworked in 1974 for disposal of natural gas scrubbing operation waste. When disposal operations commenced, the well had a 7-inch long string casing and utilized a 3 1/2-inch tubing set on a packer.

There have been problems with this well since it was reworked as a Class I well. In June 1975, inspection of the well revealed that of the 65 lengths of 7-inch casing in the well, 22 showed evidence of corrosion between 20 and 41 percent of the nominal wall thickness, 37 showed evidence of corrosion between 40 and 61 percent of the nominal wall thickness, and one showed evidence of corrosion exceeding 60 percent of the nominal wall thickness. In January 1976, pressure testing of the 7-inch casing revealed at least seven leaks. This problem was remedied by setting a new 5-inch casing inside the 7-inch casing (IEPA files, 1976). However, this 5-inch casing was not cemented inside the 7-inch casing; rather, it was set on a packer inside the 7-inch casing. The well then had two annuli that were kept under pressure. During this workover, an estimated 236,670 gallons of accumulated waste was disposed of in an unpermitted well completed in the Salem Limestone (IEPA files, 1976).

Since that time, there have been problems at Site G with keeping pressure on the inner as well as the outer annulus. In January 1984, the operator reported that "it has become impossible to maintain a higher pressure in the larger annulus regardless of the frequency of repressuring." He requested permission to stop maintaining the pressure (differential) in the 5-inch x 7-inch annulus altogether (IEPA files, 1984). On other occasions prior to 1984, communication had developed between the two annuli.

The Site G operator has submitted an application for this well to be permitted in its present condition under the new regulations until a replacement well can be drilled and put into operation in 1987. However, a well that does not have mechanical integrity because of communication between annulus and formations (via casing leaks) should not be operated as a Class I disposal well. Recommendation was made to the IEPA that this well should either be reworked to eliminate its problems or be plugged and abandoned (IEPA files, 1986). A final denial to operate this well became effective June 3, 1987 (IEPA files, 1987).

CHARACTERIZATION OF INJECTED WASTES

The seven Class I sites currently receive their wastestreams from on-site generating facilities. These wastestreams include wastes from the process areas, collected spillage, and contaminated surface runoff from perimeter areas of the plant property. A review of the character of these wastes indicates that three general types are disposed of in Illinois: (1) alkaline wastes (pH ~ 13) containing chlorinated organics; (2) very acidic wastes (pH <3) containing hydrochloric, sulfuric, or hydrofluoric acids with variable amounts and kinds of metals and salts indigenous to the individual process streams; and (3) moderately acidic wastes (pH 4 to 7) consisting of mixtures of organic components and various chloride and sulfate salts. The second waste type represents the largest volume of waste: 222,000,000 gallons were disposed of in 1984. Volumes for waste types one and three were 68,000,000 gallons and 11,000,000 gallons, respectively, in 1984. Injection of these wastes occurred either in the Elmhurst-Mt. Simon Sandstone, Potosi Dolomite, Devonian limestone, or Mississippian limestone at depths ranging from 1540 to 5524 feet. Figure 2 shows waste volume injected per year and cumulative injection since 1965.

The industrial process producing each wastestream, the size of each wastestream, and the average concentration for the major waste constituents are summarized in Table 3-1. A brief description of each waste is given in this section and a tabulated summary of injection waste components at each site (during a 2- to 5-year period from 1980 through 1984) is given in Appendix A. The data used to summarize each of the waste's characteristics are based upon monthly reports submitted to the IEPA by the UIC facilities as partial fulfillment of permit requirements. The records for 1980 through 1984 were determined to be representative of the wastestreams: (1) these records are more complete and detailed for the latter part of the 20-plus year period deep well injection has been practiced in Illinois; and (2) the characteristics of the injected wastestreams have remained relatively uniform over this period of more than 20 years. To ascertain the temporal variability of

Table 3-1. Summary: Waste currently disposed of in Class I injection wells.

Industry	Waste type and source	Maximum permitted Injection rate*	Average dally Injection rate (gpd)	Major waste constituents of concern and approximate average concentrations	
A	Hydrochloric acid from silicon dioxide production	400 gpm, 50psi 400 gpm, 50psi	180,000 (standby well)	Hydrochloric acid (pH <1) Chloride	1.0% 1.0%
B	Wastes from natural gas scrubbing process	30gpm,300psi	15,000†	Total Dissolved Solids (pH 6-8) Chloride Sulfate Magnesium Vanadium Iron Anthraquinone disulfonic acid	0.4% 0.1% 600 ppm 60 ppm 10 ppm 4 ppm 15 ppm
C	Hydrochloric acid and heavy metals from waste pickle liquor	260 gpm, 340 psi	17,500*	Chlorides Iron Hydrochloric acid (ph <1) Manganese Copper Nickel Zinc Chromium and lead	22% 14% 2.5% 600 ppm 25 ppm 20 ppm 3.5 ppm <1 ppm
D	Leachate from gypsum waste piles and limited production wastes from alcohol production	40gpm,250psi	350,000	Total Dissolved Solids Sulfate or sulfuric acid (pH 2-3) Phosphorus Fluoride Calcium Chromium Total organic carbon (TOC)	0.6% 2200 ppm 600 ppm 180 ppm 300 ppm <1 ppm 100 ppm
E	Hydrochloric acid from fluorocarbons production	150 gpm, 100 psi	72,000	Hydrochloric acid (pH 1 -4) Hydrofluoric acid Chloride Fluoride Arsenic Nickel Total Organic Carbon (TOC)	3.0% 0.1% 0.8% 0.04% 30 ppm 2 ppm 13 ppm
F	Caustic process wastes and contaminated surface runoff from pesticides production	450 gpm, 616 psi 200 gpm, 383 psi	186,000 (standby well)	Total Dissolved Solids Chlorides Volatile chlorinated hydrocarbons Sodium hydroxide (pH-13) Chlordane Nonvolatile chlorinated hydrocarbons	3.5% 1.7% 14 ppm 0.4% 0.5 ppm 480 ppm
G	Wastes from natural gas scrubbing process and waste brine solution	40 gpm, 300 psi	20,000†	Total Dissolved Solids (pH 6-8) Chloride Sulfate or sulfite Vanadium Anthraquinone disulfonic acid	8.3% 5.0% 100 ppm 30 ppm 21 ppm

* Injection wells at industries A, C, and E are generally operated at much lower injection rates; injection pressures may range from negative (vacuum) to low positive pressures.

† These waste volumes are highly variable on a seasonal basis, ranging from 0 to 40,000 gpd.

‡ This wastestream is generated as a 70,000 gallon batch about once every four days.

constituents associated with the injection wastes, the standard deviation (S) and coefficient of variation (CV) of the concentration for each constituent were calculated. The standard deviation is a measure of dispersion about the mean. The coefficient of variation is defined as the standard deviation divided by the mean times 100 and is especially useful for comparing the amount of variation within data sets having different means.

Site A

The waste from Site A is generated as a by-product from the production of extremely fine-grained, amorphous silica particles and is considered hazardous because the pH is low (IEPA, 1984). The waste product is hydrochloric acid (HCl), which until 1980 was codisposed with small quantities of acidic starch and nitric acid waste generated by other off-site manufacturing processes. No operational problems were reported with codisposal. Currently only the hydrochloric acid waste is being disposed of by deep well injection. The limited detailed information available describing the chemical composition makeup of the waste is given in Appendix A. All chemical analyses required by the operating permit were run for this wastestream. The injection volume of the waste has remained relatively constant in relation to time (1980-1984) with total annual gallons injected ranging from 55,200,000 to 75,800,000. Hydrochloric acid concentrations in the waste have been reduced from an annual mean of 3.20 percent in 1980 to 0.77 percent in 1984. This reduction in acid concentrations is significant, since the waste is disposed of in a dolomite aquifer in which the acid is neutralized by the carbonate components of the dolomite. This reduction in acid concentration was a safety measure to ensure that carbon dioxide (CO_2) and heat evolution generated by the reactions between the acid and carbonate formation minerals would not cause problems of oversaturation of CO_2 in the aqueous system. On the basis of monthly data for the 5 years of the record period, changes in the concentrations of waste components have shown that the suspended solids are more variable than HCl or chloride (Appendix A). On an annual basis, however, there has been relatively little variability in any of the components, indicating the wastestream is homogeneous with time.

Sites B and G

Sites B and G have similar wastestreams that include a discharge from a hydrogen sulfide (H_2S) stripping operation, compressor station drains wastes, and formation water associated with the storage and withdrawal of natural gas stored in underground formations. These wastestreams are considered nonhazardous (IEPA, 1984). At Site G, formation water removed from below the gas bubble in the natural gas reservoir to regulate pressures within the reservoir is injected with the process waste. Water from this removal constitutes as much as 75 percent of the total volume of waste injected at Site G. However, at Site B the small volume of formation water removed from above the caprock is of such quality ($\approx$10,000 mg/L TDS) that it is not necessary to inject this water back into the waste disposal formation, and thus the injection volume at Site B is smaller than at Site G.

The tabulation of data from the monthly reports indicates that more than 50 percent of the waste samples analyzed during a 5-year period (1980-1984) had pH values between 4 and 7. The major components of the waste at Site B on the basis of relative concentrations (mg/L) determined over a 2-year period (1983-1984) are Na > Cl > SO_4 > Ca > Mg > ADA (anthraquinone disulfonic acid) > V > B > F. The components of the waste and their relative concentrations are similar at Site G; however, chloride is found in greatest concentrations at Site G, reflecting the larger volume of formation water included in the wastestream and the high chloride concentration of the formation water. The absolute concentrations of such constituents as Ca, Cl, Mg, V, and ADA at Site G are generally 2 to 50 times greater than at Site B. The average monthly injection volumes, 540,000 and 600,000 gallons for Sites B and G, respectively, are similar. Seasonal variability in composition appears to be a function of natural gas demand from the reservoir during the heating season and gas storage during the rest of the year. The regulation of reservoir pressure at Site G is related to natural gas demand and ambient temperature—generally a seasonal relationship. Constituents in the wastestreams generated by the H_2S removal process (ADA, SO_4, V) have CV values ranging from 65 percent to 100 percent; the other constituents have CV values between 10 percent and 45 percent.

Site C

Pickle liquor wastes generated by the processing and finishing of steel are disposed of by deep well injection at Site C. These industrial processes generate ferrous chloride and hydrochloric/chromic acid (1.93%) solutions, whose pH values are less than 1.0. This waste is considered hazardous (IEPA, 1984). The relative concentrations of constituents in the waste are $CI > Fe > Mn > Cu > Ni > Zn > Cr$ (Table 3-1). The absolute concentrations for CI and Fe are in the 14 to 22 percent range, with most other constituents less than 25 mg/L (.0025%) (see Appendix A for exact concentrations). This waste is relatively homogeneous with time (CV values $\leq 15\%$), as would be expected, since the processing of steel requires constant conditions for product uniformity.

Site D

The major source of liquid waste at Site D is surface runoff and leachates that are collected in lagoons surrounding waste gypsum piles. These piles were generated in past site operations during the chemical processing of rock phosphate to phosphate fertilizer. This site has discontinued production of phosphate fertilizer and is currently producing a medicinal grade alcohol. The liquid waste is characterized by a low pH (2.6) and is considered nonhazardous under IEPA, 1984. The low pH is associated with H_2SO_4 which is estimated at 1.5 percent in the wastestream. The relative concentrations of constituents in the waste are $SO_4 > Na > P > Ca > F > Mg > CI > K > Hg$. The range in concentrations is from 2500 mg/L for SO_4 to several hundred milligrams per liter for Na, P, Ca, F, and Mg. Waste products from on-site laboratory facilities account for the mercury (Hg) in the waste. These Hg concentrations are in the tenth of a part per billion range. The waste is relatively homogeneous, with CV values between 10 percent and 25 percent. The variation in waste concentrations may be attributed to seasonal fluctuations in climatic conditions. Since this waste is principally a leachate, heavy rainfall and snowfall can cause variation in its concentration and volume.

Site E

The waste at Site E is an acidic byproduct from the manufacture of fluorocarbons and is considered hazardous (IEPA, 1984). The pH (<4) reflects the fact that the waste is a hydrochloric acid (HCl) and hydrofluoric acid (HF) mixture with average concentrations of 2.96 percent and .086 percent respectively. Low-volume flushes of sodium hydroxide (NaOH) change the pH of the wastestream for short periods of time from an acidic (pH<4) to an alkaline (pH>11) solution. The relative concentrations of major components in the waste are $CI > NaF > As >$ total organic carbon $>$ Ni. The average concentrations in the waste are: chloride, 7300 mg/L (occasionally can be as high as 59,000 mg/L); sodium fluoride 930 mg/L; arsenic 30 mg/L; and total organic carbon (TOC) 13 mg/L. Depending on the type of organic constituents contributing to the TOC, the organic fraction of the waste may be potentially more hazardous than the acidic nature of the waste. Identification of these organic components is necessary to ascertain the "real" potential hazard of this waste. The wastestream appears to be variable: differences between minimum and maximum concentrations vary by factors of 10 to 100, and CV values range from 30 percent to 100 percent for the various waste components.

Site F

The hazardous waste at Site F includes production wastewater and surface runoff water from on-site process areas. Runoff water comprises approximately 75 percent of the total volume of waste. A chlorinated pesticide for agricultural application is the principal product at this site. The disposal waste is not only highly alkaline (pH>13) but also contains chlorinated pesticides and other chlorinated hydrocarbons. The relative concentrations of constituents in the waste are NaCl > NaOH > hexachlorocyclopentadiene (hex) > chlordane (Table 3-1). The range in concentration of the inorganic fraction of the waste is from 0.2 percent to 12 percent. The organic fraction has concentrations from a tenth of a milligram per liter to several hundred milligrams per liter. This waste is quite variable; most CV values are equal to 100 percent, and differences between minimum and maximum values generally vary by factors of 10 to 100. A significant portion of this variability is related to precipitation frequency and intensity.

POTENTIAL FOR CONTAMINATION OF SHALLOW AQUIFERS FROM SURFACE SPILLS

The UIC regulations and regulatory practices have enforcement jurisdiction over wastestreams injected into Class I wells, beginning essentially at the wellhead and including all well equipment and earth materials penetrated or affected by the injected wastestream. All above-ground equipment necessary for well operation is also covered under UIC regulations. Upstream from the wellhead, in the piping, storage, and waste generating facility, RCRA regulations are enforced. Most spillage above ground is covered under RCRA regulations; however, leakage from the wellhead or an occurrence of backflowing of a well when the wellhead is disassembled for repairs could affect the surface environment in the immediate vicinity of the wellhead. The following discussion describes surface and near surface conditions at each of the seven deep well sites and the expected direction of movement of spilled waste fluid. Since public water supplies could be adversely affected by a spill, a brief description is given of nearby public water supply wells. The spillage or leakage of waste from the wellhead is never expected to be large in volume or frequent in occurrence. Several wells have spill collection facilities surrounding the wellhead.

Leakage of waste from the wellhead assembly at each Class I site represents a potential source of contamination of shallow aquifers present in the deposits beneath disposal sites. The potential for contamination is governed principally by the size of the spill, the character of the waste, and the nature of the deposits lying between the land surface and the aquifer. This evaluation of the potential for contamination deals only with the nature of the earth materials beneath each disposal site. It is based on descriptions of material that have been taken from well logs, soils maps and reports, and a map entitled "Potential for Contamination of Shallow Aquifers from Land Burial of Municipal Wastes" (Berg et al., 1984).

Each site has been assigned a potential-for-contamination rating based principally on the permeability and thickness of the surface deposits above the shallow aquifer(s). The rating categories are:

I. Highly permeable deposits extend downward from the land surface to the top of the aquifer; there is a high potential for contamination; spill containment facilities are highly recommended.

II. Highly permeable and moderately permeable deposits overlie an aquifer located 30 to 50 feet below the surface; there is a high to moderate potential for contamination; spill containment facilities are recommended.

III. Moderately permeable and slightly permeable deposits overlie an aquifer located 30 to 50 feet below the surface; there is a moderate potential for contamination; spill containment facilities are advisable.

IV. Slightly permeable and some moderately permeable deposits overlie an aquifer located 30 to 50 feet below the surface; there is a moderate to minimal potential for contamination.

V. Slightly permeable materials overlie an aquifer that is buried more than 50 feet below the surface; there is minimal potential for contamination.

Sites A and D

These two sites located on adjacent properties have been combined for description of the surface and near-surface deposits. Three disposal wells are located on these sites.

The soils in this area consist of the Drummer silt-clay loam and the Elburn silt loam. The Drummer consists of deep, poorly drained soil (USDA Soils Map for Douglas County) that has developed on a level to gently undulating surface along drainageways. The Elburn is similar in character, has slightly better drainage, and is located on slightly higher ground. Permeabilities are moderate, but artificial drainage is necessary in some areas for good crop production. These soils have neutral to slightly basic pH values in the lowest lying areas to slightly acidic in the higher areas. The parent materials consist of about 60 inches of loess (windblown material) overlying the Batestown Till Member of the Wedron Formation. Older till units and a thin, continuous sand and gravel layer 75 to 100 feet deep are the other types of glacial deposits in the area. A north-trending tributary of the Pesotum bedrock valley accounts for the nearly 200 feet of glacial deposits beneath these sites.

The glacial deposits provide the bulk of the water supplies for farms and residences in the area. Surface drainage moves westward and southwestward toward the Kaskaskia River. Groundwater

percolates very slowly and flows westward toward the Kaskaskia in both the glacial deposits and the uppermost bedrock.

The bedrock consists of shale and some thin, interbedded sandstone and limestone beds. These rocks of the Pennsylvanian-age Mattoon Formation provide a limited source for water supplies and are tapped only when supplies cannot be obtained from the glacial deposits. Water quality begins to deteriorate rapidly about 50 feet below the top of the bedrock surface. Figures 2-2 and 2-3 show generalized profiles of the geologic units and distribution of the primary drinking water sources.

The City of Tuscola obtains approximately half of its public water supply from wells finished in Silurian and Devonian dolomites at depths ranging from 460 to 696 feet. These wells are located on the west flank near the crest of the La Salle Anticline. The Devonian and the underlying Silurian, known as the Hunton Megagroup, lie at or near the bedrock surface in the vicinity of the city well field but are buried more than 2500 feet below the land surface at Sites A and D, which are located about 3 miles to the west. Highly mineralized water (12,460 mg/L) was sampled from the Silurian during construction of Well A2. The interface between fresh water and highly mineralized water is expected to lie on the lower flank of the anticline some distance east of these sites. A thick sequence (1600 feet) of low-permeability rock units and an interbedded aquifer separate the Silurian-Devonian from the disposal zone in the Eminence-Potosi Dolomite.

Tuscola supplements its groundwater supply by purchasing about half of the water needed from the U.S. Industrial Chemical Company. This company operates a side-channel reservoir and treatment plant on the east side of the Kaskaskia River. Surface drainage from Site A and the process area of Site D enters the river south of the reservoir; however, the waste storage piles and ponds at Site D lie northeast of the reservoir. All surface drainage from the waste storage piles and the immediately surrounding area is diverted into the surrounding waste storage ponds and then discharged into the disposal well.

Sites A and D have been assigned a Category V potential-for-contamination rating.

Site B

The drainage rate of ponded water moving through the soils of this area is moderate (USDA Soils Map for Kankakee County). The rolling topography allows excess surface water to move quickly toward drainageways that are tributary to East Branch Horse Creek. Symmerton, Andres, and Reddick soils have developed on the knoll crest, slope, and lower slope-drainageway, respectively, at the well site. The parent material is a thin loess (less than 20 inches) overlying the Yorkville Till Member of the Wadsworth Formation. Locally, this till is very clayey, and it contains small lenses of sand and gravel. Soil permeabilities are moderate on the knoll at the well site and moderately slow in the drainageways to the south and north. The glacial deposits are about 50 to 80 feet thick. Only one domestic well of record is finished in the glacial deposits in the immediate vicinity of the disposal well.

The shallow bedrock consists of Ordovician-age shales and dolomites. These units, where water yielding, are the principal sources for residential and farm water supplies. The Maquoketa Shale Group forms the bedrock surface. A very limited potential for water supply exists in the shale; dolomite intervals in this unit may provide small supplies. The principal source for water, the Glenwood-St. Peter Sandstone, lies below the Galena-Platteville Dolomite Groups in the depth interval of 550 to 800 feet. The Village of Herscher, which lies on the crest of an elongated north-south trending structural dome, obtains its water supply from a well finished in Silurian dolomite about 3 miles east of the village. Several additional bedrock wells open to the Galena-Platteville dolomites and St. Peter Sandstone have been abandoned or are currently inactive. These wells lie east of the village and about 1 1/2 to 3 miles north and east of the disposal well. Small groundwater supplies in the area are obtained from crevices in the shallow dolomite. In the shallow deposits groundwater moves downward and to the northeast. Regional shallow groundwater flows toward the north. Surface water runoff from the well site moves eastward and then northward adjacent to the sites of several village wells. Flow conditions in East Branch Horse Creek are such that no waste that might enter the surface drainage system would percolate from the stream bed and enter an underlying shallow aquifer.

Site B has been assigned a Category IV potential for contamination rating.

Site C

The drainage of ponded surface water through the O'Neil silt loam is moderate to rapid at this site (USDA Soils Map for Putnam County). This soil, developed on the Mackinaw Member of the Henry Formation, has a very high permeability and a pH level in the moderately acidic range. The sandy Mackinaw Member is relatively thick and overlies one or more sandy outwash deposits. The combined thickness of these sands is 100 to 130 feet. The basal sand unit is the Sankoty Sand Member of the Banner Formation. These sands represent a major aquifer in the area that can yield moderate to large supplies to wells penetrating them. The Sankoty Sand partly fills the bedrock valley of the Ancient Mississippi drainage system. The overlying Henry Formation was deposited during the last episode of glaciation that sent meltwater down the Illinois River Valley. Once percolating water passes through the thin silty-clayey soil zone covering the Henry Formation it moves rapidly downward to the water table zone in the Henry. The water table lies at or slightly above the flow stage elevation on the Illinois River. The river is located about 1 mile to the west. Surface drainage that does not percolate into the soil moves westward toward the river.

Most wells in the area, including those for the City of Hennepin, are finished in the sand and gravel aquifer. General groundwater flow in the vicinity of the disposal well is downward to the water table and then westward toward the river. Large producing wells in the area may alter this general flow direction as their drawdown cones traverse across the area of the well site. An extensive system of leak-collecting gutters beneath the piping and a sump pit around the wellhead are capable of intercepting leakage and spillage in the vicinity of the wellhead.

The shale bedrock of Pennsylvanian age does not yield enough water to be considered a significant source of drinking water. The underlying carbonate units of the Hunton Megagroup offer a low to moderate potential for water supply. The water is heavily mineralized and under a flowing artesian head in the river valley.

The nearest public supply well, Hennepin Well No. 5, is finished in sand and gravel about 1/2 mile to the west (downgradient) from the disposal well. To the northeast the City of Granville obtains its supply from two bedrock wells finished in the St. Peter Sandstone at depths exceeding 1700 feet. A pipeline from Granville supplies the Village of Mark with water. A water supply well under consideration for completion in the Sankoty Sand has a tentative location north or northwest of Granville. The Village of Bureau Junction has a well finished in the Hunton Group. Any significant spillage in the vicinity of the disposal well would move in the direction of the Hennepin wells and could pose a potential threat to this public water supply, but should not endanger the deep well supply at Granville or at Bureau Junction. However, it should be noted that the very high specific gravity of this waste would carry it to the base of the sand and gravel aquifer, probably causing the waste to travel through the sand and gravel below the base of these wells.

Site C has been assigned a Category I potential-for-contamination rating, since leakage or spillage of waste has a high potential for contaminating shallow aquifers beneath the site.

Site E

The surface soil profile at this site has very slow drainage. Surface drainage around the well is directed to on-site ditches. General surface drainage is to the west into a tributary of Stony Creek that empties into the Vermilion River. A sump pit surrounds the wellhead. The soils, classified as Drummer clay loam and Brenton silt loam, have moderate permeability ratings and lie in the alkaline pH range (USDA Soils Map for Vermilion County). Loess, windblown silt that is the parent material for most of the soil profile, has an estimated thickness of more than 40 inches and overlies the surficial glacial till unit, the Batestown Till Member of the Wedron Formation. This formation is a gray, silty till with a few interbedded lenses of sand and gravel. Water wells of record in the immediate vicinity of the site penetrated little sand and gravel. The total thickness of the glacial drift deposits is 95 to 130 feet. There is a general thickening of the drift toward the west into a northerly trending valley on the bedrock surface. The axis of this valley lies several miles to the west. Sands and gravels partly fill this valley and are a source for small to large groundwater supplies. A small tributary valley lying about 1 mile to the southwest of the disposal well contains a considerable thickness of sand and gravel, but another small bedrock valley lying about 1/2 mile to the north has only a limited thickness of sand and gravel. The bedrock consists of shale with a few interbedded layers of siltstone, sandstone, limestone, and coal. Water yields for wells finished in the bedrock

are limited; wells not obtaining water from the glacial deposits are finished in shallow bedrock to depths ranging from 95 to 220 feet. Figure 2-3 shows the sequence of units at greater depth and the interval in the shallow deposits having primary freshwater resources.

Groundwater flow in the glacial deposits and shallow bedrock moves toward the southwest toward either the bedrock valley beneath Stony Creek or the Vermilion River.

The nearest public water supply wells are located about 2 miles southwest of Site E. In addition, three mobile home parks have developed water supplies from seven wells finished in sand and gravel deposits at depths of 74 to 110 feet. Surface spills at the wellhead would probably not be a direct threat to these wells for the following reasons: the relatively impermeable nature of the glacial deposits at the site and the lack of sand and gravel in these deposits; the depth of the wells providing water supply and the distance between the wells and the disposal site; the relatively small volume of waste that would be involved; and the effects of neutralization by carbonate materials in the soil and dilution with existing groundwater.

Danville maintains a reservoir on the North Fork Vermilion River for municipal water supply needs. The supply intake is upstream from the discharge point of surface runoff from the site and is located about 6 miles west of the well site. All dwellings and industries in the immediate vicinity of the site have access to public water supply mains for drinking water.

Site E has been assigned a Category V potential-for-contamination rating because potential for contamination of shallow aquifers beneath this site is low.

Site F

The drainage of surface ponded water at this site is slow (USDA Soils Map of Clark County), and water that does not percolate into the subsurface will move westward into the East Mill Creek drainage system. A system of ditches and collection gutters collects the precipitation falling on the production area of the plant and directs it to one of two on-site wastewater impoundments. Water from the impoundments is discharged into the disposal well. The Stony silt loam and the associated Weir silt loam, which lies downslope immediately to the west, have developed on 50 to 70 inches of loess that overlies the Vandalia Till Member of the Glasford Formation. These soils exhibit low to very low permeability characteristics and have a moderately acidic pH level. Locally the Vandalia Till, a sandy, silty unit, is 5 to more than 15 feet thick. A thin sequence of Lierle Clay and an older till is deposited beneath the Vandalia in a small valley on the bedrock surface in the southern and western part of the plant property. A thin, discontinuous sand or sand and gravel zone may be present at or near the base of the glacial deposits. The glacial deposits range from less than 10 feet thick along portions of the east boundary of the plant property to a maximum of nearly 50 feet in the southwest. A significant deposit of sand and gravel partly fills the entrenched valley of Big Creek, which lies about 1 mile to the northeast of the well site.

The bedrock consists of a few tens of feet of shale, soft sandstone/shale, and fine-grained sandstone belonging to the Bond Formation of Pennsylvanian age. The Modesto Formation, with shale and interbedded sandstones, siltstones, and limestones, lies immediately below the Bond. Limited supplies of groundwater have been obtained from the bedrock and glacial deposits on the upland. Groundwater appears to move to the west in both the glacial deposits and the shallow bedrock. A drainage divide for both surface and groundwater is assumed to lie in the vicinity of the east line of the plant property.

The City of Marshall has constructed four sand and gravel wells, 65 to 75 feet deep, in the valley of Big Creek about 2 miles east of the site. The creek valley is incised into the upland to a depth of about 100 feet, exposing the Bond Formation in the valley walls. The cone of depression created by municipal pumpage is essentially limited to the sand and gravel deposits in the creek valley. Municipal water is available to the residents and business establishments south and southeast of the site.

Site F has been assigned a category III or possibly a category IV rating, because the potential-for-contamination of the limited shallow aquifers beneath this site is low to possibly moderate.

Site G

This site is situated on a rolling upland that is bordered by moderately incised tributary valleys of the Kaskaskia River. Bluford silt loam has developed on loess (30-55 inches thick) overlying the Vandalia Till Member of the Glasford Formation in the immediate vicinity of the well, and the Hickory gravelly loam occupies the steeper slopes in and adjacent to the downslope drainageways (USDA Soils Map of Fayette County). The Bluford consists of a deep, somewhat poorly drained soil that is slowly permeable. The Hickory soil has developed on relatively steep slopes; it exhibits moderate to good drainage for ponded water and has moderate permeability. Both soils have acidic pH levels. The Vandalia Till consists of sandy-silty material and some scattered sand and gravel deposits. On the upland the glacial deposits have a thickness of 40 to 65 feet, but bedrock is exposed along the lower slopes of the deeper ravines and stream valleys. Alluvial deposits in the stream valleys contain some sand and gravel deposits; however, these deposits are not located near the disposal well site. The disposal well is located more than 1000 feet west of the waste generating facility.

The bedrock consists of shales with a few interbedded sandstones, siltstones, and limestones in the lower part of the Mattoon Formation of the Pennsylvanian System. Along the lower slopes of Big Moccasin Creek, less than 1 mile north of the site, the Bond Formation is exposed. The upper bedrock lacks significant potential for yielding water to wells. Sandstones capable of yielding small supplies exist below a depth of 200 feet, but groundwater from this depth is too mineralized for use as a potable water supply.

There are no public water sources in the immediate area of the site, but a few wells for domestic and farm use have been developed in the glacial deposits and the shallow bedrock. Wells that do exist in the upland are shallow and subject to drought conditions, producing low yields of poor-quality water. The thin sand and gravel deposits in the Kaskaskia Valley and its larger tributaries are the only significant source for water supply in the area.

Site G has a Category IV rating because the potential for contamination of the limited aquifers in the shallow deposits beneath the site is low.

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4 FATE OF INJECTED WASTES

The major concern about deep well injection of hazardous waste is that the injected waste will migrate undetected into an underground source of drinking water (USDW). The creation of caverns by dissolution of the formation material by acidic waste can be of concern if the caverns are extensive enough to structurally weaken the confining layer. Another concern is that interactions between the injected waste and the formation material or water in the injection zone will result in decreased permeability of the formation, shortening the usable life of the well. This chapter focuses on what is and is not known about the (1) mobility of the injected waste, (2) its interactions with the injection formation, and (3) the effectiveness of the monitoring procedures used to assess whether or not the waste is adequately contained.

MOBILITY OF INJECTED WASTES

Three factors govern the mobility of wastestream components in geologic formations: (1) the mobility of each pollutant molecule within the formation fluid that is carrying it (the diffusion rate); (2) the extent to which each pollutant molecule sorbs onto or reacts with the solid material forming the surfaces of the pores through which it moves, and (3) the distance the formation water carrying the pollutant travels. The first factor is sometimes important in the slower flow of unperturbed aquifer systems that move a fraction of an inch per day to less than a few inches or a few feet per year. In such systems, some of the diffusing solute molecules can move significantly faster than the average velocity of water flow and thus appear to be traveling faster than the water itself (Peyton, 1986; Relyea, 1982). Under the conditions of deep well injection, however, this effect can be considered negligible over the initial life period of the well when compared to the velocity at which the underground waste front moves radially from the borehole in a deep injection well. The initial velocity may be on the order of a few to ten feet per day, but the velocity progressively decreases, and near the end of the normal life expectancy (20 yrs) of the disposal well, the front may advance radially from the well at only a few tens of feet per year. Diffusion could also be a contributing factor in upward migration through improperly abandoned wells that may penetrate any part of the disposal zone receiving injected waste, whether in or beyond the calculated area of review.

Sorption can result in retardation of the flow of waste components relative to the advancing water front, because most components at some point become associated with the pore surfaces in the rock matrix rather than moving freely with the injected liquid phase. For inorganic materials such as heavy metals, this retardation occurs primarily by ion exchange with clay minerals. In clay-rich surficial soils ion exchange may initially cause some components to travel ten times slower than the advancing water front (Griffin et al., 1980). Injection formations that contain only small amounts of clay materials can be expected to offer only a small amount of retardation to sorbable components because there is a limited sorption capacity. After the clay at a given position in the disposal zone is saturated with the component, no more component is retained and "breakthrough" occurs. The breakthrough front moves radially away from the well bore. For a very concentrated solution of a given waste component, this breakthrough may be almost immediate, whereas for a dilute solution the rate of movement of the breakthrough front may be very slow.

Movement of injected organic waste components such as pesticides or solvents may be retarded in the disposal formation by sorption to the formation materials. The extent of sorption directly affects the migration velocity of relatively insoluble organic material. If the organic component has limited solubility in water, the undissolved component may physically coat the solid material and thus no longer move with the wastestream. This situation, however, is usually undesirable in deep well injection, since it frequently results in a decrease in permeability of the formation, necessitating higher injection pressures to obtain the desired injection rate. The mobility of water-soluble organic compounds, in contrast to that of slightly soluble ones, tends to be the same as the water itself

(Sutton and Barker, 1985), so that a range of behaviors from strong retention to almost no retardation of the pollutant can be encountered, depending upon the water solubility of the organic chemical and the clay content of the earth materials through which the waste components pass.

Perhaps more important than the sorption characteristics of waste components onto formation materials are the characteristics of porosity in the formation into which the wastestream is being injected. The information cited in the preceding paragraphs is generally obtained from laboratory experiments using columns packed with fine-grained, relatively homogeneous material and is thus applicable only to isotropic porous media (having the same characteristics of porosity in ail direction). Flow and sorption/ion exchange characteristics of isotropic media are relatively easy to model and test in the laboratory. Prediction and test procedures for wastewater and waste component distribution and fate in actual formations (porous and fractured anisotropic media) used for injection are difficult. Waste components moving through relatively large channels may have difficulty reaching a solid surface at which they have opportunity to undergo sorption or ion-exchange reactions. In addition, there is less surface area contacted by the liquid waste in this case than there is when a waste passes through fine- to medium-grained porous media. Therefore, in fractured or other anisotropic media considerably less retardation may take place, and prediction of retardation factors becomes practically impossible (Freeze and Cherry, 1979). Thus, the only safe assumption to make for fractured media is that the waste components move with a velocity approximately equal to that of the advancing water front.

Porosity and permeability can vary greatly in anisotropic media. The injected waste may travel preferentially in one direction rather than radiate symmetrically from the well, as is typical for waste injected into isotropic media. When this occurs, part of the expanding waste front may travel considerably farther than would be expected in isotropic media.

In some cases a rapid chemical reaction occurs between a waste component and formation material in which both are transformed to other substances with different properties. The most important example is the neutralization reaction between acid wastes and carbonate rocks (limestone or dolomite) that produces salts. Although the salts may be soluble and quite mobile, moving at the velocity of the water itself, the *property* of acidity is retarded, advancing at the rate at which it fails to be neutralized. Thus, while injection of acid wastes may be of concern because of potential formation subsidence (large crevices and cavities can be created as formation material is dissolved by the waste components flowing past it), the acidity of the waste is being neutralized by the formation.

The calculations frequently used to determine the area of review assume that injection takes place in a porous, isotropic medium, but actual disposal zones have variable degrees of anisotropy. Anisotropy produced by crevices and channels present in fractured media can cause significant channeling of waste components along the trend direction of these features. There is an increased possibility that flow thus concentrated along fracture trends may cause wastes, displaced formation water, and the injection pressure front to migrate beyond the position calculated for these parameters in an isotropic, homogeneous porous medium. Under such conditions of anisotropic and nonhomogeneous flow the expansion of the critical isobar on the pressure front in the injection zone beyond the calculated radius of the area of review may generate a potential risk for USDW before the end of the established life expectancy of the well. The critical isobar is defined as the constant pressure-line threshold at the top of the injection zone which, if exceeded, would generate a positive hydraulic gradient between fluid in the injection zone and fluid in overlying USDW. Under ideal conditions the position of the critical isobar never extends beyond the boundary of the area of review during the established life expectancy of the well. Anisotropy in the disposal zone most likely will cause incursion of the critical isobar into the region beyond the area of review. The procedure for calculating the area of review should be modified to incorporate the anisotropy and nonhomogeneity of the rocks constituting the disposal interval. If this information is not available, a suitable safety factor should be included in the determination of the area of review. Any incursion of the critical isobar beyond the area of review may place USDW at risk because the region beyond the area of review may include improperly plugged wells or other features that could compromise the integrity of the primary confining interval.

INTERACTIONS BETWEEN INJECTED WASTES AND FORMATIONS

Wastes injected into any disposal zone may interact with the native groundwater and/or minerals in the earth materials of the disposal zone. Such interactions may be beneficial, neutral, or detrimental to waste injection and therefore may affect both the safety and efficiency of the disposal well. Demonstration of compatibility of the waste with components of the proposed disposal zone is required as part of the feasibility report submitted with the permit application; however, the types of experiments conducted to date would not detect any but the most immediate and obvious evidence of interaction between formation material and injected waste.

In recent years, increased public awareness of issues involved in deep well injection has led to questions about the significance of chemical interactions under conditions in the formation used for disposal. However, until this awareness developed, there was little impetus for either industry or regulatory agencies to conduct detailed studies of formation interactions with wastes; thus, only limited in situ data are available on the character of the waste and formation interactions. Sampling technologies and protocols are only now beginning to be developed, and studies have been proposed to collect representative samples from formations and model these reactions. The following information, synthesized from the literature, is an introduction to the potential reactions, complexities, and resulting problems that can take place in waste injection zone environments.

In Illinois, wastes are injected into sandstone, limestone, or dolomite aquifers. The mineral composition of these aquifers has been summarized by Warner and Lehr (1977). A typical sandstone aquifer may consist of 66.8 percent SiO_2 (quartz), 11.5 percent feldspars, 11.1 percent carbonate minerals, 6.6 percent micas and clays, 1.8 percent iron oxides, and 2.2 percent other minerals. Roedder (1959) stated that sandstones containing less than 0.15 percent clay minerals may not exist anywhere in the United States, except for small deposits of exceedingly pure glass sand. Limestone and dolomite aquifers are primarily calcium or magnesium carbonates but may contain as much as 50 percent noncarbonate minerals. The relative potential for these minerals to react with the injected wastes follows the general trend of clays > carbonates > feldspars > micas > quartz.

Studies by Mungan (1965), Bayazeed and Donaldson (1971), Nuttig (1943), Roedder (1959), and Warner and Lehr (1977) identified potential problems associated with waste and formation interactions such as (1) changes in pH and ionic strength, (2) destruction of physical bonding of clay particles, (3) chemical solution of various clays, (4) dissolution/precipitation, and (5) adsorption or exchange. These reactions, which could cause pore blockage and changes in the character of the waste and reduce rates of movement of some waste components, could have detrimental effects on the injection potential of the formation. However, reactions such as dissolution can also have beneficial effects, such as increasing the injection potential of the formations (by increasing their effective porosity) and at the same time reducing the acidity of the wastestream.

Water sensitivity analyses of sandstone core samples from the Mt. Simon Formation, a formation currently used for disposal in Illinois, showed a slight decline in permeability when a brine solution was injected into the core samples. The observed decrease in permeability was attributed to blockage of small pores by dislodged particles. Injection of demineralized water into the cores resulted in a 47 percent loss in permeability (Bayazeed and Donaldson, 1971). Mungan (1965) and Jones (1964) have shown in separate studies that changes in ionic strength and pH cause small pores to be blocked by particles dislodged by dispersion of clays or by dissolution of either calcareous cements by acids or siliceous cements by alkaline solutions. Pore blockage and the resulting decreases in formation permeability can be reduced or eliminated by the introduction of divalent cations and by incremental changes in solution ionic strength of the wastestream. Differences in clay properties govern the degree to which the permeability of a formation will be affected; montmorillinite, illite, and kaolinite have progressively less effect on causing a change in permeability. Conditions leading to pore blockage may exist in some saline sandstone aquifers of Illinois; however, compatibility studies can identify potential pore blockage problems and suggest appropriate changes in disposal practice to avoid disruptive blockage in the disposal zone.

The interactions of injected wastes with carbonate minerals are especially significant when acidic wastes are injected into dolomite and limestone formations. The prevalent reaction between such wastes and formations used for disposal in Illinois is the dissolution of calcium carbonate or calcium-magnesium carbonate. This dissolution forms water, carbon dioxide, calcium or magnesium

chlorides, and sulfates or fluorides, with the ultimate neutralization of the acid. The most serious problem that can result from this dissolution is the formation of large quantities of carbon dioxide, which can, under some well conditions, exceed the solubility limit and/or critical temperature/pressure of the system. When this happens, the sudden evolution of carbon dioxide can cause a "blowout," in which the effervescense of the liquid in the well causes geyserlike ejection of gas and liquid at the surface. This problem is covered in more detail in Chapter 6. As noted, acidic waste neutralization in carbonate injection zones enlarges the flow paths and may generate caverns in the disposal zone. Extensive cavern development may affect the competence of overlying geologic units.

Other problems associated with dissolution of aquifer materials may affect the permeability of the injection zone. Roedder (1959) reported formation of gels when calcium carbonate reacted with an acid; however, it was suggested that variations in rates of dissolution of $CaCo_3$ resulting from temperature and pressure differences at the injection zone depth may alter gel formation. The permeability of carbonate rock units that become oversaturated with carbon dioxide and certain calcium salts may decrease. At present, acid wastes disposed of in carbonate formations in Illinois have caused no serious change in the permeability of formations as monitored by injection and annulus pressures.

A case study of injected waste effects on the formation minerals was described by Champlin et al. (1967) and Bayazeed and Donaldson (1971). They injected simulated wastes similar in composition to the waste generated at site C into sandstone cores from the Mt. Simon Formation. A mixing zone occurred at the interface between interstitial and injected fluids, and iron was the major component sorbed onto the sandstone. Behind the waste front were areas in which the acid had been neutralized by reactions with the sandstone and its cementing agents, and areas in which iron depletion had been caused by combined sorption and precipitation. These studies concluded that (1) reactions of the acid with the sandstone formation will increase the porosity and permeability of the sand and offset any plugging effects from iron deposition in the formation pores; and (2) long-term storage of the waste in the formation will neutralize the acid. Selm and Hulse (1960) noted, to the contrary, that iron tends to cause plugging of sand formations and has been the direct cause of the failure of many injection wells. Monitoring data from Site C have shown no significant changes in the injection rate and only a small increase in injection pressure during the 19-year life of this well.

Roy et al. (1987) studied inorganic reactions between wastes collected from sites A and F and samples of Mt. Simon Sandstone, Potosi Dolomite, and Proviso Siltstone. These studies were conducted in batch mode under low oxygen conditions and at temperatures and pressures simulating subsurface disposal conditions. The waste from site A was partly or entirely neutralized by dissolution reactions with carbonate and clay mineral components in the rock samples. Carbon dioxide generation was not significant and no exsolution of a gas phase was detected. The waste from site F dissolved silicates in the tested formation samples and was rendered nonhazardous (by pH criteria) under some of the experimental conditions. Modeling of the solutions generated by these reactions— using thermodynamic principles—did predict some of the geochemical interactions; however, empirical investigations may be needed to complement the modeling efforts.

There are many other possible inorganic reactions between injected wastes and primary and secondary formation minerals. Minerals such as gypsum ($CaSO_4$) and limonite (hydrated ferric oxides) are known cementing agents for sandstones which, upon their dissolution and reprecipitation, can cause pore blocking. Brucite ($MgOH_2$) has also been noted as a potential cause of pore blockage adjacent to the well bore at Site F (Mehnert et al., in preparation). Reactions of micas and authigenic feldspars with acidic solutions are generally slow, resulting in the release of potassium or sodium.

Reactions of organic constituents with formation minerals are more unpredictable than are those involving inorganic constituents. In Illinois no data illustrating in situ chemical reactions of the organic compounds contained in wastes have been presented by the industries utilizing underground injection for disposal of organics. Generally, polar organic compounds are readily adsorbed onto clays and silicates. Warner and Lehr (1977) noted that problems relating to reduction of permeability by adsorption of polar organics are normally more severe in sandstone than in carbonate formations.

Because of the myriad of interactions between wastes and the formations used for disposal and the variability of downhole conditions, problems that may occur in the formation must be considered before injection begins. Compatibility and water sensitivity studies have been developed (Hewitt, 1963; Stiff and Davis 1952a,b) to help in diagnosing potential problems. Compatibility studies conducted by deep well operators at the time of initial well permitting did not indicate expectation of any significant reactions of incompatibility. However, these studies were very limited in scope and duration and were run under conditions that are not representative of actual downhole conditions. Those studies may not be adequate to detect any but the most obvious and rapid chemical interactions. Compatibility testing is one area of the permitting requirements that needs improvement, but adequate testing protocols are currently not available and must be developed. Monitoring data from the seven well sites continue to show no significant plugging of the injection zones.

INTERACTIONS BETWEEN INJECTED WASTES AND INTERSTITIAL WATERS

Formations acceptable as injection zones must contain interstitial water having a total dissolved solids (TDS) concentration greater than 10,000 mg/L. The injection zones currently in use have waters with TDS concentrations ranging from 14,000 to 61,000 mg/L. These interstitial waters, characterized as saline solutions, have sodium and chloride concentrations of 1 percent to 4 percent. Major accessory components in these saline solutions are calcium (Ca), magnesium (Mg), and sulfate (SO_4) with iron (Fe), zinc (Zn), boron (B), nitrate (NO_3), and silica (Si) in trace amounts. Injection data for 1984 show that the injection wastes have TDS concentrations ranging from 1051 to 332,159 mg/L. At several well sites small volumes of fresh water are injected at the end of each injection cycle to clear the tubing of waste; the well at Site C prior to 1986 also injected fresh water (annulus flush) during each injection cycle. Where data are available for comparison, the wastes have lower pH values, lower Ca and Mg concentrations, and higher CI and SO_4 concentrations than the water in the formations used for injection.

Chemical incompatibility between interstitial and injected waters occurs when chemical reactions between the two liquids cause gas evolution, precipitation, or some type of deposition. Selm and Hulse (1960) and Headlee (1950) classified these reactions as physical and chemical. Physical reactions involve changes in temperature, pressure, evaporation, and condensation that can lead to precipitation, dissolution of solids, or evolution of gases. The most common chemical reactions involve the precipitation of (1) alkaline metals such as Ba, Ca, Sr, typically as carbonates and/or sulfates, (2) metals such as Al, Cd, Cr, Fe, Mn, Ni, Zn, As, Hg, Pb in the carbonate, hydroxide, or sulfide forms, and (3) organics through polymerization. Oxidation-reduction reactions may involve chemical as well as biological interactions and are important in the geochemistry of liquids being injected and those present in the formation.

Some gases held in solution in either the formation fluid or the injected waste will come out of solution and develop a separate gas phase in response to certain temperature and pressure changes. Above the critical temperature for some gases, the gas cannot be held in solution. As previously noted, CO_2 is representative of one such gas and is a major product of acid neutralization in carbonate rocks. Carbon dioxide effervescence can be controlled by keeping the temperature in the disposal zone below the critical temperature for this gas and reducing the acid concentration in the waste to a level that does not produce gas saturation after the acid has been neutralized (Crews, personal communication, 1985; Panagiotopoulos and Reid, 1986). Pressure appears to control physical properties of the liquid phase of some waste components. For example, C_{57}, which readily plugs filters at atmospheric pressure, is said to readily flow into the disposal zone, a fractured porous medium, where the bottom-hole pressure is much greater than atmospheric pressure (Brown, personal communication, 1985).

Chemical reactions are complex and may involve several simultaneous processes (e.g., redox, pH changes, sorption between the injection and interstitial fluids and the formation minerals). In addition, many reactions are affected by changes in physical parameters as well, particularly with the elevated temperatures and pressures of disposal zones. The reactions of the alkaline earths and heavy metals with carbonates and bicarbonates are generally caused by changes in the equilibrium between CO_2, HCO_3, and CO_3. Such changes can result in the precipitation of the carbonates or bicarbonates of divalent cations such as Ca, Mg, Fe, or Mn.

Leenheer, Malcolm, and White (1976) identified organic products in samples of groundwater containing injected waste that were taken from wells located a distance of 1400 to 2700 feet from the injection well. The samples had a post-injection residence time of 2 to 4 years. The results indicated that some of the organic compounds originally present in the waste had undergone degradation to different compounds. Plugging of the injection wells resulted from the precipitation of calcium salts of the organic acids and from the release of carbon dioxide.

Other oxidation-reduction reactions commonly occurring in deep well injection scenarios involve the oxidation of H_2S by some oxidizing agent associated with the injected fluid. A common reaction is the oxidation of H_2S by chromium compounds, which are commonly used in the treatment of cooling water. The oxidation of ferrous iron by dissolved oxygen or by changes in pH can result in the formation of ferrous hydroxide, which is relatively insoluble. Bacteria such as sulfate-reducing bacteria are common in formation and injection fluids; these bacteria reduce sulfate to sulfides, which can subsequently cause precipitation of insoluable ferrous sulfides and sulfur. Biocide is injected during each disposal cycle at Site C to inhibit growth of iron bacteria and any other bacterial activity that would clog the injection zone or borehole face in the injection zone.

The interactions that may take place between the fluids injected and those in the formation and minerals in the formation are determined by the site-specific chemical constituents present and the chemical and physical forces acting on these constituents. The first step in determining interactions between certain aqueous components (Stiff and Davis, 1952a,b) is to analyze the fluids to ascertain their chemical compositions; in addition, chemical equilibrium models can be used to predict the theoretical activities of aqueous species and to calculate the saturation indices for selected minerals (Truesdell and Jones, 1974; Plummer et al., 1976; Ball et al., 1979). Laboratory compatibility studies are also useful for predicting fluid interactions and may have better predictive value than equilibrium models.

Current UIC facilities in Illinois have performed limited compatibility studies to determine interactions between their specific wastes and injection zone minerals and water. These studies involve batch-type experiments in which various percentages of the waste are mixed with either actual or simulated waters from selected formations. These solutions are allowed to react and are evaluated for the amount and type of precipitate formed. The waste is also passed through samples of formation materials to determine gas evolution, plugging of pores with reactants, and other waste/disposal zone mineral reactions. Compatibility studies are generally of short duration and are not performed under temperatures and pressures associated with the injection zone. Only a few column studies have been conducted in which waste is percolated through actual formation cores. Additional basic research is needed to develop standardized methods to determine waste interactions with water and minerals from the selected formation.

MONITORING OF INJECTED WASTES

No direct monitoring of the injection formation to assess chemical interactions has been done in Illinois. On-site monitoring of well injection and annulus pressures at the wellhead is currently the only means to ascertain if reactions detrimental to the performance of the well are taking place. To date, monitoring data have not indicated any occurrence of reactions detrimental to formation permeability at any of the injection wells. Figures 4-1 and 4-2 show the injection and annulus pressures of four disposal wells for a 5-year period. Three of these four wells have utilized a pressurized fluid seal, and one a pressured flow-through annulus design. The figures were developed by averaging the maximum daily pressures on a quarterly basis and plotting the average relative to time. The relatively constant pressures suggest that if reactions are occurring between the waste and formation minerals and water, they have not been deleterious to well performance. This type of monitoring reflects only those reactions that affect formation permeability and does not indicate if (or what) other reactions are taking place.

A review of the monthly monitoring reports submitted to the regulatory agency by the injection control facilities has in many instances indicated that monitoring requirements established in the operating permit were either insufficient to completely characterize the wastestreams, were not strictly adhered to (some analytical results were not consistently reported), or both. For example, there have been instances noted in the monthly reports in which sample collection and preparation procedures were inadequate. In one case, volatile components were lost during week-long sample

4-6

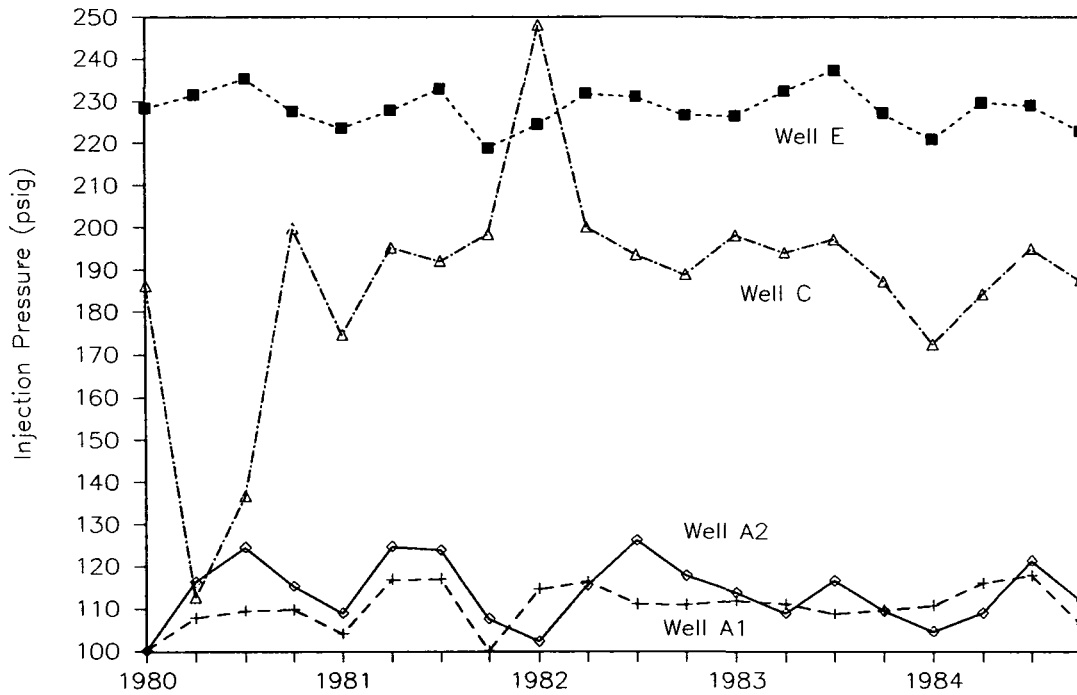## For Packerless Class I Wells

Figure 4-1 Five-year summary of injection pressures for four disposal wells in Illinois.
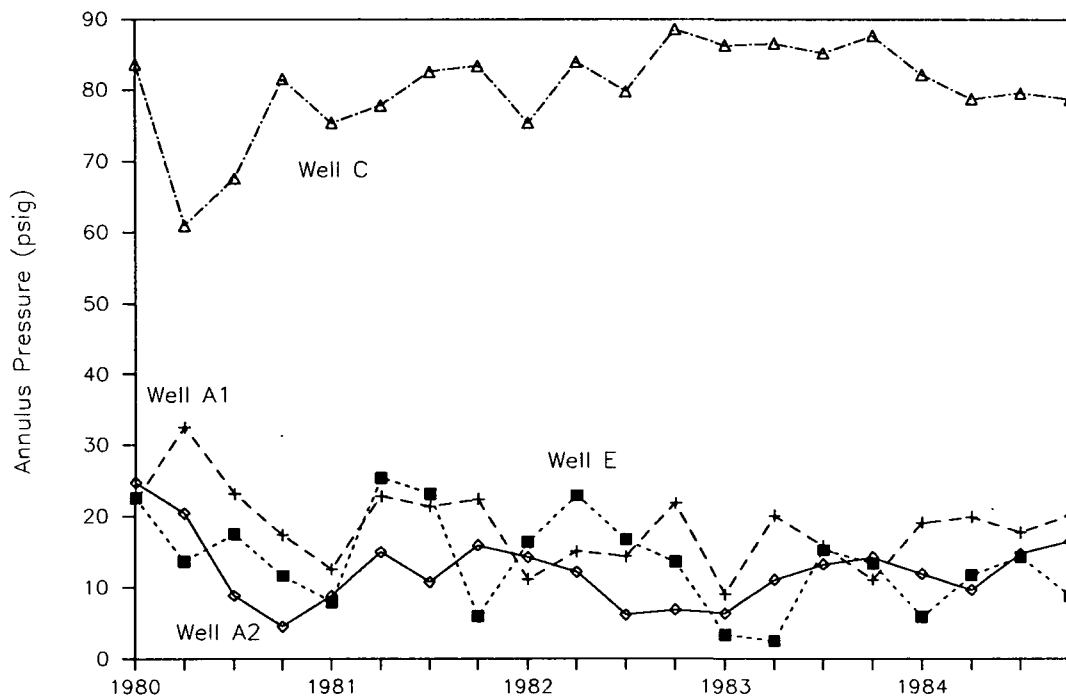
For Packerless Class I Wells

Figure 4-2 Five-year summary of annulus pressures for four disposal wells in Illinois.

collection periods, and in another the organic phase of the wastestream was discarded and the aqueous phase analyzed for organic compounds. In cases such as these, the expected (and generally, relatively innocuous) components were monitored while potentially hazardous unknowns may have been allowed to bypass the analytical monitoring procedure. Although monitoring practices appear to be improving, it is clear that a thorough characterization of the wastestream must be required of all Class I UIC facilities.

No one set of monitoring guidelines will adequately address all types of disposal wastes. Complete inorganic and organic analysis (gas chromatography/mass spectrometry) of the injected waste should be required, and results of these analyses should be submitted at the time of permitting of the disposal well and on a specified basis (quarterly) thereafter. Characterization of a wastestream should not be limited to analyzing for specific components on the EPA toxicity or priority pollutants lists, but should require identification and quantification of all detectable components. Using analytical data from such a survey, knowledgeable regulatory personnel can establish monitoring guidelines on a case-by-case basis.

In addition to monitoring the character of a wastestream, it is important to determine that the fluid disposed of has remained in the disposal zone and has not found a path of movement up the borehole or leaked through the caprock to overlying aquifers. The integrity of a disposal well, including the cement grout around the casings, is determined through mechanical integrity testing and well monitoring procedures. Well monitoring is discussed later in this chapter.

Typically, feasibility studies and tests of cores from drilling must demonstrate the integrity of the caprock at the site of a proposed injection well. However, if, despite test indications, a disposal well operation does develop a leak directly through the caprock, injected wastes or displaced formation water could enter an overlying aquifer.

In the event that an injected contaminant escapes from the confinement of the disposal zone and reaches a potable aquifer, it may go undetected for an indefinite period of time unless a mechanism is established to detect and to keep track of the path, volume, and character of the escaped waste. The mechanisms for accomplishing this task of monitoring should become part of the requirements of the permit for Class I wells. Determining the presence and concentration of the predominant organic and inorganic chemical species in the wastestream is essential to the monitoring process: if monitoring in the first aquifer above the confining zone reveals the presence or increased concentration (above background) of components known to occur in the wastestream, a leak through the confinement may have occurred.

PROBLEMS ASSOCIATED WITH MONITORING WELLS

The subject of monitoring wells has been a controversial one as far as regulation of underground injection is concerned. Monitoring wells have been routinely employed in RCRA regulations and other shallow groundwater studies, but are not as commonly included in deep well injection operations.

Three general types of monitoring wells have been used nationally in conjunction with injection wells (Warner and Lehr, 1977):

Well Type	Objective
1. Constructed in injection formation	a. Obtain geologic data b. Monitor pressure in injection formation c. Determine rate and direction of wastewater movement d. Detect geochemical changes in injected wastewater e. Detect shifts in wastewater-saline water interfaces
2. Constructed in or immediately above the primary confining unit	a. Obtain geologic data b. Monitor pressure in tested interval c. Detect leakage through confining unit
3. Constructed in the lowermost USDW	a. Obtain geologic data b. Detect evidence of freshwater contamination from disposal activities

Completing monitoring wells in the same formation into which injection is taking place is the only direct means of determining the rate and direction of the wastewater plume. Because in most cases the hydraulic properties of the injection zone will deviate from the ideal of isotropy and homogeneity, several monitoring wells will be necessary in order to intercept and define the plume radiating from the well bore. The most compelling argument against the use of such wells in the injection formation is that they provide another potential pathway for the escape of the injected material. In Illinois only one such well is in use (Site F). This well is located more than 1/4 mile from the nearer of two injection wells.

Monitoring wells placed in or just above the confining unit can detect changes in pressure and water chemistry indicative of leakage. If the confining unit is relatively thin or somewhat fractured, this type of monitoring well is justified. In many cases, particularly in injection zones found in Illinois, the confining unit is relatively thick and contains no aquifers suitable for monitoring. No monitoring wells of this type are in use in Class I operations in Illinois.

The most commonly used type of monitoring well is typically completed in shallow aquifers or associated tight materials (including deposits classified as USDW) to detect contamination from surface or near-surface waste disposal. This type of well is usually required in RCRA regulations.

In many areas of central and southern Illinois the USDW interval is thin, and because of the character and depth of these aquifer(s), RCRA and UIC monitoring wells could conceivably be completed in the same aquifer. Monitoring wells placed in the lowermost USDW near Class I disposal wells would use construction and sampling procedures similar to those employed for RCRA monitoring wells. This type of monitoring well is the least costly and provides an opportunity for detecting the initial entrance of contaminants that move into the USDW, yet does not offer a potential pathway for escape of the injected waste. In Illinois the disposal zones lie at moderate to great depth below the USDW and one or more aquifers typically occur between the USDW and the primary confining units. Because fluid moves under a hydraulic gradient, any waste driven through the primary confining unit by a gradient generated during injection activities will enter the first overlying aquifer. This aquifer may be within the confining interval or above it. If the USDW lies directly above the confining interval, any waste fluid penetrating the confining interval will enter the base of the immediately overlying USDW. Once this overlying aquifer is reached, fluid will tend to move horizontally within it. One or more strategically placed monitoring wells in the aquifer just above the primary confining unit would provide an acceptable position for monitoring leakage through the confining interval, but would not provide a direct potential pathway for escape of wastes from the injection zone.

In deciding the type of monitoring to use with a Class I injection operation, the cost and the potential risks involved must be weighed against the information that will be gained. A monitoring strategy must be developed to provide criteria for selection of siting, depth, parameters to be tested, and testing frequency; this strategy can then be used to determine the best type of monitoring system and the most appropriate position relative to the disposal well for such a system.

Monitoring wells required below the USDW should be finished deep in the first permeable formation above the confining layer in order to provide early detection of any waste that migrates through the primary confining interval. A well finished in a permeable horizon immediately above or in the top of the confining interval would provide an appropriate position for monitoring of the piezometric surface and collection of water samples for chemical analysis.

Mandatory monitoring outside the operating injection well has not been required in Illinois. Data from this type of monitoring could be a significant additional means of verifying the practice of deep well injection as a viable, safe disposal method for hazardous wastes. Making this type of monitoring mandatory appears to be an important step toward increasing public confidence in deep well disposal. However, additional work is needed to develop an appropriate monitoring strategy and a regulatory framework. Specific monitoring requirements will vary within that framework and should be carefully reviewed on a case-by-case basis by a panel of groundwater monitoring experts; this review should take place prior to the initial permitting of the facility and should be repeated at each permit renewal in light of any new information which has been acquired.

Any monitoring conducted in the first significant permeable zone (aquifer) above the disposal zone should be done for selected parameters at specified frequencies (e.g., continuously, quarterly, annually). Appropriate parameters, including surrogate parameters, would depend on the hydraulic properties of the rocks and the relative characteristics of the overlying formation water and the injected wastes. Standard, easily run testing and analytical procedures are available for indicating breakthrough of components in the waste or displaced formation fluid and detecting organic and inorganic constituents in the low microgram-per-liter range. Some level of monitoring should be continued at the site even after the well is no longer used for waste disposal to ensure that later intrusion of the waste into the overlying formation does not occur. Monitoring should continue until the pressure buildup generated by injection dissipates.

WASTESTREAM CLASSIFICATION AND TOXICITY DETERMINATION

Wastestream Classification

The most common constituents found in the injection wastestreams can be grouped into three general types reflecting their relative toxicity and/or undesirability in potable water supplies.

- Type 1 constituents are extremely undesirable, highly toxic, and unacceptable in potable waters.

- Type 2 constituents are undesirable, but unless present in extremely high concentrations have minimal detrimental health effects.

- Type 3 constituents may be allowable in potable water but not desirable because of their effect on the aesthetic quality of the water.

Organic components such as the chlorinated hydrocarbons would be classified as Type 1 constituents. Compounds in this category, such as chlordane, are extremely toxic and have maximum allowable EPA water quality criteria standards ranging from .01 to 100 µg/L (ppb). For other organic compounds such as hexachiorocyclopentadiene ("hex") there is less information regarding toxicity. Data available indicate that "hex" concentrations in the 1 to 10 µg/L range are toxic to or bioaccumulate in mammals and aquatic species (Chow and Griffin, 1983). Arsenic and mercury may also be considered members of the Type 1 classification; these have water quality standards of 50 µg/L and 2 µg/L, respectively.

Fluoride and vanadium, in sufficient concentrations, can be considered Type 2 constituents. These constituents, when in high concentrations, may have detrimental health effects, but in low concentrations can actually have beneficial effects.

Iron, manganese, chloride, sulfate, calcium, and magnesium would be considered in the Type 3 class. These constituents are found in many potable water supplies. EPA water standards for sulfate and chloride, for instance, are 250 mg/L, with iron limits at 0.3 mg/L. Many of these substances reduce the aesthetic quality of water, causing staining, hardness, or possible odor, but have no known detrimental health effects.

Above-ground removal or reduction in concentration of most Type 1 and Type 2 contaminants from the wastestreams is possible and can be done in an environmentally acceptable manner. Treatment of wastestreams to remove or reduce these contaminants to an acceptable concentration level can almost eliminate the potential risk of contaminating drinking water sources. However, as will be seen in Chapter 7, this treatment is, in general, significantly more expensive than deep well injection alone.

Toxicity

Toxicity data are generally categorized into two types: acute and chronic. Acute toxicity can be detected soon after exposure of the test organism to the substance and is frequently expressed as the dose or concentration of a substance that is lethal to 50 percent of the test population (LD_{50}). Chronic or long-term toxicity is more difficult to assess than acute toxicity and generally involves a detailed search for physiological changes. These changes are induced after long-term exposure to sublethal concentrations of the substance of interest. Chronic toxicity testing is very expensive and it may take years before conclusions of a chemical's chronic effects can be made. Results from chronic toxicity testing may or may not bear a recognizable relationship to those obtained from acute toxicity testing.

Another specific type of toxic substance testing is for mutagenicity, using for example, the Ames test. In this test the reversion of a particular strain of Salmonella bacteria has been found to have a fairly high correlation with mutagenicity and carcinogenicity in mammals. This type of toxicity may have little obvious relationship to the types discussed above.

It is obvious that considerations of acute toxicity only are not sufficient in assessing the potential public health hazard from potable aquifer contamination. If partial waste treatment is to be required before injection, guidelines should be developed from literature data on the various toxicities and used to classify a waste component on the basis of the nature and extent of treatment it would require. Presumably, different treatment objectives would be established for Type 1, 2, and 3 components. In addition, guidelines would have to be established to determine whether the toxicity data available in the literature were adequate for purposes of classification of components by type.

POTENTIAL HAZARDS OF DEEP WELL INJECTION

The site of the greatest impact of hazardous wastes on USDW lies in leaks in the piping upstream from the wellhead of the receiving disposal well. Delivery of the wastes to the disposal zone via the disposal well represents very little or no potential impact on the USDW or the surface environment because Class I well construction and operational requirements provide continuous and periodic verification of the condition of well components. The UIC regulations are also stringent for all conditions in the disposal zone and its confinement; however, the siting of monitoring equipment at the wellhead makes such monitoring increasingly remote for each discrete volume element in the disposal system as the elements lie further from the well bore. Thus, verification of disposal zone conditions and the precise fate of the waste in the disposal zone and its confinement are less discernible and verifiable with distance from the well bore. The two most serious potential hazards of deep well injection are (1) contamination of surface soil, surface water, and shallow groundwater by accidental spillage at the wellhead, and (2) contamination of USDW by migration or escape of waste components and displaced formation water.

Although subsurface injection appears to have a low potential impact on USDW, any subsurface condition that causes deviation from expected operational conditions can potentially affect both the well and the integrity of the disposal zone and its confinement. Pore blockage by build-up of debris or precipitate decreases injection capacity. An increase in pressure to maintain injection capacity increases the stress applied to the disposal horizon. Blockage can also develop from gas generation. In addition to causing an operational problem, any gas entering the well could damage the well or cause a blowout. Confinement integrity compromised by collapse of excessively developed caverns resulting from neutralization of acidic wastes in a carbonate aquifer offers a potential path of migration to shallower horizons.

Although the harmful effects of chemical interactions from injection and the risks of USDW contamination and surface spills have been small, their potential must be acknowledged and further attempts must be made to minimize these risks. Although siting of Class I facilities in environmentally sound geologic settings is possible in many areas of Illinois, an adequate monitoring program is essential for ongoing verification of subsurface confinement integrity and fate of the waste. Monitoring above the primary confinement of the disposal zone offers an observation port between the disposal zone and the overlying USDW. Such monitoring would offer a means of verifying the risks to USDW associated with specific disposal activities. To facilitate effective waste management, it is essential to characterize the wastestream at all times, including the character and range of concentration of each waste constituent. Extreme variation of waste concentration and character should be avoided in order to maintain greater quality control of the injected stream. An obvious way of assuring such quality control if a significant deviation in chemistry of the contributing streams exists is to use batch mode operations in collecting, mixing, and treating of contributing streams and then injecting the wastestream. Such procedures should be required where necessary in Class I disposal operations.

On the basis of the limited evidence to date, it appears that deep well injection is a viable disposal option, probably preferable to landfill disposal. However, it should be noted that significant and numerous incidents of hazardous waste breaching of landfilling confinement have been documented. The hard lesson learned from contamination produced from inadequate landfilling practices — the result of many factors but principally a lack of adequate research — points to the need for research

on the fate of the injected wastes in the disposal environment. Destruction of the hazardous components before injection is always preferable to long-term storage of toxic materials as a method of disposal. It is the responsibility of all parties involved (legislators, regulators, waste-generating industries, and the public) to make an informed decision about what constitutes acceptable risk in waste disposal and to adjust regulations and regulatory practices, if necessary, to achieve an acceptable level of protection for our USDW.

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5 UIC PROGRAMS IN THE UNITED STATES

CURRENT STATUS OF CLASS I WELLS IN ILLINOIS

Packerless Wells

At the time Illinois received primacy to regulate its UIC program under the new regulations, four Class I wells in the state had packerless completions. One of these employed a dynamic flush (i.e., fresh water was pumped down the annulus of the well during injection to force the injected waste away from the well casing and into the injection zone). The other three utilized static fluid seals of kerosene or diesel oil, which were maintained in the annulus under pressure. Three of these packerless designs have been disapproved by the IEPA under the new regulations because they do not provide the same degree of protection as a packer completion would provide in each of the wells.

Site A Wells. The "alternative to packer" designs of Wells A1 and A2 were disapproved by the IEPA on January 31, 1986, for the following reasons (IEPA files, 1986): (1) they did not demonstrate the same level of protection as that of a packer completion; (2) the annular monitoring systems would not adequately detect leaks that might occur during injection; (3) the positions of the waste-oil interfaces could not be determined at every moment; (4) annulus pressures would not be greater than injection tubing pressures at all depths in all cases; and (5) the monitoring systems did not demonstrate the ability to detect leaks prior to stabilization of the wells during long shut-in periods after injections had ceased.

Site A received notices from the IEPA on August 11, 1986, of intent to deny permits to operate its Class I wells under the new regulations unless the following points of denial were resolved (IEPA files, 1986): (1) the wells did not have packers or approved alternatives to packers; (2) the wells were not shown to have mechanical integrity under 35 Ill. Adm. Code 730.108; and (3) failure on the part of the permit applicant to submit correct quarterly operational reports under 35 Ill. Adm. Code 730.113.

A packer was installed in Well A2 in May 1987. The IEPA plans to issue a draft permit for Well A2 shortly after mid-1987. Plans for installing a packer in Well A1 are currently being finalized (IEPA files, 1987).

Site C Well. The "alternative to packer" design of the Site C well was disapproved by the IEPA on December 31, 1985, for the following reasons (IEPA files, 1985): (1) it did not demonstrate the same level of protection as that of a packer completion; (2) the annular monitoring system would not adequately detect leaks that might occur during injection; (3) the annular monitoring system required a 24- to 48-hour shut-in period after cessation of injection before it could detect potential leaks; and (4) monthly reports showed "extremely low" annulus pressures (after the 24- to 48-hour shut-in period), which were below the minimum pressure that would indicate the presence of possible leaks.

In November 1986 a new casing through the entire length of the well, a new wellhead, and a packer with a kerosene-capped/water-filled annulus were installed at Site C. Well tests to demonstrate mechanical integrity under 35 Ill. Adm. Code 730.108 and to evaluate the workover were satisfactory. A draft permit is scheduled to be issued to the facility during the third quarter of 1987 (IEPA files, 1987).

Site E Well. The Site E well is the only Class I well in Illinois that has had its packerless design accepted by the IEPA under the new regulations. Acceptance of the system followed modifications made in 1986 that are described in Chapter 6 in the section on packer versus packerless design.

Site E received a draft permit in August 1986 to operate this well under the new regulations (IEPA files, 1986). A final permit decision had been delayed because a public hearing had been requested

by citizens of the City of Danville, Illinois, as provided for in 35 Ill. Adm. Code 705, Subpart E. This hearing was held in Danville on December 17, 1986, and the testimony became part of the public record. Site E contested the draft permit (issued March 30, 1987) on the basis of inability to comply with its requirements (IEPA files, 1986), and appealed the final permit (issued May 5, 1987) to the Illinois Pollution Control Board. The most prominent complaint is with a condition that will require Site E not to exceed a designated maximum HCl concentration in the plant's injected waste. A plan proposed at the public hearing by the Site E operator to neutralize the waste before injection is to be incorporated into the permit and will be installed and operational within one year. A new draft permit containing modifications is scheduled for issuance to the facility during the third quarter 1987 (IEPA files, 1987).

Final Denial to Operate Under the New Regulations

Site F.   Site F received a final denial to operate Well F1 as a Class I well under the new regulations on November 1, 1985, for the following reasons (IEPA files, 1985): (1) failure to provide information about the well required by the IEPA; (2) the proposed contingency plan (to be followed in case of emergency) was inadequate to ensure proper response to emergencies; (3) the proposed plugging and abandonment plan was inadequate to ensure that the well would be plugged and abandoned properly at the end of its useful life; and (4) the well cannot be tested to meet mechanical integrity requirements of 35 Ill. Adm. Code 730.108(b).

The well has not yet been plugged and abandoned. The condition of the well was assessed in June 1987, and revised plans for its plugging and abandonment will be made and submitted for approval (IEPA files, 1987).

Site G.   Site G has received a final denial to operate Well G1 as a Class I well under the new regulations effective June 3, 1987, for the following reasons (IEPA files, 1987): (1) failure to conduct mechanical integrity testing to meet the requirements of 35 Ill. Adm. Code 730.108(b); (2) failure to demonstate absence of fluid movement adjacent to well persuant to 35 Ill. Adm. Code 730.108(c); (3) failure to demonstrate that the well is operated in a manner that prevents upward migration of injected fluids into USDW; (4) failure to submit a corrective action plan for abandoned wells in the area of review; and (5) failure to submit a complete application per requirements of 35 Ill. Adm. Code 705.123. This final denial was appealed to the Illinois Pollution Control Board on June 2, 1987 (IEPA files, 1987).

Permits to Construct and Operate New Class I Wells in Illinois

Site F.   Site F received a final permit to construct and operate a new Class I well (F3) on November 3, 1986, to replace Well F1 (IEPA files, 1986). Plans were to complete the well in the Devonian-Silurian interval; however, the Site F operator has opted not to drill the well immediately.

Site G.   Site G received a final permit on October 21, 1986, to construct and operate a new Class I well at the facility to replace the existing well (IEPA files, 1986), and drilled the well in the summer of 1987.

Draft Permits Awaiting Final Review

Site F is scheduled to receive a draft permit for operation of Well F2 during the third quarter of 1987. Site D is also scheduled to receive a draft permit for operation of Well D during the third quarter of 1987. A final decision on these draft permits has not yet been made (June 1987).

UIC PROGRAMS IN OTHER STATES

State and Federal Regulatory Agencies

Information compiled for this chapter, obtained in 1985 from mail and telephone surveys of, and selected visits to, USEPA regional offices and state regulatory agencies, is summarized in Tables 5-1 and 5-2 and in Figure 5-1.

States having UIC programs were first categorized as to whether they have primacy or are regulated by USEPA regional offices. States in which primacy is being considered or in which Class I activity is being phased out were also categorized. States having primacy were further surveyed to obtain and compare information concerning their respective UIC programs.
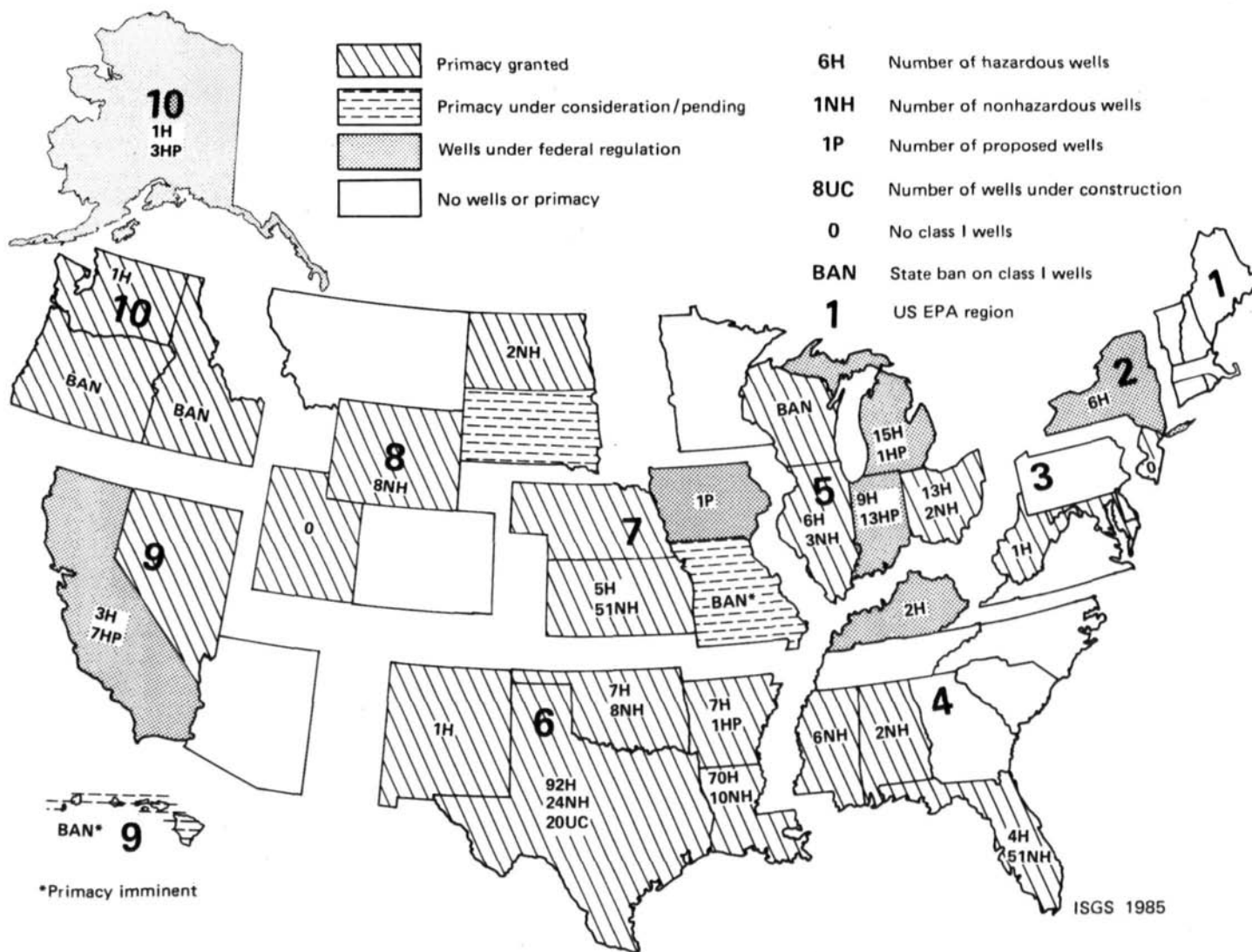
Figure 5-1 Regulatory status of Class I wells in the United States (1985).

Table 5-1. Status of primacy for states with Class I wells **(1985).**

REGION	Primacy granted; has existing wells	Primacy granted; has no wells existing	Primacy granted; has ban on Class I wells	Primacy granted, but Class I wells being phased out	Class 1 wells under Federal regulation	Primacy under consideration or pending
I						
II		New Jersey			New York 6H	
III		Maryland, Delaware (ban on Class I hazardous)		West Virginia IH		
IV	Mississippi 6NH Florida 51NH, 4H			Alabama 2NH	Kentucky 2H	
V	IHinois 6H, 3NH, 2P Ohio 13H, 2NH		Wisconsin		Michigan 15H, 1HP Indiana 9H, 13HP	
VI	Texas 92H, 24NH 20 under construction Louisiana 70H, 10NH New Mexico 1H Oklahoma 7H, 8NH Arkansas, 7H, 1HP				Oklahoma 1NH	
VII	Kansas 5H, 51NH	Nebraska			Iowa 1P	Missouri* (has banned Class I)
VIII	Wyoming 8NH North Dakota 2NH	Utah				South Dakota
IX					California 3H 7HP	Hawaii** (has banned Class I)
X			Oregon Idaho	Washington 1H	Alaska 1H, 3HP	

*primacy imminent at time of publication

H: hazardous wells
NH: nonhazardous wells
P: proposed wells

Table 5-2 Summary: UIC programs for Class I wells in primacy states (compiled in 1985 and updated early in 1986).

Region	State	Annual fee for permit	Add. fee based on waste type or volume	Downhole camera Inspection	Monitoring above con-fining zone	Packerless (fluid packer) well design allowed	Packerless wells operating	Area of review min. fixed radius (mi)	Commercial operations allowed	Area permits allowed	Comments
II.	New Jersey	no	no	no	no	hasn't been considered	no	**2**	no	yes	Class I wells will most likely never exist due to geologic limitations.
III.	Maryland	no guidelines set	no	yes	no	no	**1/4**	no	no	Existing well in W Va. is
	Delaware	down at present									being phased out.
	West Virginia		no	yes	no	no	**1/4**	no	no	
IV.	Florida	no	no	yes	yes	only on municipal wells	yes	**1**	yes	yes	These states have bans on new Class I hazardous waste wells.
	Mississippi	no	no	no	yes	no	no	**2-1/2**	yes	yes	Existing wells are being phased out.
	Alabama										
V.	Illinois	yes	volume	no	no	yes	yes	**1/4**	under consid-eration	no	
	Ohio	yes	hazard. wells	no	no	no	no	**1/4**	no	no	
	Wisconsin										Class I wells banned in Wis.
VI.	Texas	no	no	no	no	yes	yes	**2-1/2**	no	no	Has 11 commercial wells at 9 sites.
	Louisiana	annual inspect. fee	no	no	case-by-case	no	no	**2**	no	no	
	New Mexico	no	no	no	case-by-case	yes	no	**2-1/2**	no	yes	
	Oklahoma	pending	pending	no	yes	no	no	**1**	yes	no	Nonhazardous well on Indiana land is under Region 6 jurisdiction.
	Arkansas	yes	no	no	yes	no	no	**1/4**	no	no	
VII.	Kansas	yes, on hazard. wells	volume	no	no	yes	yes	**1/2**	yes	yes	Commercial operation allowed only in non-hazardous wells.
	Nebraska	yes	no	no	yes	hasn't been considered	no	**2**	hasn't been considered	no	Injection by gravity flow only.
VIII.	Wyoming	no	no	no	case ■by-case	no	no	**1/4**	no	no	
	North Dakota	no	no	no	no	no	no	**1/4**	yes	yes	Approval required for each waste at comm. oper.
	Utah	no	no	no	no	no	no	**2**	yes	yes	For comm. oper., RCRA guidelines are followed.
X	Idaho										Class I wells banned due to geologic limitations and lack of knowledge of deeper sedimentary units. Non-operating well in Washington will soon be plugged and abandoned.
	Oregon										
	Washington										

Regulatory authority responsibility for Class I wells in the various states is administered by a lead regulatory agency or shared among more than one state agency. The UIC program in Illinois for Class I wells is administered by the Illinois Environmental Protection Agency.

Status of UIC Programs as of 1985

Twenty-three states have primacy to regulate their own Class I UIC programs. Of these states, two (Maryland and Delaware) have banned Class I hazardous waste injection, while three others (Wisconsin, Oregon, and Idaho) have banned all Class I waste injection. Three states are in the process of phasing out their Class I injection wells: Alabama and Washington, where geologic considerations have been cited, and West Virginia, where the only disposal well is being phased out by the owner for economic reasons. Alabama has placed a ban on the construction of new Class I wells. Three others (Utah, New Jersey, and Nebraska) have no Class I injection wells at the present time. Primacy is imminent in Hawaii and in Missouri, and those two states have already imposed bans on Class I activity. These statistics are shown in Figure 5-1.

Several other states are in the initial phases of considering primacy, but a significant period of time may elapse before documents requesting primacy have been completed and the necessary legislative and judicial machinery are in the final preparation stage. Several additional states are looking into the process required for seeking primacy. The regional EPA offices have expressed a desire to meet with regulatory staffs of the states within each region that have or expect to have primacy of UIC programs.

In 1985, 249 Class I hazardous waste wells and 162 Class I nonhazardous waste wells existed in the United States; 48 more Class I wells were either proposed or under construction. Of the hazardous waste wells, 213 (86%) were under state regulation; two of the state regulated wells were being phased out. Of the nonhazardous waste wells, 161 (99%) were under state regulation; two were being phased out. Of the 48 wells either proposed or under construction, 23 (48%) would be under state regulation. Most of these wells are located in Texas and Louisiana (Table 5-1). Several unclassified injection wells are known to exist in Tennessee. These figures constantly change as new wells are drilled and put into service and existing wells are retired from service.

Primacy states were surveyed in 1985 to obtain information on specific points of interest within their UIC programs (Table 5-2). These points included fees, downhole camera inspection, monitoring above the confining zone, fluid packer well design, area of review, commercial operation, and area permits. Five states impose annual fees for Class I well injection; of these, two (Illinois and Kansas) have imposed additional fees based on waste injection volume, and one (Ohio) imposes an additional fee for hazardous waste injection. Florida requires periodic downhole camera inspections of its Class I wells. Five states require monitoring of the interval above the caprock, although any state could require such monitoring if it were deemed necessary. In 1985 four states (including Illinois) had Class I wells operating with fluid packer well designs. Most primacy states require an area of review larger than the 1/4 mile called for in the earlier Federal regulations.

A variety of factors can influence a state's decision to seek primacy, and may also influence the degree of injection activity within the state. These factors include economic growth, growth rate of waste-generating industrial development, geologic constraints, presence and degree of development of an oil and gas industry, regional trends, political and environmental inputs and stresses, historical problems with old injection wells or hazardous waste management practices, and new or pending legislative statutes and interpretations thereof.

At present no commercial Class I injection wells exist in Illinois, but they are not prohibited by the current regulations or practices. Because of the extreme difficulty in predicting the fate of the various injected wastes in commercial wells, the operation of these wells should be very tightly regulated or prohibited. If they are to be allowed, it is recommended that IEPA draft and have in place regulatory practices for commercial wells in anticipation of potential permit applications for such wells. These regulatory practices must require that compatibility tests be made with all wastes previously injected as well as those currently being considered for injection, and that compatibility of all such wastes be demonstrated. The practices should also require that an up-to-date record be kept of all wastes injected throughout the operational history of each commercial well.

COMPARISON OF ILLINOIS UIC PROGRAM WITH UIC PROGRAMS IN OTHER STATES

Comparison with Primacy States

The regulations of all state-operated UIC programs closely resemble the Federal regulations from which they originated. Illinois was one of several states whose regulatory deep well injection program provided input into existing Federal UIC regulations. There are differences, however, in the manner in which each state's regulations are enforced.

One difference among state programs is the permitting process. The permitting process in Illinois has been discussed in detail in Chapter 1. As part of that process, the Illinois State Geological and Water Surveys provide technical consultation to the IEPA during permit review. For comparison, applications for Class I waste disposal permits in Ohio must be reviewed and approved by five state agencies, and a Permit to Drill must be applied for and received before application can be made for a Permit to Operate any proposed UIC facility.

The general pattern for the regulations in the UIC program under the 1974 Safe Drinking Water Act was largely based on state programs developed by Texas and Louisiana for Class I and II wells. Many components of the regulations existing today in these states and in Illinois are basically little changed from those enforced before the states received primacy. Many of the procedures used to evaluate data submitted in feasibility studies, obtained from well testing, and collected from in-well monitoring were developed by states having a large number of wells. As other states have developed their UIC programs, additional procedures have been developed and/or modified.

Close interaction among staffs of the various states and EPA regions is beneficial as these developments take place. As disposal activities in Class I wells increase, close cooperation of all persons involved in designing, operating, regulating, and evaluating these wells becomes more essential to ensure protection of drinking water resources.

Issues in Other States

Certain concerns other states have in administering their UIC programs are not issues in Illinois now but could become important issues in the future: the subsurface disposal of radioactive wastes, the sharing of wells between industries that generate similar wastestreams, top-secret wastestreams generated on military installations, commercial wells and well fields, and highly toxic wastestreams. Several states have voiced concern over the lack of uniformity in classification of several types of wells throughout the United States and from region to region.

Heavy contamination of surface waters and land surface in the vicinity of large concentrations of petrochemical and related industries has caused several states to move heavily into permitted Class I wells for the disposal of generated wastes. Surface environment contamination has been noticeably decreased, but these states feel that too rapid a change in the regulations or regulatory practices on either a state or federal level could cause a significant, though temporary, diversion of contaminants back into the surface environment.

Political, environmental, and geologic constraints in other states strongly affect how state programs are operated, who operates them, and whether or not deep well injection is even a possible or desired disposal alternative. Some states that rely heavily on groundwater obtained from great depths for their daily water needs are reluctant to practice deep well waste disposal or expand existing programs. Geologic constraints (such as high degrees of faulting, lack of suitable disposal formations, and areally unpredictable changes in water quality) have prevented or precluded development of deep well waste injection. In other states, deep well waste injection is geologically and economically feasible, but is not and may never be practiced because of public or environmental concerns.

TRENDS IN UNDERGROUND INJECTION PRACTICES

The 1984 RCRA Amendments

The regulating and regulated communities in the United States have great interest in the 1984 Amendments to the Resource Conservation and Recovery Act (RCRA). According to the amended law passed in November 1984, the USEPA has authority to ban land disposal of certain hazardous

wastes or to require certain levels or methods of pretreatment before disposal. The implications are far-reaching, as this law gives the USEPA authority to restrict or eliminate the practice of deep well injection of hazardous liquid waste.

The Underground Injection Practices Council

The Underground Injection Practices Council (UIPC) is a national organization formed in 1984 to enhance communications between the states, the Environmental Protection Agency, the regulated community, and the public and disseminate knowledge about underground injection. The UIPC is also involved in education and research on injection wells and injection well technology.

It is important that Illinois exchange information and technology concerning underground injection with other states. Such communication and exchange is vital to maintaining an updated and informed position on trends in the field of underground injection.

6 UNRESOLVED ISSUES CONCERNING ILLINOIS DEEP WELL DISPOSAL

Controversial issues related to Class I underground injection discussed in this chapter include alternative theories to explain well blowouts in Illinois; relative merits of packer and packer-less well designs; the degree of safety of injection into formations under high hydrostatic heads; the adequacy of methods used to determine area of review; and monitoring strategies.

THEORIES ON BLOWOUTS IN ILLINOIS

Site A Blowout

Several theories have been proposed to explain the cause of the Well A1 blowout, and recommendations have been made as to how such a blowout could be prevented in the future. Site A's Senior Petroleum Engineer stated at the time of the blowout:

> From an analysis of the well pressure and flow records, it is concluded that intermittent disposal of large amounts of heavy acid causes a temporary buildup of carbon dioxide gas pressure in the vicinity of the well bore. Continued routine well disposal operation with pond water (weak acid) appears to dissolve and disperse this gas in a period of a day or two. Indications of loss of well capacity previously ascribed to tubing deposits may actually be caused by this temporary pressure buildup (IEPA files, 1975).

The engineer recommended that (1) future well repair operations should be conducted only after several days of freshwater flushing has cleared the formation of carbon dioxide gas pressure; (2) a blowout preventer should be used whenever the well is to be opened up for any reason; and (3) the casing-tubing annulus should be monitored closely to prevent sudden buildup of pressure and possible tubing collapse (IEPA files, 1975).

A statement from USEPA Region V (IEPA files, 1984) reads: "it is our belief that the pressurization of the disposal zone by carbon dioxide generated in situ by the chemical reaction between the acidic wastes and the carbonate formation caused the effluent backflow." Region V personnel disagreed with the Site A operator's reasoning that a "gas pressure buildup" due to lower solubility of CO_2 in the strong acid compared to the weaker solutions normally injected was the cause for the blow-out. Rather, their hypothesis was that the critical temperature of CO_2 (88°F) was exceeded during the disposal of the 31.5 percent HCl waste, resulting in reduced solubility of the CO_2 generated, coupled with a possible increase in the rate at which it was released from solution due to greater reactivity of the acid at higher temperature. Above the critical temperature, all CO_2 released was in the gaseous state; the result was pressurization of the disposal zone by the gas, followed by loss of injectivity and finally the blowout. Region V (IEPA files, 1984) concluded that

> regardless of whether the [Site A] well blowout in August 1975 was on account of the gas pressure buildup or conditions related to the critical properties of carbon dioxide, there is little doubt the primary reason for the incident is the chemical reaction between the acid effluent and the carbonate formation. The latter continues to be a real ... danger to the safety of waste disposal operations of this type ...

> The injection of concentrated waste into a formation with which it can chemically react to produce carbon dioxide is inherently unsafe. It appears that an increase in the temperature of the waste emplacement formation beyond the critical temperature of carbon dioxide (88°F), resulting from inadvertent variations in the disposal operation, can result in the pressurization of the formation by carbon dioxide gas. Such a condition poses an ubiquitous threat to the safety of USDW through possible vertical or lateral effluent migration. Preventing the formation of carbon dioxide

gas within the formation by maintaining the injection zone and effluent temperatures well below 88°F appears to be a short term and probably superficial solution to the immediate problem ... A more durable and safer solution to acid waste disposal into carbonate formations, however, would be the surface treatment of the acid wastes to render them chemically inert prior to subsurface emplacement.

The cover letter of this USEPA report (IEPA files, 1984) states that

the occurrence of similar well blowouts in other facilities disposing acid wastes into carbonate formations cannot be ruled out unless the underlying cause viz. the chemical interaction of acid and disposal formation leading to the generation of carbon dioxide is eliminated. This can be done by the simple neutralization of the acid with alkali or limestone or by other suitable methods prior to deep well disposal. A less desirable and possible less practical alternative would be to render the waste essentially nonreactive by dilution with fresh water. Also, it does not appear that the cost of treating the acid waste to make it permanently inert would be overly burdensome to the operator, especially considering the resulting safety of the well operation.

Michael J. Barcelona of the Illinois State Water Survey pointed to the injection of the $CaCl_2$ brine as contributing to the blowout. He stated:

It is clear that the 'blowout' of the [Site A] well in 1975 was the result of nonroutine operations where very strong acid was pumped more rapidly than the formation would accept it. If, in fact, as the USEPA (IEPA files, 1984) supposes, CO_2 (gas or liquid) buildup due to reaction of the acid with the dolomite is the actual cause of the blowout, *"normal" operations* would be expected to require steadily increasing injection pressure to continue pumping.

It is unlikely that temperatures lower than 88°F would be encountered in the zone of reaction since the reaction of HCl with $CaMgCO_2$ is exothermic [gives off heat]. While their discussion of CO_2 liquid-gas equilibria is logical, liquid CO_2 would only build up at low temperatures, high pressures, and in low solubility media. $CaCl_2$ solution pumped at a high rate (and probably high pressure) as a measure to clear the "blocked well" probably provided these conditions necessary for a buildup of CO_2 prior to the blowout.

Thus, rather than the normal operation of these wells, it is the contingency plans which need careful scrutiny to ensure that neither casing failure due to overpressuring the system nor conditions where CO_2 could exist as a liquid (which would overpressure the system also) can occur (IEPA files, 1984).

Kamath and Salazar (1986) further elaborated on the conclusions reached in USEPA Region V (IEPA files, 1984). Fundamental considerations of the phase behavior of CO_2 indicate that the safe and trouble-free operation of a well injecting acid into a carbonate formation is based on the condition that the produced CO_2 associated with the fluids around the well bore be in the liquid, not gaseous, state. This condition will be met if the "effective" downhole temperature is kept below 88°F, the critical temperature of carbon dioxide. The safety of wells disposing acid into cavernous carbonate formations can be totally assured if this condition is met (Kamath and Salazar, 1986).

According to Kamath and Salazar (1986), injection of acid at a temperature greater than 88°F set up the scenario for the blowout. At this temperature, nearly all fluid in the injection zone was associated with CO_2 in the gaseous state. A CO_2 "gas cap" may have formed as a result, possibly augmented by inhibition of CO_2 removal downstream by conversion to carbonate, which is known to be unstable at higher temperatures and low pH. If this were the case, there could have been an adequate volume of high pressure gas near, though not yet in, the well bore.

Kamath and Salazar (1986) stated that the $CaCl_2$ injection triggered the blowout. They reason that the parting of the tubing resulted in the escape of the light annulus oil up the tubing, with subsequent escape of the high pressure (CO_2) gas into the annulus by buoyancy. This caused a similar "reverse

flow" in the injection zone. This gas pressure buildup in the annulus "snowballed" due to rapid expansion of the gas as it rose, augumented both by the smaller diameter of the 300-foot Fibercast casing (4 1/2-inch) at the bottom of the well and by the partial blockage of this Fibercast casing by the 317-foot section of parted tubing that had not yet been removed. The result was the large blowout.

Panagiatopoulos and Reid (1986) concluded that there is a critical value for the inlet acid concentration to a carbonate disposal well that should not be exceeded. This limit is 6 weight percent HCl; the disposal of waste acid involves no serious hazards, provided care is taken to limit the inlet acid to this or a lower concentration (Panagiotopoulos and Reid, 1986).

Panagiotopoulos and Reid (1986) theorized that when the strong acid (31.5% HCl) came into contact with the formation, CO_2 was evolved as a new, less dense phase. Because the phase was less dense, disengagement would occur with accumulation of the CO_2 in the upper part of the disposal zone cavity. If some of the CO_2 should move to the injection pipe (by buoyancy), this gas would begin to ascend. Hydrostatic head would drop and would continue to decrease due to the presence and continued expansion of the CO_2. This "percolator" effect would cause a driving force to eject fluid and vapor from the casing by two-phase flow "water-hammer" effects accompanied by a sharp pressure increase. This sequence would then draw more acid brine and CO_2 into the casing to maintain the process, and geysering would result.

Site E Blowout

The only information available documenting the blowout of the Site E well is the workover report quoted in Chapter 2 (IEPA files, 1976), which states that the pressure buildup and blowout were believed to be caused by CO_2 gas generation. The report confirmed that CO_2 gas and water blew out from the well for 12 hours. Site E's application for permit under the new regulations made no mention of the blowout. During permit review, the Site E operator made the following statements about prevention of blowouts in the well during injection of high-concentration HCl waste:

> In an operating well injecting acidic wastes of a varying concentration, it is both practical and technically valid to regulate average concentration ... While prolonged injection of concentrated acid could create a potential well blowout situation, periodic injection of concentrated acid followed by periods of injection of dilute or basic material averaging less than 6 percent should be considered safe ... As you know the ... well has been used for injection of dilute HCl for 12 years ... Based on the plant operation, prolonged injection of concentrated hydrochloric acid does not occur. Both the age of the injection well and average acid concentration must be considered in limiting the acid strengths to be injected into dolomite formations. Based on the above considerations and the past performance of the well, a maximum (average) concentration of 6 percent per month HCl will provide for a conservative degree of safety in preventing well blowout due to the release of CO_2 (IEPA files, 1986).

In response to a Site E waste temperature restriction proposed by the IEPA in a draft permit issued in August 1986, Site E staff stated that "we cannot currently meet this limit and we believe that there is no need to do so. Our own studies and those of MIT Professor Dr. Robert Reid show that more than adequate CO_2 control can be achieved by limiting the strength of injected acid. The past 13 years of our well operation witness to this fact" (IEPA files, 1986).

In response to a proposed restriction on HCl concentration of injected waste made in the draft permit, the Site E operator stated that "Dr. Reid's (Panagiotopoulos and Reid, 1986) study conservatively demonstrates that HCl concentrations up to 6 percent by weight may be safely injected over continuous and extended periods of time into carbonate formations. Again, this has certainly been verified by years of trouble-free injection at both our facility and others in Illinois" (IEPA files, 1986). The Site E operator goes on to state in the same document that "this limit should be expressed as an average limit."

In a conversation with Reid (Nealon, verbal communication, 1986), the conclusions of Panagiotopoulos and Reid were clarified: Reid stated that their conclusion was that a 6 weight percent

maximum, not average, concentration of HCl could be safely injected into a dolomite formation. A 6 weight percent average concentration, he said, would be acceptable only if the maximum concentration did not exceed 8 weight percent.

A draft permit has been issued to Site E to inject wastes containing up to 7 percent by weight, total acidity, and from April 1, 1988, to the expiration of the permit the total acidity shall not exceed 5 percent by weight. By April 1, 1988, the site operator will have installed an operational neutralization system for plant process wastewater.

Measures Recommended to Prevent Blowouts

The only well blowouts to occur in Class I wells in Illinois have occurred at facilities permitted to dispose of strong HCl into a dolomite formation. *[Given this fact and the studies summarized above, the authors have recommended to the IEPA that the concentration of HCl injected into a dolomite formation be limited by a maximum absolute concentration, not a maximum average concentration (IEPA files, 1986). Another acceptable alternative is to neutralize the HCl in the wastestream prior to injection into the dolomite formation, rendering it chemically inert. We do not believe it is necessary to impose injection temperature restrictions that would limit the maximum waste temperature to 88°F, because the formation itself will ultimately control the temperature of fluids in the injection zone. We also have recommended that the injection of brines under high pressures for the purposes of clearing blocked tubing or "killing" wells (where fiberglass or fiber-cast tubing is used) prior to workovers be prohibited in Illinois. This will contribute to safe operations by reducing the possibility of parting a well's injection tubing.]*

PACKER VERSUS PACKERLESS DESIGNS

Debate continues as to whether packerless well designs provide the same degree of protection to USDW as packer completions. At the time Illinois received primacy, four packerless wells were in operation; use of three of those has since been denied by the IEPA under the new regulations, and the fourth has been accepted.

Packer Completions

A packer is an expandable device that is placed at the bottom of a well casing (long string) to seal off its annulus from material being produced from, or injected into, a well (see Figures 3-2 to 3-5). In the case of an injection well, it ensures that the casing of the well is protected from contact with wastes being injected. Since the packer is set in the casing, an oil blanket is typically spotted under the packer to prevent contact between the injected waste and the short length of well casing beneath the packer.

Because the annulus is completely sealed off (by the packer at the bottom and by the wellhead at the top), it can be pressurized with kerosene or some other fluid. If a leak develops in the casing, packer, or injection tubing, a drop in this annulus pressure results, thus alerting the injection well operator that a potential problem exists. Another advantage is that if a leak in the injection tubing should occur, the movement of fluid would be from annulus into tubing, ensuring protection of the casing from contact with injected fluid. In many instances in Illinois, this principle in operation has led to the early (and timely) discovery and identification of well problems (IEPA files).

An example of what can happen if warning signs are not heeded is the 1974 incident at Site D (see Chapter 3). The well was allowed to continue operation for months after a packer leak was first suspected, and annulus pressure was maintained at half the injection pressure. Severe tubing and casing damage immediately above the packer resulted (IEPA files, 1974, 1975). At present, annulus pressure in Class I wells in Illinois must exceed injection tubing pressure at all times, even when injection is not occurring. The annulus pressure must also be high enough to maintain a positive differential pressure from annulus to tubing along the entire length of the annulus. This provides "round-the-clock" monitoring of the well's integrity.

One disadvantage of packered wells is that the casing below the packer is isolated from the injected waste only by the oil blanket, which is spotted below the packer. There is no way to continuously monitor the thickness of this blanket to ensure that a sufficient thickness of oil remains to protect the casing and the bottom of the packer from contact with injected waste. An effective way to

periodically monitor this thickness would be to inject a small amount of a radioactive tracer along with the blanket when it is emplaced. A radioactive tracer logging tool could then be used to verify the thickness of the blanket.

Packerless Completions

Two types of packerless completions exist: static fluid seals and dynamic fluid seals. In a static system, a fluid less dense than the injected waste and the natural formation water (such as kerosene) is placed in the annulus. By adding enough of this annular fluid to force the contact of the formation water with the lighter density kerosene to the vicinity of the base of the tubing, a pressure can be maintained in the annulus (since the annular fluid will float). Should a leak in the casing or injection tubing occur, the annular fluid would be lost to the formation or the tubing; the subsequent drop of annulus pressure would alert the injection well operator that a potential problem exists. Also, the movement of fluid out of (instead of into) the annulus protects the casing from contact with the waste.

A dynamic system is the same as a static system except that water is always the annular fluid and is injected into the annulus during waste injection cycles. The downward movement of this water forces the injected waste down the well bore and away from the well casing. When injection is not occurring, this system acts as a static system.

Well A1 has a static fluid seal and uses kerosene as an annular fluid; this well will have a packer installed later in 1987. Weil A2 had a packer installed in May 1987. Well E employed a dynamic system until the well was rebuilt following the 1973 failure; it now has a static system that has been approved by the IEPA for use under the new regulations. Well C had a dynamic system until November 1986, when a packer was installed.

Adequacy of Dynamic Fluid Seals.   Dynamic fluid seals cannot ensure protection of USDW for the following reasons: (1) they cannot detect leaks that might occur during injection; (2) they require long shut-in periods (during which well operation ceases) following injection cycles in order to stabilize enough to detect possible leaks; and (3) water is much less acceptable as an annular fluid because of its potential to corrode metal casing and because the density differential between it and natural formation waters is not as great as between light oil and natural formation waters.

During injection cycles, water is pumped down the annulus while waste is injected down the tubing. If a leak were to develop or if the tubing happened to part during an injection cycle, this would remain unknown until the injection ceased and the annular pressure stabilized. Because of the smaller density difference between annular water and formation fluids, the loss of water from the annulus to the tubing could go undetected. When Well C was inspected for the first time in 1975 (since its startup in 1968), it was discovered that at sometime in the previous 10 years the lower 100 feet of tubing had parted in the well, resulting in the loss of the lower 42 feet of casing; the loss was undetected until the tubing was pulled for its first workover. Had the casing developed other holes higher up, these could have gone undetected also. However, the effectiveness of this dynamic flush annulus is noted in the lack of corrosion on the part of the steel collar above the end of fibercast joint where the tubing parted.

Adequacy of Static Fluid Seals.   The drawback of static fluid seals is the dynamic vertical movement of the waste/light oil interface in response to temperature and pressure changes. As stated before, light oil can be held under pressure in a packerless well annulus: because it floats, it is trapped between the sealed wellhead and the formation water that wants to rise to its natural static water level in the well bore. If a leak develops, the fluid has a means of escape, and the pressure drops, signaling a problem. However, when the fluid escapes, the waste/oil interface begins to rise in the well. If this interface rises so that the waste comes into contact with the steel casing in the well, problems could result, depending upon the degree to which the waste interacts with the materials of which the casing is constructed.

In the current well (Site E) that has a static fluid seal, hydrochloric acid is the waste material. This well has acid-resistant casing at the bottom of the well, cemented in place with an acid-resistant epoxy cement. The remaining major portion of the casing in this well, however, is made of carbon steel, which is not acid-resistant. To safeguard the well, a method of monitoring the position of the waste/oil interface must be utilized.

In the past, equilibrium equations have been utilized to estimate the position of the waste/oil interface in a packerless well. Since the injection tubing and annulus are open at the bottom, the pressure exerted by the fluid in the injection tubing must equal that exerted by the annulus fluid and annulus pressure. The waste/oil interface will move up or down in response to the relative increase or decrease in pressure exerted by either fluid and to the thermal effects on annular fluid density.

By assuming that the waste/oil interface is located at the bottom of the injection tubing to begin with, equations can be used to calculate the change of position of this interface when certain variables (such as fluid specific gravities, fluid densities, and temperature) change. Another assumption made is that changes in the interface can be detected by changes in annulus pressure. The use of these equations has major drawbacks:

• Annulus pressure is the only variable that is monitored continuously. Fluid specific gravities, fluid densities, and downhole temperatures can only be approximated; all variables except pressure are recorded once a week, but can change continuously.

• To use these equations to estimate the effects of changes in these parameters on the position of the interface, an assumption must be made as to where the interface is at the beginning. The assumption that it is at the bottom of the casing or tubing (whichever is the shallower) may not be correct.

• If a change in annulus pressure is noted, all other variables must be measured and then plugged into an equation before the position of the waste/oil interface can be estimated.

• In a potential emergency, there might not be time to make such calculations continuously.

Site E has utilized a conductivity-measuring system to alert plant personnel of a rise of the waste/oil interface into the basal section of the carbon steel casing of the well. In the past, a pair of lead anodes, spaced 3 feet apart, was attached on the outside of the tubing. Wires connected to the anodes were hooked into an alarm system at the surface; the 3-foot gap between the anodes was a gap in the circuit. If the waste, having considerably higher electrical conductivity than the annular fluid, rose in the annulus and covered both anodes, the circuit was closed and the alarms sounded. Although useful in concept, the early designs of the system were plagued with problems and were unreliable. The anodes were set in the carbon steel casing immediately above the Fibercast casing, and during the early history of the system there was no way to check wire continuity. There was also no procedure used to check the system by raising the annulus fluid/waste contact to the anode rings.

A new anode system was constructed and installed at Site E in April 1986. The system has two pairs of lead anodes at depths of 3559 and 3562 feet and 3572 and 3575 feet, all inside the 4½-inch Fibercast casing component of the well. Each anode is connected to the surface by two wires, which are in turn connected to alarms in the plant's control room. The system forms an open circuit; if the waste, having greater electrical conductivity than the annulus oil, rises in the annulus of the well and covers both anodes in any one of the two pairs of rings, the circuit is completed between them, and the alarms are set off. Because the anodes are inside the Fibercast casing, any rise of the waste/kerosene interface can be detected before the waste reaches the steel casing. When the alarms sound, oil is pumped into the annulus and the well is shut down. Site E has successfully tested this system by backflowing kerosene from the annulus, allowing the water/kerosene interface to rise to the anodes and activate the high-conductivity alarms in the plant's control room. Upon activiation of the alarms, kerosene is pumped back into the annulus and the alarms are allowed to shut themselves off. This system is to be tested quarterly.

The anode system is backed up in two ways. First, there are two pairs of anodes. If the function of one pair should be questioned, the second can be used to verify the proper function of the first, or be used as a backup until any problems can be investigated. Second, each anode has two wires attached to it. These two wires form a closed circuit, which is continuously monitored by passing current down one wire, across the anode, and up the other wire. If a wire breaks (and interrupts the current), a different alarm is activated in the plant's control room.

Pros and Cons of Packer/Packerless Construction

An injection well must be constructed so as to conduct waste to the injection zone without having contact with USDW below the surface of the earth. This requirement is met by adequately casing the well so as to isolate the USDW (and all other aquifers) from the injected waste stream. It follows, then, that the casing itself must also be kept isolated from the injected waste. The purpose of installing a packer in a well is to provide a barrier against any rise of waste in the well bore that could contact the casing of a well. Even if a leak were to develop in the injection tubing, casing, or the packer itself, the packer provides a barrier beyond which the waste cannot rise. Maintaining the annulus pressure above the injection tubing pressure ensures that, in the event of a leak, fluid movement will be out of the annulus and not into it. Oil spotted below the packer is intended to protect the short length of casing (known as a stinger or tail pipe depending on the type of packer used) below the packer from contact with the waste stream. However, there is no way (at the present time) to continuously monitor the thickness of this oil blanket.

A packerless well does not have an immovable barrier (i.e., a packer) to isolate the casing from the injected waste. At best, it has an alarm system (as at Site E) to alert plant personnel that waste is rising in the well; at worst, calculations using approximations of pertinent variables are made to estimate the position of the waste/oil interface. One advantage that an alarm system has is that plant personnel know if the very bottom of the steel well casing is threatened by contact with waste. As with a packered well, maintenance of annulus pressure at a level higher than the injection pressure ensures the movement of fluid out of, not into, the annulus in the event of a tubing leak. However, any escape of fluid from the annulus is accompanied by a rise in the waste/oil interface. Even with an alarm system that is proven to work effectively (as at Site E), a well that can allow a potential rise of the waste/oil interface into its casing does not afford that casing the same degree of protection as a packer would. Monitoring of annulus pressure provides a continuous monitor of aquifer response to injection in a packerless well.

The packer well design meets the intent of the regulations for annulus design; however, the packerless well design may be approved by the regulating agency if it can be demonstrated that this design equals or exceeds the protection offered by a packer design in protecting USDW. *[The authors recommend that all new Class I wells in Illinois consider use of a packer design, but also acknowledge that the packerless design may be a preferential choice under narrowly defined geologic, operational, and waste-type conditions.]*

INJECTION INTO FORMATIONS WITH HIGHER HEAD THAN OVERLYING USDW

A recently raised concern is the safety of Class I waste disposal into a formation that is under a higher natural pressure, or hydrostatic head, than the USDW that overlie it. In this case, the potential exists for any well to backflow, under its own power, into or above an overlying USDW or even onto land surface if the hydrostatic head is great enough.

Potential for Backflowing

The Mt. Simon Formation in Illinois generally has a higher head than the aquifers overlying it. It is a favorable disposal zone in central Illinois because of its thick, permeable injection zone and extremely high total dissolved solids (TDS) content. However, its potentiometric surface is generally higher than the USDW overlying it, and, in fact, is near, at, or above land surface in areas of Illinois where the high TDS content makes it eligible for use as a disposal zone.

The potential of the Mt. Simon to backflow into a waste disposal well was illustrated by the failure of the Site E well in 1973. Although the high pressure head in the Mt. Simon was not the cause of the failure, it did cause backflowing of lighter density injected waste and some formation water through the well (through the damaged outer casing) into an overlying aquifer, the Potosi Formation. Two circumstances acted in Site E's favor during that incident: (1) the Potosi Dolomite is not a USDW at the site (it contains water having more than 10,000 mg/L TDS); and (2) when part of the well casing was destroyed, the backflowing waste had an avenue of escape into a nonpotable aquifer (the Potosi). If a cased well finished in the Mt. Simon at this site were filled with fresh water, the potentiometric surface of this aquifer would be above land surface.

Upon the failure of the Site C well in 1976, an estimated 200 to 300 gallons of water (of neutral pH) backflowed out of the well tubing into the pit which houses the well at the facility (IEPA files, 1976). It has been surmised that further backflowing of the well was prevented because of the presence of higher-density water that had moved into the well bore.

Another example, not related to waste disposal, further illustrates the point. In 1977, a water supply well was drilled in Mount Prospect, Illinois, a suburb of Chicago. This well was completed in the Ironton-Galesville and upper Mt. Simon aquifers. The upper Mt. Simon is a major water-supply aquifer in northeast Illinois, although the lower part of the formation contains water of unacceptable drinking water quality (Sasman et al., 1982). The well was capped in 1978 and not pumped again until June 1981. During that time, high-TDS waters were drawn upward from the lower Mt. Simon under the influence of the much higher pressure head in the Mt. Simon and backflowed into the Ironton-Galesville, causing contamination of that aquifer (SWS files).

Class I Disposal into the Mt. Simon Formation

Two Class I wells in Illinois, one hazardous and one nonhazardous, currently inject waste into the Mt. Simon Formation. Although the wells are adequately cased through all USDW, a concern has been raised about backflow potential due to the natural high pressure head existing in the disposal zone. The operators of both wells have requested increases in their maximum allowable injection pressures in current applications for permit under the new regulations.

Site B

At Site B, Mt. Simon observation wells showed potentiometric surface levels to be above land surface at some locations within the facility in 1985 (IEPA files, 1985). Pressurization of the Mt. Simon by gas storage in the upper part of the formation further contributes to increased pressures within the formation. Injection of waste from the nonhazardous natural gas scrubbing operation occurs at a lower interval in the formation.

About 195 feet of confining zone (the shales of the Eau Claire Formation) separates the Mt. Simon from the lowest USDW, the overlying Ironton-Galesville Sandstones. The Ironton-Galesville contains water of less than 3000 mg/L TDS in this area. In addition, all formations between the Eau Claire Formation and the Maquoketa Shale Group are hydraulically connected in this area. It is imperative, then, that the injected waste be effectively confined to the injection zone.

The well itself was not originally drilled for waste disposal; it was constructed in 1965 for gas storage and converted to a waste disposal well in 1974. The well was tested for mechanical integrity in 1982 when the injection tubing was replaced; testing scheduled for 1987 has been completed. The well has had several acid treatments to improve injectivity since its conversion but the condition of the well has not been assessed since these treatments.

Site C

The fresh-water potentiometric surface of the Mt. Simon disposal zone at Site C is currently above land surface. This is clearly indicated by the need to use pressures of up to 100 psi at the wellhead in order to inject fresh water into the well following each waste disposal cycle.

At a mechanical integrity test of the well conducted October 24, 1983, special attachments had to be placed on the wellhead in order to accommodate the logging tools to be used during the test. During this operation, the IEPA representative present noted that "when well service unit personnel pulled the lubricator off of the wellhead a good 6-inch-high water head flowed above the top of the casing (tree)."The portable electric pump was turned back on to keep the pit clear (IEPA files, 1983).

Site C is located about 20 miles south of the northern margin of the area where the Mt. Simon is considered suitable for injection of wastes into Class I wells (see Figure 2-6). The Ironton-Galesville aquifer, which immediately overlies the Eau Claire confining unit, has a limited areal extent of water containing greater than 10,000 mg/L total dissolved solids in the vicinity of this well and is used for water supplies some 15 miles to the east-northeast.

The Illinois State Geological Survey has stated that "injection under present operating conditions appears quite acceptable," but in response to the request for increased injection pressure (to almost

800 psig), stated that "the technical review committee has some reservation in allowing high pressure injection both at the site and with the existing disposal facility design" (IEPA files, 1986). In November 1986, the well was reworked by adding a new wellhead, a new 5-inch long string casing, and a packer completion; however, the siting problem remains.

Recommendations

In scenarios described in this section, the potential of the Mt. Simon Formation to backflow into a well bore has been highlighted, and occurrences of this phenomenon have been documented. Communication to overlying aquifers could occur in any disposal zone in which the natural hydrostatic head exceeds that of the overlying aquifers.

In Class I deep well injection into any geologic formation in Illinois in which the natural hydrostatic head is near or greater than the natural hydrostatic head of any overlying USDW or land surface, the maximum allowable injection pressure permitted should, at the very least, be limited to values that ensure the integrity of the disposal system. In some parts of Illinois, banning injection or denying permits for new injection wells may have to be considered in the future. Additional data are needed to define the conditions in any formation in which injection of significant volumes of waste could adversely affect the disposal system and thus endanger human health and the environment.

AREA OF REVIEW AND MONITORING: CONCERNS AND RECOMMENDATIONS

Existing Models and Requirements

In 35 Ill. Adm. Code 730.106, an equation is presented for determining the radius of the area of review of a disposal well:

$$r = \frac{(2.25\,K\,H\,t)^{0.5}}{(S\,10^{x})^{0.5}} \qquad\qquad \text{where } x = \frac{4\pi\,K\,H\,(W\text{-}BG)}{2.3\,Q}$$

and where

       r = radius of endangering influence from injection well (feet)
       K = hydraulic conductivity (feet/day)
       H = thickness of
            injection zone (feet)
       t = time of injection (days)
       S = storage coefficient (dimensionless)
       Q = injection rate (ft^3/day)
       B = observed original hydrostatic head of injection zone (ft) measured from the base
            of the lowermost USDW
       W = hydrostatic head of USDW (ft) measured from the base of the lowest USDW
       G = specific gravity of fluid in the injection zone.

This equation is a modification of the Theis equation, used to predict the change in potentiometric head of an aquifer, at a given point in time, caused by pumpage from (or injection into) that aquifer. The modified equation assumes that the pressure head in the overlying USDW is greater than that of the injection zone when the well is drilled, and that both of these heads are known. It models the buildup of the head (cone of impression) in the injection zone with time. As the modeled injection continues, the head in the injection zone eventually exceeds that of the USDW at the well and at gradually increasing distances from the well. The equation predicts the distance from the well, after a specified period of time, beyond which the head in the injection zone is still less than that in the USDW (i.e., the point where the injection cone of impression intersects the potentiometric surface of the USDW). Theoretically, this is the point at which injection pressures cannot cause fluids to migrate from the injection zone. The distance from the well to this point is called the radius of the area of review.

In some cases in Illinois, the potentiometric head of the injection zone was (or could be) greater than that of overlying USDW before the well was drilled. In these situations, the radius of the area

of review is infinite, as injection zone heads will always exceed those of the USDW, and the potential for fluids to migrate from the injection zone into USDW will always exist and will increase with increasing duration of injection. Conversely, in other cases in Illinois the potentiometric head of the injection zone will always be less than that of overlying USDW (even during injection periods). In these situations, the radius of the area of review is zero. Section 730.106 (c) states that "if the area of review is determined by a mathematical model ... the permissible radius is the result of such calculation even if it is less than 402 meters (1/4 mile)."

These extremes point out one problem in determining to what distance from the well a permit applicant should seek to find the location of potential avenues of escape in an "infinite" area of review; on the other hand, it can be dangerous to neglect to look for potential avenues of escape on the basis of the modified Theis equation calculating a "zero" area of review.

Determination of the potentiometric heads of the injection zone and USDW is in itself a problem at existing Class I well sites. During the drilling of new wells, drill stem testing of the formations will reveal their potentiometric heads. For the most part, however, this was not done during the drilling of existing Class I wells in Illinois. If the equation in 730.106 is to be used for existing wells, these potentiometric heads must be estimated. In some cases, they cannot be estimated with any certainty.

The use of the modified Theis equation to calculate the radius of an area of review is not effective: it does not take into account all possible well scenarios, multiple well systems, reservoir conditions, and other variables. A pressure-buildup model that accounts for non-ideal and/or actual reservoir conditions is more appropriate: some industries in Illinois have resorted to using such models, most notably the model presented in Warner et al. (1979). This model and others are presented or referenced in the Proceedings of the International Symposium on Subsurface Injection of Liquid Wastes (1986).

Even if the use of more suitable models were mandated in the regulations, a problem would still exist with implementing the regulations at existing Class I well sites in Illinois. There is only limited detailed hydrogeologic information on Illinois Class I well sites, and values for parameters that would be used in models are mainly estimates, not actual test data. In some cases, data are taken from gas storage or petroleum production zones some miles away from the Class I site (IEPA files). Even in those cases, useful data are scarce. The best model is only as good and as accurate as the data input into it.

Another option available to permit applicants is to use a fixed-radius area of review. The minimum fixed radius required by 35 Ill. Adm. Code 730.106 is 1/4 mile, although Illinois industries have used 2½ miles in their current permit applications at the request of the IEPA. All but one industry (Site F) have chosen to use a 2½-mile, fixed-radius area of review. With the lack of extensive hydrogeologic data, the fixed radius appears to be the only option available for existing Class I wells in Illinois. At least two industries (Sites B and C) would probably have infinite areas of review were they to use the equation in 730.106; operational data (IEPA files) suggest that other industries might have had "zero" areas of review had they been able to use it.

Monitoring in the Injection Zone

The ultimate means of tracking waste movement in the injection zone would be to monitor it. Monitoring wells placed in the aquifer above the confining zone would detect any migration of waste through the confining zone that might occur; however, this would not allow tracking the waste or monitoring pressure buildups away from the borehole in the disposal zone. The only possible means currently available to monitor waste migration and pressure buildups is to construct monitoring wells in the injection zone.

Monitoring at Sites B And G

At Site B, many gas storage wells penetrate the top of the Mt. Simon Formation (in the upper Mt. Simon where gas is stored, above the waste injection zone) and also the Galesville Sandstone. At Site G, gas storage and petroleum production/brine disposal wells penetrate formations above and below the waste injection zone. There are, however, no wells available at either site to track the movement of waste or buildup of pressure in the injection zone.

Monitoring at Site F

At Site F a monitoring well was completed in the Devonian injection zone to monitor for the presence of chlordane, which would give an indication of the rate of waste movement (assuming no loss of chlordane during transport) when the waste front had traveled that radial distance into the formation. Chlordane was detected in samples within the first year of installation of the monitoring well (IEPA files); however, the source of the Chlordane has been debated ever since it was first detected. Four possible explanations are that the waste front reached the monitoring well; contamination occurred during well construction; contamination occurred during well sampling; and fallout of Chlordane occurred from the atmosphere. This single well appears to have been ineffective in monitoring movement of the waste front.

Constraints Against Monitoring

As noted previously, monitoring the aquifer above the confining zone would only tell whether or not the waste had migrated through the confining zone and would not track the waste front or monitor pressure buildups away from the well bore. However, monitoring wells in the injection zone would provide potential means of escape for injected wastes; this makes such monitoring undesirable.

An additional constraint to both monitoring schemes is cost. The cost of drilling enough monitoring wells into the injection zone or into the aquifer above the confining zone could be very high. For this reason it has not been done (except at gas storage sites) and will not be done voluntarily by industries in Illinois with Class I wells. Without any monitoring and without sufficient data to accurately model the injection scenario over time, industries over the past 20 years have been unable to confirm the estimated position of the waste and pressure fronts and the magnitude of the waste component concentrations and pressure buildup between the fronts and the injecting well.

Conclusions and Recommendations

Knowledge of the geologic and hydrologic characteristics of the subsurface environment at an injection site and in the surrounding region is fundamental to the evaluation of the suitability of the site for wastewater injection and to the design, construction, operation, and monitoring of injection wells (Warner et al., 1986). For any new Class I well applications in Illinois, techniques for modeling pressure buildup due to injection should be proposed along with plans for appropriate tests that will be conducted to collect data for the modeling. Because monitoring in the disposal zone is not recommended, the pressure buildup model would be the only method of estimating pressure buildup and waste front movement with time. It is imperative, then, that proper planning and engineering be carried out during the design and permitting stage to ensure that sufficient useful data will be collected to attain the most accurate model possible.

Given the current lack of detailed hydrogeologic data for existing Class I well sites in Illinois, it appears that the fixed-radius area of review is the only option available to determine the area around the well that must be surveyed for possible avenues of escape of injected fluids. All references in 35 Ill. Adm. Code to a 1/4-mile minimum area of review should be changed to require a 2½-mile minimum. (It is recognized here that this value of 2½ miles is arbitrary and has no scientific basis.) In all cases (i.e., for both proposed and existing wells), the IEPA should have authority to extend a well's area of review if the added precaution is deemed necessary (for example, where an area of review extends into a town or city or into an area of influence surrounding a public water supply source, or where geologic conditions are known or expected to be less than optimum).

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7 EVALUATION OF ALTERNATIVES TO DIRECT INJECTION WELL DISPOSAL*

INTRODUCTION

The current evaluation of the Class I UIC program by the Illinois State Legislature may result in changes in regulations and/or regulatory practices affecting liquid industrial waste disposal in one of three general ways: (1) current disposal practices will be continued, with only minor changes in the regulations and/or regulatory practices; (2) additions to the regulations and regulatory practices may mandate treatment and removal of hazardous or toxic waste components prior to injection well disposal; and (3) deep well injection may be banned entirely as a disposal option for liquid industrial wastes.

In this section treatment technologies and disposal methods that may be considered as alternatives to current deep well injection practices if the UIC regulations should be changed are identified and evaluated. Because both existing and future waste generators may be affected by a change in the regulations, technical and economic evaluations made in this section were developed for several important waste-type categories, each representing a specific class of related waste components.

Appropriate disposal options and related treatment requirements for each waste-type category were developed for the two possible scenarios that could result from UIC regulations changes requiring removal of hazardous waste components prior to injection well disposal or a total ban on injection well disposal. Comparative evaluations were made of the direct capital and operating costs and social, environmental, and economic impacts of each of these scenarios, as well as for currently approved injection well disposal practices.

Because the results obtained are based on generic waste-type categories, the information developed can be used along with specific waste characterization data to estimate costs and summarize the benefits, risks, impacts, and potential trade-offs associated with treatment and disposal alternatives for any industry that might be a candidate for injection well disposal under the present regulations. This approach was then applied to the specific wastestreams of existing industrial injection wells in Illinois to estimate total costs and other impacts that may result from changes in UIC regulations.

CHARACTERISTICS OF ILLINOIS INJECTION WELL WASTES

There are currently seven industrial facilities in Illinois that utilize Class I injection wells for disposal of aqueous liquid wastes. The sources and quantities of wastes being injected are summarized in Table 3-1, along with the approximate concentrations of the major waste constituents of concern. These wastestreams all have high concentrations of mineral acids, bases, or neutral salts, and most share the hazardous characteristic of "corrosivity" and contain other constituents of environmental concern. Some also contain specific hazardous constituents, such as heavy metals, arsenic, pesticides, and volatile and nonvolatile chlorinated hydrocarbons.

The wastes currently disposed of by injection into Class I wells are primarily aqueous wastes (mostly water), have high concentrations of inorganics (acids, bases, and salts) and dilute concentrations of toxic organics, heavy metals, or other hazardous components, and are generated in relatively large quautities. Other industrial wastes having these same characteristics would be potential future candidates for injection well disposal within Illinois, provided the regulations and other factors are favorable.

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* Chapter 7 was prepared jointly by the UIC Project Staff and the consultant, Engineering-Science, Incorporated (M. Guthrie).

Although many different types of industries produce liquid wastes having these general characteristics, the composition of the wastes (both individual constituents and their concentrations) can vary widely from one industry to another; also, liquid wastes from different industries often contain some of the same individual contaminants, although the overall mixture is quite different. For these reasons, it is helpful to classify these wastestreams according to their major constituents rather than to consider them individually or by industrial categories.

Another reason to classify wastes according to their major constituents is that different waste treatment technologies are used to remove or destroy different types of contaminants. The characteristics of a particular waste will therefore determine the best treatment technology to use. Since many wastes share the same types of contaminants, the selection and evaluation of treatment alternatives for the liquid wastes currently being disposed of (or that may be disposed of in the future) in injection wells can be based on a relatively small number of generic waste-type categories.

The major contaminants present in wastestreams currently disposed of in Class I injection wells within and outside Illinois can be grouped into seven general waste-type categories, each representing a class of chemical contaminants sharing the same general characteristics:

- Mineral acids and bases
- Inorganic salt solutions
- Heavy metals
- Cyanides
- Halogenated hydrocarbons
- Nonhalogenated organics (solvents and other compounds)
- Pesticides

Most wastestreams considered for injection well disposal contain contaminants representing more than one of these waste-type categories. Table 7-1 identifies the general waste-type categories represented as major constituents in the wastes generated by a selection of various industries in Illinois.

IDENTIFICATION OF ALTERNATIVE DISPOSAL OPTIONS

The selection of treatment alternatives for a particular waste depends not only on the general waste-type categories it represents, but also on the level of treatment required for disposal under the applicable state and federal regulations. Some treatment technologies can achieve lower residual contaminant levels than others, although the costs of achieving a greater degree of treatment are usually higher. Selecting the most cost-effective treatment alternative requires consideration of all available disposal options and the short-term/long-term impacts of these options.

On the basis of the general waste-type categories identified above, the following disposal options were identified:

- Injection well disposal after treatment
- Publically Owned Treatment Works (POTW) after treatment
- Surface water discharge (NPDES permit) after treatment

These disposal options refer only to the treated aqueous wastestreams; other disposal options must be used for the solid or liquid residues generated during such treatment. Unless otherwise noted, it was assumed that all such residues must be disposed of in a secure landfill, and that any hazardous residues generated during treatment would be subject to chemical solidification with bulking and drying agent(s) and fixation with chemical bonding agent(s) prior to landfill disposal to reduce the potential for leachate production and the contamination of near-surface aquifers. Solidification/fixation might also be necessary in the case of nonhazardous but highly soluble salt residues.

Direct chemical fixation of the liquid wastes for landfill disposal was not considered to be a generally viable treatment and disposal alternative because of the high cost of fixation relative to other treatment technologies available. (Chemical fixation and landfill disposal may be economical for some small-volume wastestreams containing difficult-to-treat contaminants.)

Table 7-1. Waste categories produced by selected industries.

Waste-type Categories	Automotive and appliances	Chlor-Alkali	Electronics	Electroplating	Farm and agrichemicals	Inorganic chemicals	Iron and steel	Landfill leachates	Leather tanning	Metal finishing	Mining	Organic chemicals	Paint and inks	Petroleum refining	Petrochemicals	Pharmaceuticals	Plastics and synthetic fibers	Waste management (commercial)
Inorganic acids	•		•	•		•	•	•	•		•	•		•	•			•
Inorganic bases	•	•		•		•	•					•					•	•
Inorganic salts		•			•	•	•	•	•		•			•	•			•
Heavy metals	•	•	•	•		•		•	•	•	•	•	•		•		•	•
Cyanides	•		•	•		•	•	•		•						•	•	•
Halogenated hydrocarbons	•	•	•	•				•		•		•	•		•		•	•
Pesticides					•							•						•
Nonhalogenated organic solvents	•		•				•	•		•		•	•	•	•	•	•	•

Incineration was also judged to be an impractical disposal option for the wastestreams considered, for several reasons. (1) These wastes are mostly water (typically 90% or more by composition), and the energy costs associated with routine burning of wastes with such a high water content would be prohibitive. (2) Most of the wastestreams under consideration (see Table 7-1) contain inorganic, rather than organic, contaminants. These inorganics, which include mineral salts, acids, bases, and heavy metals, are not destroyed by incineration. In addition, the high concentrations of inorganics present can cause a variety of operating problems, including corrosion, erosion, plugging, and slag formation. (3) Many inorganics will vaporize at the temperatures applied during hazardous waste incineration, requiring off-gas scrubbers for air pollution control. Such scrubbers capture vaporized materials in a waterstream, thereby producing an aqueous waste with high concentrations of the same inorganics that will require treatment prior to disposal. In other words, traditional incineration will accomplish very little when applied to mostly aqueous wastes with high levels of inorganics.

Although not evaluated in detail, another disposal method—recycling and reuse of the treated aqueous wastestream or a concentrated residue generated during its treatment—has potential application for certain wastes. Recyle and reuse options must be evaluated on a case-by-case basis, which makes them difficult to consider in the context of this report. For example, it may currently be less expensive to dispose of wastes in injection wells than to reuse them (which may include sale to another industry). However, when compared to the treatment costs that could be imposed by a change in the UIC regulations, recycle and reuse options may become economically attractive. In addition, while it may not be economical to recycle and reuse the liquid wastestream itself, any solid or liquid residues generated during its treatment may be sufficiently concentrated to have reuse value. Several potential recycle/reuse options are discussed later in this chapter.

Table 7-2. Illinois drinking water standards.

Constituent	Concentration (mg/L)
Arsenic (total)	0.05
Barium (total)	1.0
Cadmium (total)	0.010
Chloride	250.
Chromium	0.05
Lead (total)	0.05
Manganese (total)	0.15
Nitrate-nitrogen	10.
Oil (hexane-solubles or equivalent)	0.1
Phenols	0.001
Selenium (total)	0.01
Sulfates	250.
Total Dissolved Solids	500.
Chlorinated hydrocarbon insecticides	
Aldrin	0.001
Chlordane	0.003
DDT	0.05
Dieldrin	0.001
Endrin	0.0002
Heptachlor	0.0001
Heptachlor Epoxide	0.0001
Lindane	0.004
Methoxychlor	0.1
Toxaphene	0.005
Organophosphate insecticides	
Parathion	0.1
Chlorophenoxy herbicides	
2,4-Dichlorophenoxyacetic acid (or 2,4-D)	0.1
2-(2,4,5-Trichlorophenoxy)-propionic acid,	0.01
(2,4,5-TPor Silvex)	

Source: State of Illinois Rules and Regulations Title 35: Environmental Protection, Subtitle C: Water Pollution, Chapter I: Pollution Control Board, Part 302: Water Quality Standards, Subpart C: Public and Food Processing Water Supply Standards; as amended through April 1, 1984.

Waste reduction, which includes practices that reduce or eliminate the volume or hazard potential of wastes injected into the subsurface, is becoming recognized as a major long-term component of the nation's hazardous waste management strategy. The 1984 amendments to RCRA require that the biennial reports of all facilities that generate, treat, store, or dispose of hazardous wastes must include a description of efforts at the facilities to reduce the volume and toxicity of the hazardous waste generated, and a statement describing any such efforts must be placed in the operating file at the facility. However, because generators are not required to have a waste reduction program, a simple statement that a generator has no waste minimization program complies with the reporting requirements.

There are no enforced waste minimization requirements for Class I injection wells in Illinois, and technical evaluation of treatment options or process modifications that could reduce the volume or toxicity of the waste to be injected are not required. An initial evaluation is attempted in this chapter; however, the analysis is limited by insufficient process and economic information. Many industries have found that some waste reduction approaches result in major cost savings, and this may be the case for some of the industries practicing underground injection in Illinois. An independent engineering evaluation of each facility should be required as part of a facility's application for a permit and periodically thereafter. If the evaluation shows that a waste reduction method is technically and economically feasible, the facility might be required to incorporate the treatment in its operation.

Table 7-3. Illinois effluent standards for surface discharges.

Constituent	Concentration (mg/L)
BOD_5	30.
Ammonia nitrogen (as N)	3.0
Phosphorus (as P)	1.0
pH	6.0-9.0
Arsenic	0.25
Barium	2.0
Cadmium	0.15
Chromium (hexavalent)	0.1
Chromium (total)	1.0
Copper	0.5
Cyanide	0.10
Fluoride	15.0
Iron (total)	2.0
Lead	0.2
Manganese	1.0
Nickel	1.0
Oils (hexane soluble or equivalent)	15.0
Phenols	0.3
Silver	0.1
Zinc	1.0
Total suspended solids	15.0
Mercury	0.0005

Source: State of Illinois Rules and Regulations Title 35: Environmental Protection, Subtitle C: Water Pollution, Chapter I: Pollution Control Board, Part 304: Effluent Standards, Subpart A: General Effluent Standards; as amended through April 1, 1984.

Note: Water Quality Standards established under Parts 302 and 303 may require lower effluent limits than shown for specific cases.

TREATMENT REQUIREMENTS FOR DISPOSAL OPTIONS

Currently, there are no state or federal regulations upon which to base treatment requirements for injection well disposal of treated wastes (as an alternative to the current use of Class I disposal wells for untreated wastes). Similarly, there are no generally established pretreatment standards for wastewater discharge to a POTW; rather, these are determined on a case-by-case basis. However, there are established Illinois water quality standards for drinking water and effluent standards for direct discharge (Tables 7-2 and 7-3, respectively).

Several assumptions have been made in estimating, for this evaluation, the level of treatment that might be required for each of the various disposal options.

Injection Well Disposal

It has been assumed that if pretreatment for injection well disposal is required, the treated waste-stream would have to meet the established drinking water quality standards (Table 7-2) for all parameters except total dissolved solids, chlorides, and sulfates. These exceptions were assumed because, according to existing UIC regulations, Class I disposal wells must inject wastes only into rock units already containing highly mineralized water (at least 10,000 mg/L total dissolved solids) that includes high levels of chlorides and sulfates. Given the high mineral content of the wastes under consideration, it is not likely that injection well disposal would be an economical disposal option if a lower mineral content were required for injection well disposal. Therefore, no limit on total dissolved solids was assumed for injection well disposal.

Direct Discharge (NPDES Permit)

The established effluent standards for discharges into a receiving stream or lake (Table 7-3) have been assumed to define the level of treatment required for direct surface discharge. However, local situations may require a greater degree of treatment to meet water quality standards established for the receiving stream or lake. In addition, industrial category effluent guidelines promulgated by the USEPA may require that parameters in addition to those included in the National Pollutant Discharge Elimination System (NPDES) regulations also be regulated on an industry-by-industry basis.

Although there is no specific limit on the salt (total dissolved solids) concentration required for surface discharge, water quality standards established for the receiving lake or stream must be met. The limit on total dissolved solids established under the general-use water quality standards (Title 35, Subtitle C, Chapter I, Section 302.208) is 1000 mg/L. On the basis of information regarding dilution by the receiving water, background levels of total dissolved solids, and the experience of the IEPA, it was assumed that the limit on total dissolved solids for direct surface discharge will be no lower than 6000 mg/L (0.6%). While this was the level assumed for identification and evaluation of treatment alternatives, different levels may be determined for specific situations through consideration of stream dilution and mixing-zone requirements (Sections 302.102 and 302.103 of Title 35, Subtitle C, Chapter I).

Discharge to Publicly Owned Treatment Works (POTW)

A POTW is designed to remove the contaminants measured by these conventional monitoring parameters: total suspended solids (TSS), biochemical oxygen demand (BOD_5), ammonia nitrogen (NH_3-N), total phosphorus (P), and oil and grease (O&G). It was assumed that the treatment requirements for discharge to a POTW will be the same as for direct discharge (see Table 7-3).

However, POTWs are not effective in removing heavy metals and other toxic contaminants, and furthermore, such contaminants may cause operating problems when introduced into a POTW. Therefore, the treatment requirements for these nonconventional parameters (for heavy metals and other toxic contaminants) were assumed to be the same as for direct discharge. It was also assumed that a total dissolved solids limit of 6000 mg/L would have to be met to avoid operating problems caused by high salt levels in the receiving POTW, although different values may be determined for specific situations on the basis of background levels and dilution provided by the other wastewater entering the POTW. Industrial category effluent (pretreatment) guidelines promulgated by the USEPA may result in the addition of new waste constituents to the list in Table 7-3 or changes in the concentration limits of existing items in this list.

ALTERNATIVE TREATMENT TECHNOLOGIES FOR WASTE-TYPE CATEGORIES

Technologies for aqueous waste treatment can be grouped into two basic classes: those that destroy a target contaminant or cause its permanent conversion into a less hazardous form, and those that remove the target contaminant from the wastestream but at the same time produce a concentrated waste residue. For most of the waste categories, several competitive treatment technologies available can achieve the required level of treatment anticipated for the three disposal options under consideration.

Mineral Acids and Bases

The treatment objective for acidic or basic wastestreams is to achieve a neutral pH range (between 6 and 9) in the treated effluent; this same pH range has been assumed for all three disposal options. Neutralization is achieved by adding either acidic or basic chemicals to the wastewater under controlled conditions. As a result, the total dissolved solids (or salt) concentration of the waste is increased. Thus, if a particular wastestream is strongly acidic or basic, it will be converted to a high mineral salt waste upon pH neutralization.

The only alternatives to be considered in treatment for pH control involve selection of the neutralization chemical. Lime (either hydrated or quicklime) and caustic soda (sodium hydroxide) are the main chemicals used for acidic wastes, although in some cases limestone, soda ash (sodium carbonate), or other neutralizing agents may be applied. Basic wastes are neutralized by using

sulfuric or hydrochloric acid. The chemical (operating) and capital costs of pH neutralization depend mostly upon the strength of the acidic or basic wastestream and the chemical neutralizing agent selected for use.

Inorganic Salt Solutions

Wastes that contain very high concentrations of inorganic salts in solution are difficult and expensive to treat to achieve the total dissolved solids level required for direct surface discharge or discharge to a POTW (the discharge limitation is assumed to be 6000 mg/L in both cases, although different values may be determined on a case-by-case basis). Although technically possible, it is usually not economically feasible to treat these wastes to a level required for drinking water use (500 mg/L), or to match the general-use surface water quality standard (1000 mg/L). As was previously discussed, a high inorganic salt concentration was not considered to be a problem for injection well disposal.

Three treatment processes are commonly used for removing dissolved solids (salts) from aqueous wastestreams: reverse osmosis, electrodialysis, and evaporation. The treatment of fluoride salts, commonly removed by a chemical precipitation process similar to that used for heavy metals removal, is not discussed.

Reverse Osmosis. This is a process in which water flows under pressure out of a concentrated salt solution, through a polymeric membrane, and into a solution of low-salt concentration. The membrane, although porous, has very small openings that pass water but retain the dissolved salt (ions). Pressure on the salty side of the membrane is required to overcome the natural osmotic pressure that would otherwise cause water to flow toward the saltier side until both sides of the membrane are at equal salt concentrations.

Depending on the membrane selected and the initial salt concentration in the waste, dissolved solids levels of 100 mg/L or less can be achieved using reverse osmosis. However, the process generates a brine or concentrated salt solution as a by-product that cannot be disposed of by conventional means. Although there may be recovery/reuse potential for such low-grade brine solutions, it can be assumed that these will require chemical solidification and fixation for landfill disposal.

About 300 full-scale plants worldwide use reverse osmosis for desalination of sea water or brackish water (which have TDS concentrations up to 35,000 mg/L). Reverse osmosis has been used very successfully in the treatment of electroplating rinse waters to meet the effluent discharge requirement and to recover concentrated metal and salt solutions for reuse. A few other full-scale uses of reverse osmosis can be found in the treatment of sulfite streams from the pulp and paper industry and in food processing.

Electrodialysis. This process, similar to reverse osmosis, also involves the selective diffusion of dissolved salt (ions) through a semiporous membrane. However, instead of using pressure on the salty side of the membrane, electromotive force (voltage) is used to overcome the natural osmotic pressure that develops during the concentration process: electrodes are placed on both sides of the membrane to establish an electrical potential (charge difference) across the membrane. There are actually two types of membranes: those that pass cations (positively charged ions) and those that pass anions (negatively charged ions). These two types are generally used together to remove dissolved salts, which are simply solutions of both cations and anions, the sum of whose charges equals zero.

Again, depending on the membranes selected, dissolved solids levels of 100 mg/L or less can be achieved using electrodialysis. As with reverse osmosis, a concentrated brine solution is produced which can be assumed to require chemical fixation and disposal in a landfill.

Electrodialysis has been used for desalination since the 1950s. Hundreds of such units, some of which process more than a million gallons per day, are in use throughout the world. Most of these are used in the production of potable water from brackish well or river water. In the food industry, electrodialysis is used for desalting whey and de-ashing sugar. The chemical industry uses the technique for enriching or depleting solutions of process chemicals and for removing mineral constituents from product streams.

Evaporation. Evaporation is used to boil away a volatile liquid (in this case, water), producing a concentrated solution or crystalline solid consisting of nonvolatile dissolved solids (salts). Evaporation is a well-defined and established process used throughout industry to recover and concentrate nonvolatile products from volatile liquid streams. When applied to relatively large volumes of primarily aqueous wastes, evaporation is an effective but very energy-intensive concentration process; it produces a treated wastestream that is basically high-purity water, unless volatile contaminants are also present in the waste. As with reverse osmosis and electrodialysis, evaporation produces a concentrated brine solution that must be disposed of by chemical solidification and fixation or evaporated to produce a solid crystalline waste salt. The additional equipment and energy required for crystallization and recovery of the salt would easily be offset by the reduced costs for chemically fixing and landfilling a much smaller volume of material.

Heavy Metals

The broad classification of heavy metals refers to a large number of elements that exist in aqueous solution as multivalent cations (ions with a positive electrical charge of two or more). Some heavy metals such as cadmium, chromium, copper, lead, mercury, nickel, and vanadium are toxic at relatively low concentrations. Others, such as iron, are far less toxic but still require control. Two elements of related concern, although not heavy metals, are arsenic and fluoride. These elements occur as anions, which can be removed by the same basic treatment processes used for heavy metals removal.

The type of process used to remove heavy metals from wastewater depends on the influent concentration, the required treated effluent concentrations, and the individual chemistry of the particular metals under consideration. The two main types of metal removal technologies are chemical precipitation and ion exchange, both of which concentrate the metals into a smaller volume wastestream for separate disposal.

Chemical Precipitation. The solubility of most heavy metals is highly dependent on both pH and the presence of other chemical species in the water. By changing the chemistry of the water, heavy metals and other elements, including fluoride, can be made to precipitate (come out of solution), forming solid particles that can be removed from the water by filtration, gravity clarification, and other common technologies. These solids, in the form of a liquid sludge, must then be further treated for disposal. Sludge treatment may consist of dewatering or chemical fixation or both prior to landfill disposal, depending partly on the metals present and the disposal requirements established for the landfill to be used.

Two general types of chemical precipitation are used for heavy metals removal. The first and most common method is to raise the pH of the water to a high level, typically between 8.5 and 11.5, using lime (calcium hydroxide) or caustic soda (sodium hydroxide). The optimum pH value (the point of minimum solubility) depends on the specific metal and the nature and amount of other chemical species in the water. Depending on the chemistry of the wastewater, a number of reactions can occur that result in the formation of insoluble metal carbonates, hydroxides, and metallic complexes involving phosphates, sulfates, calcium, magnesium, and other chemical species. Although not heavy metals, arsenic and fluoride are common hazardous contaminants that can also be removed by chemical precipitation, most commonly by adding lime. The resulting arsenic and fluoride sludges are handled and disposed of in the same way as the heavy metals sludges.

The second type of chemical precipitation is sulfide precipitation. Also based on raising pH levels (typically between 9 and 12), this method requires addition of the sulfide anion to the water. Both sodium sulfide and ferrous sulfide are commonly used. Although more costly and somewhat more dangerous, sulfide precipitation has several advantages over the more common hydroxide precipitation: (1) it achieves lower effluent concentrations than hydroxide precipitation for many heavy metals; (2) it is effective for precipitating several metals in complexed or chelated form that would otherwise (under hydroxide treatment) remain in solution; and (3) sulfide precipitation can be used to remove hexavalent as well as trivalent chromium, thereby eliminating the need for a separate chromium reduction step.

Chromium presents a peculiar problem, since it commonly exists in two distinct forms that differ in toxicity and solubility characteristics. Hexavalent chromium (chromium VI) is much more soluble and more toxic than trivalent chromium (chromium III). Therefore, an additional treatment process,

called chromium reduction, is often used to convert chromium VI into chromium III prior to hydroxide precipitation. There are several chemical reducing agents used in this process, including sulfur dioxide, sodium sulfite, sodium bisulfite, sodium metabisulfite, and ferrous sulfate. The choice of chemical reducing agents depends on several factors, including costs, safety, and ease of operation.

Table 7-4 shows the relative effluent concentrations achievable for several heavy metals and arsenic using either hydroxide or sulfide precipitation. The particular characteristics of any given wastewater may result in effluent values for individual metals that are higher than those given in Table 7-4.

Ion Exchange.   When chemical precipitation cannot achieve the required effluent metals concentrations, or when the influent metals concentrations are too low to make chemical precipitation feasible, ion exchange can be used for heavy metals removal. The ion exchange process, as its name implies, results in an exchange of a nonhazardous cation, usually hydrogen or sodium, for heavy metal cations. A similar process is used in home water softeners to remove calcium and magnesium to prevent scale formation.

The ion exchange process can achieve extremely low metals concentrations, but it produces either a brine or an acid regeneration stream that must be treated for disposal. It has been assumed that this regeneration stream, which also contains the heavy metals removed by the process; must be chemically fixed into solid form for disposal in a hazardous waste landfill. In the case of mercury, the ion exchange resin can be retorted and the mercury recovered. The cost of ion exchange (per mass of metal removed) is also high, making it uneconomical for use on wastestreams containing high concentrations of metals.

Cyanide

The most common method of treating cyanides is chemical oxidation. During oxidation, cyanide is first converted to cyanate, a less toxic and biologically degradable chemical, after which it is completely oxidized to carbon dioxide and nitrogen gas. When biological treatment follows cyanide treatment, partial oxidation to cyanate may represent an acceptable level of treatment, and this level of treatment has been assumed for the disposal option of discharge to a POTW. Essentially complete oxidation of both cyanides and cyanates has been assumed to be required for the direct discharge and injection well disposal options. The cost of complete oxidation is obviously much higher, since additional chemical oxidizing agent must be used. Also, some cyanide complexes are much more resistant to oxidation, which can affect process efficiency in certain cases.

Table 7-4. Typical effluent concentrations achievable for selected heavy metals, using chemical precipitation technologies (values in mg/L).

Metal	Hydroxide/carbonate	Sulfide	Other
Arsenic	0.03	0.05	0.003-0.05*
Cadmium	0.01-0.5	0.008	0.05†
Chromium (III)	0.02-1.0	—	—
Copper	0.05-1.0	—	—
Fluoride	8.0-20	—	—
Lead	0.02-0.5	—	—
Manganese	0.1 -1.1	—	—
Mercury	—	0.01-0.02	0.0005-0.01*
			0.0003-0.002‡
Nickel	0.1 -1.0	—	—
Zinc	0.01 -1.5	—	—

* Iron or alum coagulation
† Ferrous hydroxide coprecipitation
‡ Activated carbon treatment
Note: Actual effluent levels achievable will depend on individual wastewater matrix and influent metals concentrations.

Source: Patterson, J. W., October 1976, Technology and Economics of Industrial Pollution Abatement: Illinois Institute for Environmental Quality, IIEQ Document No. 76/22.

Chlorine Oxidation.   Three main types of chemical oxidizing agents are used for cyanide destruction. The most common of these is chlorine, which can be used in the form of chlorine gas (dissolved in water as hypochlorous acid), sodium hypochlorite, calcium hypochlorite, or chlorine dioxide. Chlorine oxidation is usually performed at alkaline pH levels of 9 to 10, which greatly reduces the reaction time for cyanide destruction. The use of chlorine compounds has several advantages, including low cost and ease of use, but there are also safety hazards associated with using chlorine compounds (particularly with chlorine gas). Also, chlorine does not selectively oxidize cyanide, and other oxidizable materials present will represent a chlorine demand. Another problem is that chlorinated organics can be formed during the process; for example, if phenol is present, toxic chlorinated phenols may be formed, potentially creating an additional treatment requirement.

Hydrogen Peroxide Oxidation.   A second but less commonly used chemical oxidizing agent for cyanide destruction is hydrogen peroxide. Chemical costs for hydrogen peroxide are similar to those for alkaline chlorination (at least to convert cyanides to cyanates), although hydrogen peroxide is a somewhat weaker oxidant than chlorine. Like chlorine, hydrogen peroxide is not a selective oxidizing agent, and organics or other oxidizable materials will represent a peroxide demand. However, the use of hydrogen peroxide will not result in the formation of chlorinated by-products.

Ozone Oxidation.   The strongest chemical oxidizing agent used for cyanide destruction is ozone. Ozone is an unstable gas that cannot be stored and must be generated at the site where it is used. An ozone generator produces ozone through an electrical discharge in the presence of air or oxygen. High energy costs are associated with the generation of ozone but ozone is easy to handle, eliminates storage requirements, and will not form chlorinated by-products. Like chlorine and hydrogen peroxide, ozone is a nonselective oxidizing agent, and any oxidizable materials present will represent an additional ozone demand. However, when ozone is used in combination with catalysts, such as ultraviolet light, it can destroy metal-complexed cyanide, which is resistant to other means of oxidation.

Halogenated Hydrocarbons

Halogenated hydrocarbons are compounds made up of carbon, hydrogen, and elements from the halogen group: chlorine, bromine, fluorine, and iodine. These compounds present several difficult environmental problems, not the least of which is that they are extremely resistant to biodegradation and are toxic at relatively low concentrations. Two concentration technologies are commonly used for removing halogenated hydrocarbons from aqueous wastes: liquid-phase carbon adsorption, and airstripping followed by gas-phase carbon adsorption or off-gas incineration. A family of catalytic oxidation processes, such as photolytic ozonation (the combination of ozone and ultraviolet light), can also destroy halogenated organic compounds.

Liquid-Phase Carbon Adsorption.   When halogenated hydrocarbons are present in relatively low concentrations (less than a few hundred milligrams per liter) it is frequently most economical to remove them by using liquid-phase granular activated carbon adsorption. A variety of organic compounds, including the halogenated hydrocarbons, adsorb very well onto activated carbon. (The process is sometimes used to remove inorganics such as mercury, although this is a much less common application.) As the wastewater passes through a carbon adsorption column, organic molecules become attached and concentrate themselves on the surface of the activated carbon. The carbon must then be periodically regenerated or disposed of in a landfill.

The regeneration of spent activated carbon involves placing the carbon into a high-temperature furnace in an absence of oxygen, to volatilize and destroy the adsorbed organics. In nearly all cases, regeneration is performed off-site by the carbon supplier. Halogenated compounds require specially designed incineration facilities, including those for carbon regeneration, since the halogen elements will aggressively attack commonly used furnace (refractory) materials, increasing the cost of regeneration.

Liquid-phase activated carbon adsorption can usually achieve very low (<1 ppm) levels of many different organics, but the minimum levels achievable for any given compound will depend on the waste composition. Some organics are adsorbed more readily than others, and a more strongly adsorbed compound may displace a more weakly adsorbed compound when introduced into a carbon column. Therefore, it must be determined which compounds in a particular wastewater will

break through first, so that these can be monitored to determine when the carbon must be replaced. The reversibility of adsorption, as implied in the displacement of one compound by another, is of concern when landfill disposal of spent carbon is considered; therefore, it can be assumed that chemical fixation or other treatment of the carbon prior to disposal will be required to reduce this potential for desorption of organics into the leachate.

Airstripping and Off-Gas Treatment.   When the concentration of volatile organic compounds is high (more than 0.5%) airstripping can be an economical method of removing them. The basic process is to provide intimate contact between the wastewater and air stream to greatly increase the rate at which these compounds volatilize. This process is usually performed in a stripping tower; wastewater flows downward in the tower and air flows upward through a series of trays or a bed of special media used to increase the surface area in the tower.

The off-gases, which are primarily air laden with water vapor and lesser amounts of the volatile organics stripped from the wastewater, must often be treated prior to discharge to the atmosphere. Treatment consists of vapor-phase activated carbon adsorption, although in some cases the off-gas is burned in an incinerator. As previously mentioned, a specially constructed incinerator is required to withstand attack of the refractory surfaces by the halogen elements. The spent carbon from a gas-phase carbon contractor is usually regenerated in place using steam, although such regeneration still requires capture and destruction of the volatile organics. The result is a very concentrated mixture of organics and steam condensate (water), which is usually disposed of by incineration. This concentrated stream may also be treated by photolytic oxidation. Vapor-phase activated carbon is rarely regenerated off-site.

A properly designed airstripping tower can usually achieve fairly low (<10 ppm) levels of volatile organics, but it is generally not economical to design a stripping tower to achieve a level of treatment comparable with that obtained using liquid-phase carbon adsorption. Therefore, airstripping is often used for first-stage pretreatment of high-concentration wastes and is usually followed by liquid-phase carbon adsorption or another treatment process.

Catalytic Oxidation.   This family of processes includes ozonation catalyzed by ultraviolet light, metal catalysts, and other related treatment processes. These processes destroy the organic compounds rather than simply concentrating them in another phase which must then itself be disposed of. Such processes, however, are just beginning to be developed (emerging technologies) and comprehensive design and cost data are not widely available; therefore, although initial studies are promising, the catalytic oxidation processes have not been discussed in this chapter.

Nonhalogenated Organic Solvents and Other Compounds

This general waste category covers a variety of chemicals under a very broad classification. Such chemicals can be divided into two groups: (1) the nonpolar solvents, including benzene, toluene, and xylene, all of which are volatile and only sparingly soluble in water; and (2) the polar solvents, including a variety of alcohols, ethers, ketones, and phenols; these compounds generally have high water solubility and lower volatility than the nonpolar solvents, making it more difficult to remove them from water.

Nonpolar Solvent Removal.   The nonpolar solvents can be removed by using the same techniques discussed for the halogenated hydrocarbons: liquid-phase carbon adsorption for lower levels and airstripping for higher levels. Conventional construction materials can normally be used for the incinerators and furnaces used in off-gas combustion and carbon regeneration, since high levels of halogens are not present.

Polar Solvent Removal.   Some of the polar solvents can be removed by airstripping, and most can be removed by liquid-phase carbon adsorption, although both processes are generally less efficient than when used for nonpolar solvents and halogenated hydrocarbons. Often the compounds that cannot be removed by one of these two methods tend to be relatively easily biodegraded, making discharge to a POTW or other biological treatment options feasible. Sometimes a specific compound can be selectively removed by other means, such as the use of synthetic organic resin adsorption to recover phenol. Also, ozone or hydrogen peroxide oxidation may be an economical way to destroy low levels of organics.

Pesticides

This general waste-type category contains a wide variety of compounds, including polar, nonpolar, and halogenated organics used as pesticides, herbicides, fungicides, rodenticides, and other such applications. The two features shared by all of these substances are environmental persistence (resistance to biodegradation) and toxicity. Treatment options available for removing pesticides from water are usually limited to liquid-phase carbon adsorption and chemical oxidation; the former treatment is more common and economical, but the latter provides a more permanent environmental solution (i.e., destruction of these compounds). The toxicity of the materials concentrated on the spent carbon increases the risk and hazards associated with carbon handling, regeneration, and disposal. There are of course exceptions to such generalizations, including some compounds that can be efficiently treated in a properly acclimated biological treatment system. However, considering the other constituents usually present in the wastestreams, the most practical alternative is usually liquid-phase activated carbon adsorption.

ASSUMPTIONS AND COSTS ASSOCIATED WITH TREATMENT TECHNOLOGIES

The capital investment and direct operating costs associated with each of the alternative treatment technologies were estimated, over a range of waste flow rates, on the basis of information available in the literature. This type of cost estimating is used during the earliest, or conceptual, phase of a capital project before any design work is done, and is useful for identifying order-of-magnitude costs and comparing the costs of various alternatives. The level of accuracy associated with these costs is therefore not very high, and actual costs may range from - 50 to + 100 percent in the worst case. A summary of the cost estimates developed for the previously identified treatment alternatives is presented in Table 7-5. More detailed discussions of the assumptions used in making these estimates are provided in this section.

Unless otherwise noted in the following discussions, all costs were based upon cost estimating curves published in Volume IV of the USEPA Treatability Manual (USEPA, 1980) (1) or its revision (USEPA, 1983). Treatment cost estimates found in the literature for the same process may differ greatly; many estimated costs found were significantly below those given in the USEPA references. However, the use of cost data from this reference provided internal consistency from one process to another. Deep well injection costs were estimated from curves presented in a report by the U.S. Department of the Interior, Federal Pollution Control Administration (1970).

The USEPA developed separate cost estimates for three types of costs: total capital investment, total direct operating costs, and total annual costs. Total capital investment refers to the one-time engineering and construction costs for the project, exclusive of depreciation and interest charges. Total direct operating costs are the annual costs for labor, materials, fuel, chemicals, and power. Total annual costs include overhead, taxes, insurance, administrative costs, and depreciation and interest on the capital investment. The specific assumptions used for the estimates and a breakdown of the cost items estimated are presented in Table 7-6.

The original cost information from the USEPA (1980) was based on the *Engineering News Record* (ENR) Construction Cost Index of 3119. The cost data on deep well injection (U.S. Dept. of Interior, 1970) were developed in 1969 and were based on an Engineering News Record (ENR) Construction Cost Index of 1285. A more recent ENR Construction Cost Index of 4180 was used to update these costs to March 1985 dollars. Given the level of accuracy associated with these costs, separate adjustments were not made for labor, chemicals, electricity or cost elements other than construction. Instead, these costs were also updated, using the ENR Construction Cost Index.

Table 7-5. Summary: Estimated costs for treatment technologies, in thousands of dollars (3/1/85).

Treatment technology	Waste type categories	Total capital Investment (waste flow In mgd)				Total direct operating costs (waste flow in mgd)				Total annual costs (waste flow in mgd)			
		0.001	0.01	0.10	1.00	0.001	0.01	0.10	1.00	0.001	0.01	0.10	1.00
Reverse osmosis*	Inorganic salts	—	—	255	1206	—	—	108	440	—	—	142	587
Electrodialysis*	Inorganic salts	—	42	201	1005	—	64	161	697	—	127	268	1005
Evaporation*	Inorganic salts	—	—	243	1220	—	—	1080	9000	—	—	1334	9600
Chromium reduction†	Heavy metals (Cr VI)	94	469	2412	—	46	214	1340	—	147	402	2412	—
Chemical Precipitation†	Heavy metals	—	—	402	2010	—	—	228	1005	—	—	410	1554
pH neutralization	Mineral acids & bases	—	—	241	1206	—	—	182	804	—	—	318	1195
Ion exchange*	Heavy metals	—	—	938	4691	—	—	107	670	—	—	255	1340
Alkaline chlorination	Cyanide	268	1206	6700	—	60	228	1340	—	134	362	2412	—
Liquid-phase activated carbon absorption	Pesticides, halogenated hydrocarbons, organics	—	—	496	2278	—	—	316	3087	—	—	438	3415
Airstnpping without off-gas treatment	Halogenated hydrocarbons, other organics	—	—	322	1742	—	—	120	228	—	—	255	1340
Airstripping with off-gas treatment (carbon)	Halogenated hydrocarbons, other organics	—	—	644	3484	—	—	313	1186	—	—	583	3410
Chemical solidification, fix-ation, and landfillmg	Concentrated brine solutions (liquid wastes)	—	—	—	—	242	2430	—	—	—	—	—	—
Chemical solidification, fix-ation, and landfillmg	Heavy metals sludges (solid wastes)	—	—	—	—	300	—	—	—	—	—	—	—
Injection-well disposal‡	All aqueous liquid wastes	—	—	639	783	—	—	144	261	—	—	293	485

* Does not include disposal costs for waste brine residues generated during treatment. Estimated costs for treatment and disposal of these brines are presented under "Chemical Solidification and Landfill Disposal" and should be added to Total Direct Operating Costs and Total Annual Costs for Reverse Osmosis, Electrodialysis, Evaporation, and Ion Exchange whenever appropriate. Costs are based on volume of brine solution treated for disposal.

† Does not include disposal costs for metals sludge residues generated during treatment. Estimated costs for treatment and disposal of these sludges are presented under "Chemical Solidification, Fixation, and Landfilling" and should be added to Total Direct Operation Costs and Total Annual Costs for Chromium Reduction and Chemical Precipitation whenever appropriate. Costs are based on volumn (1000 gallons) of the dewatered sludge (30 percent dry weight).

‡ Deep well injection costs shown are calculated from data presented in reference 2. The cost figures from actual wells in Illinois are one and one-half to two times higher than shown here.

Table 7-6. Cost estimating methodology and unit cost assumptions.

Cost component	Assumed value	
Total capital investment		
Direct Costs (DC)		
Purchased equipment & installation	100%	PE&I
Instrumentation and controls	10%	PE&I
Piping	21%	PE&I
Electrical equipment and materials	13%	PE&I
Buildings	26%	PE&I
Yard improvements	7%	PE&I
Service facilities	41%	PE&I
Indirect costs (IC)		
Engineering and supervision	29%	PE&I
Construction expenses	32%	PE&I
Contractor's fees	7%	PE&I
Contingency	27%	PE&I
Total fixed capital investment (FCI)	3.13	PE&I
Working capital (WC)	0.47	PE&I
TOTAL CAPITAL INVESTMENT (TCI = DC + IC + WC)	3.6	PE&I
Total direct operating costs		
Labor		(L)
Materials		(M)
Chemicals		(C)
Power		(P)
Fuel		(F)
TOTAL DIRECT COSTS (TDC = L + M + C + P + F)		
Total annual costs		
Plant overhead	(60%	L)
Taxes and insurance	(2%	FCI)
General and administrative expenses	(40%	L)
Depreciation	(10%	FCI)
Interest on working capital	(12%	WC)
TOTAL ANNUAL COSTS (TAC) = (TDC + L + 12% FCI + 12% WC)		

Source: USEPA, *Treatability Manual, Volume IV-Cost Estimating,* Office of Research and Development, EPA-600/8-80-042d, Appendix A, July 1980.

When sources other than the USEPA (1980, 1983) were used for costs, the methodology outlined in Table 7-6 was followed as far as was possible. Other assumptions were also made that corresponded to those used by the USEPA (1980). For example, exponential scaling factors were used to adjust costs upward or downward, based on wastewater flow. The general equation used to scale costs up or down was as follows:

$$\text{cost in dollars} = (\text{constant}) \times (\text{flow in mgd})^{(\text{scaling factor})}$$

where the scaling factors used were: chemicals 1.0
    electricity 1.0
    materials 1.0
    equipment 0.7
    labor 0.3

Reverse Osmosis

The equipment required for reverse osmosis usually includes membrane modules, feed, product, and concentrate tanks, high-pressure pumps, prefilters and pumps, stainless steel piping, and flow and pressure instrumentation. The cost estimate was based on these equipment items as applied in a rinsewater recovery system for an acid nickel plating operation. A 24-hour-per-day, 330-day-per-

year operation was also assumed. However, the total direct operating costs presented by the USEPA (1980) included a very low estimate of labor (less than 1 hour per day). This was probably an inadvertent result of the original cost data used in developing the curve, which came from an actual reverse osmosis system within a production facility where presumably no significant additional labor costs were incurred. Since actual labor costs can usually be expected to be greater than this, the direct operating costs in Table 7-5 include realistic costs estimated by the USEPA (1980) to be 12 hours per day for a 0.1-mgd facility and 18 hours per day for a 1.0-mgd facility.

The concentrated brine solution produced by reverse osmosis typically ranges from 10 to 25 percent of the influent waste flow. Disposal options and costs for this material are discussed later (see Treatment and Disposal of Concentrated Brine Solutions) and are not included under the costs for reverse osmosis in Table 7-5.

Electrodialysis

The costs for electrodialysis systems depend not only on the volume of water treated but also on the amount of salts removed. A number of different systems can be employed for fairly selective recovery of specific ions (for example, heavy metals) or the less selective concentration of high-strength inorganic salt solutions. Specific equipment selection and application can have a significant impact on capital costs.

Electrical power costs are high for electrodialysis and typically constitute more than half the total direct operating costs; thus, electrodialysis has higher operating costs than reverse osmosis for similar applications.

As with reverse osmosis, electrodialysis produces a concentrated brine solution that is typically between 10 and 25 percent of the volume of the original waste feed. The costs for treatment and disposal of this waste brine are discussed later (see Treatment and Disposal of Concentrated Brine Solutions) and are not included under the electrodialysis costs in Table 7-5.

Evaporation

The USEPA (1980) did not develop cost estimates for evaporation under the same assumptions used for the other technologies. However, another USEPA report (1976) contains cost information on a six-effluent evaporator used for concentration of kraft black liquor (waste from pulp and paper manufacture). This evaporator was designed for a 2.4-mgd (1670 gpm) feed capacity, which is greater than that used with most wastestreams under consideration for injection well disposal. Based on the change in the ENR Construction Cost Index from 1976 (annual average 2401) to March 1985 (4180), the total capital investment for this evaporator in current dollars would be $2.26 million. To provide direct comparison with other treatment processes, an exponential scaling factor of 0.7 was used to adjust the total capital investment for a 1.0-mgd evaporator, the cost of which would be $1.22 million. A 0.1-mgd system was similarly estimated at $243,000. These values would increase significantly if corrosion problems (high chlorides) required the use of exotic construction materials.

In the same USEPA report (1976) the total direct operating costs for evaporation were estimated at $1.06 per 1000 pounds of water (about 120 gal) evaporated. Therefore, the annual cost for a flow of 1.0 mgd would be about $3.0 million (1976 dollars). It was also shown that about 95 percent of the total direct operating costs associated with evaporation were energy costs (USEPA, 1976). Since 1976, the cost of fossil fuels has increased much faster than the rate of inflation. Coal prices have more than doubled, while natural gas prices have increased by a factor of more than five. Therefore, assuming an average increase in energy costs of 200 percent, the total direct operating cost in 1985 dollars for a 1.0-mgd evaporation facility would be about $9.0 million per year. Assuming a scaling factor of 1.0 for power and 0.3 for labor, the direct operating costs for a 0.1-mgd system were estimated to be $1.08 million per year. The total annual cost for incineration, based on the approach in Table 7-6, was estimated to be about $9.6 million for a 1.0 mgd facility.

For waste treatment, complete evaporation is more common than partial evaporation to produce a concentrated brine solution. The advantage of complete evaporation is that chemical fixation and landfill disposal of a crystalline salt is much less costly than similar treatment for a concentrated brine solution. If complete crystallization is not required, however, the operating costs discussed

earlier could be reduced in proportion to that fraction of the water volume that is not evaporated. (This is reasonable since most of the operating cost is for the energy to evaporate the water.) The costs for chemical fixation and disposal of brines and salt are not included under evaporation in Table 7-5, but are discussed later (see Treatment and Disposal of Concentrated Brine Solutions).

Chromium Reduction

The equipment normally associated with chemical reduction processes includes storage and contact vessels, metering equipment, agitators, and instrumentation for determination of pH and degree of completion of the reduction reaction. The cost of treatment varies greatly with individual plant locations and wastes. Capital costs depend upon such factors as the type, volume, and composition of the waste, the degree of treatment required, the treatment process(es) selected, availability of required services, and the specific material to be recovered (i.e., metals, chemicals, or water).

For the purpose of this estimate costs were calculated for the chemical reduction of chromium waste from a plating operation using sulfur dioxide treatment (USEPA, 1980). Included are the costs of separating the precipitated chromium (III) for disposal, using a rotary filter. It has been assumed that this sludge will have to be chemically solidified and fixed for landfill disposal. The costs of chromium sludge disposal are not included in the chromium reduction costs in Table 7-5, but are discussed later (see Treatment and Disposal of Heavy Metal Sludges).

Chemical Precipitation

Chemical precipitation is usually the most economical method for removing heavy metals and other elements (such as fluorides, compounds, phosphates, and arsenic) from solution, especially when present at high concentrations (>10 mg/L). The capital investment and operating costs for chemical precipitation depend on the specific wastewater to be treated, and wastes containing some particular combinations of metals may require two or more sequential precipitation steps to optimize removal. Materials of construction and sludge handling and disposal methods are additional variables that affect the costs.

Materials other than heavy metals may be precipitated during pH neutralization and require similar separation and concentration for disposal. A common example of this occurs when lime is used to neutralize sulfuric acid wastes; this process results in the generation of insoluble calcium sulfate (gypsum). Therefore, the costs for pH neutralization of sulfuric acid wastes can be assumed to be about the same as for metals precipitation.

For the purpose of this estimate a three-stage pH adjustment system was assumed with lime as the neutralizing chemical (hydroxide precipitation) (USEPA, 1980). A lime storage silo, slaker, and slurry tank were also included. A gravity clarifier and rotary filter were assumed for separation and concentration, respectively, of the precipitated metal sludge. The waste assumed for this system (USEPA, 1980) was actually a sulfuric acid mine-drainage wastestream (0.15% sulfuric acid) from which gypsum would be precipitated. The lime usage rate required for neutralization was about 1200 mg/L of waste (5 tons per million gallons).

It was assumed that the metals containing sludges generated by this treatment process would require chemical solidification and fixation for landfill disposal. The costs associated with sludge disposal are not included in the estimates in Table 7-5; however they are discussed later (see Treatment and Disposal of Heavy Metals Sludges).

pH Neutralization

Some of the wastes under consideration contain high concentrations of mineral acids or bases which, upon pH neutralization, will not cause the precipitation of solids. For example, hydrochloric acid and sodium hydroxide wastestreams will require only pH neutralization (unless they also contain heavy metals or other contaminants that will come out of solution). Although the USEPA (1980) did not develop separate costs for these cases, the equipment involved will be essentially the same as for chemical precipitation minus the gravity clarifier and rotary filter for sludge dewatering (both are relatively expensive). Therefore, the total capital investment for straight pH neutralization was figured at 60 percent of the costs for chemical precipitation.

Operating costs for pH neutralization are most significantly affected by the chemical requirements, which in turn depend on the amount and strength of the acid or base to be neutralized (for chemical precipitation, nearly 70 percent of the direct operating costs were for chemicals and only 25 percent for labor). It was assumed that without solids separation and dewatering, total direct operating costs for pH neutralization would be 80 percent of those for chemical precipitation and that only 20 percent of this amount would be for labor.

The total annual costs were estimated on the basis of the previously stated assumptions, following the procedure outlined in Table 7-6. The costs were also updated to March 1985 dollars, using the current ENR Construction Cost Index.

Ion Exchange

Ion exchange is frequently incorporated into systems with other treatment processes, such as reverse osmosis, for removal of lower concentrations of metals. In most cases, separate cost data are not available solely for ion exchange. In addition, many practitioners are reluctant to divulge treatment cost data; even though costs may vary widely, they depend primarily upon the stream size and composition.

For the purpose of this cost estimate, data were generated for a dilute mixed acid wastestream from a metal finishing operation (USEPA, 1980). The assumed design basis included a three-bed ion exchange system in duplicate trains for simpler regeneration, with a 24-hour- per-day, 350-day-per-year operation.

The regeneration of ion exchange beds, following their exhaustion with heavy metals removed from the water, involves the use of either an acid or a brine (sodium chloride) solution that must be disposed of after use. The regenerant waste, in addition to containing salts or acid, will have a high concentration of the heavy metals removed during treatment. Typically, the volume of this regeneration stream is between 5 and 10 percent of the total throughput volume. Disposal of this metals and brine solution (an acid regeneration stream will require pH neutralization) may include several recycle or reuse options. Otherwise, this brine will have to be chemically solidified and fixed for landfill disposal in a manner similar to that for brines from reverse osmosis, electrodialysis, and evaporation. The costs for disposal of the regenerant wastestream are not included in the estimates of ion exchange costs in Table 7-5, but they are discussed later (see Treatment and Disposal of Concentrated Brine Solutions).

Alkaline Chlorination (Chemical Oxidation)

Only very simple equipment is required for chemical oxidation, and the equipment required for alkaline chlorination is not greatly different from that required for use with hydrogen peroxide or other chemical oxidizing agents. This includes storage vessels for the oxidizing agents (and perhaps for the wastes), metering equipment for the oxidant and wastestreams, and contact vessels with agitators to provide suitable contact of oxidant and waste. Some instrumentation is required to determine the concentration and pH of the water and the degree of completion of the oxidation reaction. The process is monitored by using an oxidation-reduction potential (ORP) electrode. Ozonation, another type of chemical oxidation, requires additional capital and operating costs associated with the ozone generating equipment, which is fairly energy-intensive.

The cost of treatment depends greatly on the individual situation, and capital costs are affected by such factors as the type, volume, and composition of the waste; the specific treatment process selected; availability of required services; the degree of treatment required; and the nature of the material to be oxidized (for example, complexed versus free cyanide). For the purpose of cost estimating, data were generated for the chemical oxidation of copper cyanide and sodium cyanide waste from a plating operation, using sodium hydroxide and chlorine treatment (Connor, 1984). (These costs did not include treatment for copper, which is covered under chemical precipitation.) No significant waste residues are generated during alkaline chlorination, although subsequent pH neutralization and dechlorination may be required in some cases.

Liquid-Phase Granular Activated Carbon Adsorption

The equipment required in a liquid-phase granular activated carbon system typically includes carbon contactors, pumps, carbon storage tanks, controls and instrumentation, and the carbon itself. Spent carbon must be removed for regeneration or disposal (usually by incineration). In large systems (more than 1000 pounds-per-day carbon usage), on-site regeneration may be economical, but for most systems it is more common to use a carbon service that includes supply of fresh carbon, change-out of spent carbon, and regeneration of spent carbon.

The USEPA (1980) did not include costs of regeneration/disposal of spent carbon in its estimates for carbon adsorption. Therefore, it was assumed that a carbon service will be used, and that the total cost will be about one dollar per pound of carbon supplied. Assuming that the capacity of the spent carbon is about 0.2 pound of COD (chemical oxygen demand, a measure of organic concentration) per pound of carbon and that the amount of COD removed by the carbon is 200 mg/L, the average daily carbon usage for a system treating 1.00 mgd would be 8340 pounds. A system treating only 0.10-mgd would require 834 pounds per day of carbon. From these assumptions, the estimated annual costs for carbon service would be $304,000 for a 0.10-mgd system and $3,040,000 for a 1.00-mgd system. These costs have been added directly to the total direct operating cost and total annual cost estimates made by the USEPA (1980) and are presented in Table 7-5.

Airstripping without Off-Gas Treatment

Depending on the nature and amount of organics to be removed by air stripping, vapor-phase carbon treatment of the off-gas may or may not be required. Conventional air strippers for wastewater treatment resemble typical cooling towers in that they contain plastic or wood packing and have openings near the bottom to permit air to enter the tower. Water is introduced at the top and flows downward while the air is pulled or pushed upward through the tower by a fan or low- pressure blower. Such a system was assumed in the cost estimates presented in Table 7-5.

Airstripping with Off-Gas Treatment by Vapor-Phase Carbon

Costs for air stripping with vapor-phase carbon treatment developed by the USEPA (1980) were not based on the same conditions and assumptions made in estimating the stripper alone. Furthermore, the nature and amount of organics present can significantly affect design of an off-gas treatment system. However, common experience indicates that a more sophisticated stripping tower design along with vapor-phase carbon treatment system for the off-gas more than doubles the total capital investment. (Incineration of the off-gases is an even more expensive option, which may be triple the capital investment required for a conventional airstripping system.) Under these assumptions, the total capital investment for airstripping with vapor-phase carbon adsorption presented in Table 7-5 is double that for conventional airstripping without off-gas treatment. The total direct operating costs and total annual costs were also assumed to be about double. An additional operating cost exists for the residue generated by vapor-phase carbon treatment, however.

Unlike liquid-phase carbon adsorption systems, vapor-phase carbon systems do not require routine removal of spent carbon for regeneration. The carbon in these systems is regenerated in place using steam; a small-volume, high-organic concentration waste residue must then be disposed of. Usually, disposal consists of drumming this residue for incineration; the cost can range from $50 to $100 per drum, depending on the organic concentration and specific organics present. Assuming that the combined airstripper and vapor phase carbon systems remove 200 mg/L of mixed halogenated and nonhalogenated organics (with specific gravity of 1.0) from the waste and that these are mixed with water (condensed from the steam during regeneration) in a ratio of one part organics to four parts water, an average of 1000 gallons (20 drums) per day of waste residue will be produced by a facility treating 1.0 mgd of wastewater. On the basis of a disposal cost of $75 per drum, the annual increase in total direct operating costs would be $548,000. Under the same assumptions, the increased operating costs for waste residue disposal at a 0.10-mgd facility would be $55,000. These costs were added to the doubled values for total direct operating costs and total annual costs for presentation in Table 7-5.

Treatment and Disposal of Concentrated Brine Solutions

Several possible options exist for recovery and reuse of the waste brine solutions generated during reverse osmosis, electrodialysis, evaporation, and ion exchange treatment. These include use in chlor-alkali processes, electrolytic hypochlorite production, crystallization for use as road salt, and

selective metals recovery. In many cases, recovery and reuse can be accomplished at low cost if not on a break-even basis. However, recovery and reuse options must be evaluated on a case-by-case basis and will depend on the presence of contaminants other than common salts.

For cases in which recycle or reuse is not an option, it has been assumed that disposal will consist of chemical solidification and landfilling. Solidification is accomplished by adding materials such as sodium silicate and/or cement, lime, fly ash, and cement or lime kiln dust to the waste in weight proportions ranging from 20 to 100 percent of the weight of the waste, with greater amounts required for higher water contents and wastes with highly soluble constituents (such as chloride salts).

The costs of solidification and landfilling of brines are high; the major cost is for chemicals. Several case studies involving aqueous wastes containing relatively high salt concentrations showed that costs for chemical solidification/fixation can range from 11 to 41 cents per gallon (Connor, 1984). An average cost of 30 cents per gallon has been assumed for this evaluation. For concentrated brine volumes of 1000 and 10,000 gallons per day, the costs for chemical solidification and fixation would be $91,000 and $913,000 per year, respectively. For crystalline salt produced by evaporation, the disposal cost is estimated to be $35 per ton, assuming a cement-based fixation process.

An additional cost is imposed for landfill disposal. This cost typically ranges from $40 to $50 per ton for relatively nonhazardous wastes such as a solidified brine solution (USEPA, 1982). Brine solutions are difficult to solidify and are assumed to require a 100 percent addition (by weight) of the solidifying agent, or a doubling in weight of the waste for disposal. (A 50 percent weight addition was assumed for solidification of crystalline salts produced by evaporation.) Assuming a cost of $40 per ton, the respective annual landfill disposal costs for solidified brine wastes with original volumes of 1,000 and 10,000 gallons per day would be $124,000 and $1,240,000. Assuming an average load of 30,000 pounds, the annual hauling costs, based on a $3.00 per loaded mile (USEPA, 1982) rate and 50 miles (one way) distance, would be about $27,000 and $274,000, respectively.

The total treatment, hauling, and landfill disposal costs for 1000 and 10,000 gallons per day of waste brine solutions would therefore be $242,000 and $2,430,000 per year, respectively. Disposal costs of wastes from ion exchange regenerations that contain heavy metals will be higher, but solidification and fixation costs will be lower.

Treatment and Disposal of Heavy Metals Sludges

The only disposal option for metals sludges generated by chemical precipitation treatment except for their potential recovery and reuse is to landfill them after chemical solidification and fixation treatment. A similar disposal option may be required for other sludges generated during pH neutralization or precipitation processes, such as gypsum (calcium sulfate) sludges produced during neutralization of sulfuric acid with lime. Solidification and fixation processes for sludges are basically very similar to those discussed for concentrated brine solutions. However, prior sludge dewatering and the more limited solubility of precipitated waste constituents combine to make solidification and fixation a more economical solution for metal sludges than for waste brine solutions.

For the purpose of estimating the additional total direct operating costs and total annual costs associated with treatment and disposal of these sludges, it was assumed that a 30-percent solids sludge cake would be generated at a rate of 1000 gallons per day (about 135 cu ft), and would have an apparent bulk density of 80 pounds per cubic foot. These are typical characteristics for metal hydroxide sludges produced through chemical precipitation. The volume of sludge was chosen arbitrarily, since actual sludge generation rates are dependent on the types and concentrations of metals present as well as the volume of the untreated wastewater. It was assumed that sludge generation rates (dry weight basis) would be roughly double the initial concentration of metals in the wastewater. The sludge volume assumed (1000 gal per day of dewatered cake) corresponds roughly to a metals concentration of between 150 and 200 mg/L in a 1.0-mgd wastestream. It also corresponds to a metals concentration of between 1.5 to 2.0 percent in a 10,000 gallon-per-day wastestream. The relationship between mass of sludge produced and estimated treatment and disposal costs is linear.

Chemical solidification and fixation costs for cement-based treatment are typically between $35 and $50 per ton of sludge, while costs for lime-based treatment run between $6 and $30 per ton

of sludge (USEPA, 1982). The choice of solidification and fixation agents must be determined for each waste sludge and cannot be predicted on a generic basis; therefore, an intermediate cost of $30 per ton has been assumed. On the basis of earlier assumptions, which result in 5.4 tons per day of sludge (total weight), the cost of chemical solidification and fixation treatment is estimated to be $59,000 per year.

Landfill disposal costs for this sludge are estimated to be $50 per ton (USEPA, 1982), which reflects the somewhat higher degree of hazard associated with heavy metals sludges as compared with the solidified brine solutions discussed earlier. Typically, solidification of such sludges increases their volume by 20 to 50 percent; most have an apparent bulk density of 100 to 120 pounds per cubic foot (USEPA, 1976). Therefore, assuming 100 pounds per cubic foot and 175 cubic feet (130 percent of original volume) per day, the landfill disposal costs are estimated to be $159,000 per year. Hauling costs are based on $3.00 per loaded mile, a 150-mile hauling distance (which reflects the distance required to reach an adequately secure landfill), and an average load size of 35,000 pounds. The annual hauling costs would therefore be about $82,000.

The annual total direct operating costs for solidification, fixation, hauling, and landfill disposal of 1000 gallons per day of 30 percent (dry weight) heavy metals sludge would therefore be $300,000.

Injection Well Disposal

The costs of deep well injection systems for liquid waste disposal depend on a number of factors, including depth of the disposal zone, rate of injection, formation injectivity, drilling costs, well operating costs, and the need for treatment (filtration) prior to injection. The USEPA (1980) estimated a capital cost as high as $1,000,000 to $1,340,000 for a complete system but did not specify an injection rate, pressure, or well depth from which costs for different systems could be developed. Therefore, the cost estimates presented in Table 7-5 were based on cost curves published by the U.S. Department of the Interior (1970).

Assuming an injection pressure of 300 psi, which is the maximum injection pressure permitted for most existing systems in Illinois (see Table 3-1), the total capital investment costs for 0.1-mgd and 1.0-mgd systems are $693,000 and $783,000, respectively. The corresponding direct operating costs for these systems are $144,000 and $261,000 per year. (Not included in these costs is the tax assessment for injection well disposal, which in 1985 ranged from $2000 to $9000 per year, depending on the volume of waste injected.) The total annual costs for the 0.1-mgd and 1.0-mgd systems are $293,000 and $485,000, respectively. The deep well injection costs presented above were calculated from the cost data in the U.S. Department of Interior report (1970). The actual cost figures from wells within Illinois are from one and a half to two times higher than the figures shown here.

POTENTIAL SOCIETAL/ENVIRONMENTAL IMPACT OF UIC REGULATION CHANGES RELATED TO ALTERNATIVE TREATMENT TECHNOLOGIES AND DISPOSAL METHODS

As noted earlier in this section, the critical review of the UIC regulations and practices that is now in progress may result in one of three possible scenarios for deep well disposal: (1) current disposal methods (no waste treatment required) may be continued with some minor changes; (2) treatment may be required to destroy or remove all or part of the hazardous components prior to deep well injection; (3) injection well disposal may be banned altogether.

One possible reason for changing the UIC regulations and practices would be to reduce the overall societal, economic, and environmental impacts associated with the disposal of wastes currently or potentially disposed of in injection wells. The task of evaluating the economic impacts of alternative treatment technologies and disposal methods is relatively straightforward, as costs can be easily estimated. It is more difficult, however, to quantify the potential social and environmental impacts of each of the alternative treatment and disposal methods and compare them with the impacts of injection well disposal. In this section potential adverse societal and environmental impacts that may be associated with treatment and disposal alternatives are discussed.

Potential Adverse Impacts of Injection Well Disposal

Under the current UIC regulations, all injected industrial wastes (of the type under consideration in this report) must be injected only into Class I wells. The aquifers into which Class I wells discharge have a very high mineral salts content, which makes them unsuitable for drinking or irrigation according to present standards and practices. The UIC regulations of the Safe Drinking Water Act have specifically set aside all groundwater containing less than 10,000 mg/L TDS for existing and potential future drinking water use.

The major concern associated with deep well disposal is the possibility that injected waste may migrate into and contaminate fresh water aquifers. The UIC regulations address this concern by imposing hydraulic limits during well operation and identifying potential migration pathways. Migration of groundwater occurs when there is a hydraulic head gradient between the injection zone and overlying USDW and a pathway through which water can move. Fissures or cracks in the strata separating the aquifers and poorly constructed or abandoned wells can provide such a pathway. These problems can also be aggravated when injection or withdrawal activity changes natural groundwater flow patterns or when the confinement competency of the geologic formations forming the disposal system is changed by strong seismic activity.

Contamination of a fresh-water aquifer could have a potentially serious impact on any public drinking water supply obtained from the aquifer. The degree of the impact would depend on the types and concentrations of the contaminants present. In some cases, contamination could mean the loss of a potential source of drinking water. In less severe cases, the water removed from the aquifer would have to be subjected to additional treatment steps, such as activated carbon adsorption, before it could be used as drinking water. In either case, an adequate monitoring system would be required to detect the problem.

The requirement that a waste be treated to remove hazardous components prior to injection well disposal would certainly reduce the risk of contamination of one aquifer by another through inter-aquifer leakage; however, the treatment processes themselves have associated potential adverse impacts that must also be considered.

Potential Adverse Impacts of Waste Treatment Processes

Aside from the economic impact (capital and operating costs) of requiring treatment prior to injection well disposal or other forms of disposal (POTW or direct discharge), the direct impacts of the treatment technologies considered in this report (such as increased electrical power and chemical consumption, increased air emissions from the treatment processes and generation of additional power to run them, and increased potential for contamination of near-suface aquifers as a result of leaks and spills within the treatment systems) are not very significant. Other direct environmental impacts would be related to the quality of surface water and performance of treatment facilities (POTWs) receiving the treated wastes, should injection well disposal be banned altogether.

Perhaps more important, however, are the indirect impacts associated with the alternative waste treatment technologies, primarily the ultimate disposal of residues generated during treatment. These residues include sludges containing heavy metals, concentrated brine (salt) solutions, crystalline salts, spent activated carbon, and waste solvents. Some residues, such as waste solvents, can be destroyed by incineration, and activated carbon can either be incinerated or regenerated. In such cases, there will be an increase in total air emissions, and ash generated will require disposal. Other residues of waste treatment cannot be destroyed by incineration or chemical oxidation, however, and must be sent to secure landfills for disposal.

It has been assumed throughout this section that any hazardous residues generated during treatment would require solidification and chemical fixation prior to landfill disposal to reduce the possibility that hazardous materials may leach from the landfills into near-surface aquifers. Solidification and fixation do not prevent leachate formation but do reduce the rate at which hazardous substances leach out of the landfill. Even so, enough of the hazardous materials may leave the landfill, over a period of time, to pose a threat to the groundwater in the area. The long-term impact of landfill disposal is a serious concern, but the more specific concern here is whether surface disposal (landfills) represents a better solution than subsurface (injection well) disposal. In most cases, a comparison of the tightness (lack of overall permeability) and thickness of confining materials, the

existence of conditions that can cause changes in the characteristics of confining materials, and the magnitude of hydraulic head gradients between the disposed wastes and the nearest USDW shows that conditions are generally less favorable for safe disposal in the near-surface landfill environment than in the environment of a deep disposal zone.

POTENTIAL IMPACT OF UIC REGULATION CHANGES ON
INDUSTRIES USING CLASS I DISPOSAL WELLS IN ILLINOIS

To assess the potential impacts of changes in the UIC regulations, a detailed evaluation of treatment and disposal alternatives was made for the seven existing industries now using injection well disposal in Illinois (see Table 3-1). The basis for the cost estimates is the same as that described earlier in this chapter. As noted previously, the level of accuracy associated with any individual cost estimated under these assumptions may range from —50 to + 100 percent; total estimated costs should be of greater reliability, however, as overestimates and underestimates for individual items tend to cancel one another.

Current Injection Well Disposal Practice

The annual operating costs associated with current injection well disposal practice were estimated to total about $1,820,000 for the seven industries, not including special taxes paid under UIC regulations. The range of estimated operating costs was from $202,000 to $365,000. The total capital investment represented by the existing wells was estimated to be $4.71 million (March 1985 costs), with an average cost per well of $673,000, bringing the total annual costs for the seven industries to $1,820,000 (using the equation at the bottom of Table 7-6, with labor estimated to be 50 percent of the total direct operating cost). As stated before, these calculated costs for deep well injection appear to be 1 1/2 to 2 times too low, on the basis of actual experience in Illinois. This fact may make pretreatment of hazardous components before injection even more attractive.

Mandated Treatment Prior to Injection

Table 3-1 lists the characteristics of the existing wastestreams. Streams B, D, and G are nonhazardous according to regulatory definitions; the major undesirable property of these streams is the high dissolved solids (salt) content. Since Class I well injection is allowed only into aquifers with dissolved solids (TDS) greater than 10,000 mg/L (or 1%), injection of these streams would have minimal impact. Stream C contains such a high concentration of iron that treatment followed by injection would be more expensive than treatment alone. Recycling of stream C by another industry may currently border on economic feasibility, if a user could be found.

Estimated relative costs for the three options are shown in Table 7-7 for the seven industries. These estimates were prepared using standard cost curves published by the USEPA (1980) and deep well cost data quoted by a U.S. Department of Interior report (1970), with costs for each updated to March 1985 dollars using the ENR Construction Cost Index. Treatment before injection would remove acid from streams A and E and alkali and organic compounds from stream F at an estimated annual cost of 2.9 to 6.2 times that of injection alone. This represents an estimated annual economic impact on those three industries of an additional $3.2 million. The nonhazardous wastestreams of industries B, D, and G would require no treatment before injection. The pretreatment requirement would force industry C either to find a recycling market for the stream or to switch to the economically unacceptable alternative of above-ground treatment. Relaxation of the pretreatment requirement for alkaline wastestreams would lower the relative cost for industry F from 6.2 to 3.6 times the injection costs.

For the seven industries, residues generated during treatment would total 35,360 cubic yards per year, with one industry (that for which direct solidification and fixation was assumed) accounting for 30,000 cubic yards. The remaining 5360 cubic yards consists of a variety of metal-containing sludges after solidification and fixation. Another residue resulting from treatment would be about 274,000 gallons (5500 drums) per year of a mixture of water and halogenated hydrocarbon solvents recovered from regeneration of a vapor-phase carbon adsorption system. This waste solvent and water mixture would probably be incinerated. Costs of incineration and landfill disposal have been included in the operating costs above.

Table 7-7. Relative costs of deep well injection and alternative disposal options.

Disposal Option	Relative annual cost†							
	Industry with hazardous waste				Industry with nonhazardous waste			Average
	A	C	E	F	B	D	G	
Deep well injection*	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Pretreatment† Injection	2.9	N/A††	4.6	6.2‡	1.0‡‡	10‡‡	10‡‡	2.8‡
Above ground treatment††	16.3	40.0	18.7	20.8	1.3	6.8	5.4	15.6

* Note that the deep well injection costs used to generate the normalized base for this relative cost comparison appear to be 1 -1/2 to 2 times too low as compared with experience in Illinois. See text for details.

** For specific constituents removed by pretreatment see text.

† All costs normalized to estimated deep well injection costs.

†† Pretreatment/injection not feasible; see text.

‡ If neutralization of high pH is not required before injection, annual cost for industry F decreases to 3.6 times injection cost, decreasing average relative cost to 2.4 times injection costs.

‡‡ No pretreatment required.

The cost estimates stated above are for pretreatment of the hazardous components in the waste-streams as they are now injected. Many of these wastestreams are combinations of smaller streams within the plant; it might be less costly to treat each stream individually before it is mixed with the other streams. In addition, new technologies are emerging which provide more environmentally sound alternatives to landfilling.

Elimination of Injection Well Disposal Option

In all but one case the level of treatment required for direct discharge was assumed to be the same as for discharge to a POTW. The single possible exception is a requirement for biological polishing treatment similar to that provided by a POTW; therefore, this cost was not included in the total estimates made. Also not included were the costs of any sewers, pipelines, or discharge structures that may be required, nor were pretreatment charges for POTW discharge included in the annual operating costs.

The total capital investment that would be required of the seven industries if injection well disposal were eliminated was estimated to be $7.02 million; the highest investment for an individual site was estimated at $3.21 million and the lowest at $211,000. The average capital cost for each of the seven industries was thus about $1 million. The industry for which direct solidification and fixation was assumed had the second lowest estimated capital cost. More than $1.5 million was for the evaporation and fixation of mineral salts; although these salts are not considered hazardous, they were present at levels exceeding the assumed discharge limits (6000 mg/L) and therefore required removal.

The sum of the annual operating costs for the seven industries was estimated to be $18.56 million, an average per site cost of $2.65 million per year. The costs ranged from a low of $160,000 to a high value of $5.89 million, the latter representing the case in which direct solidification and fixation had been assumed. (The next highest individual cost was $4.81 million per year.) The average for the other six industries was therefore $2.11 million per year.

Of the total operating costs, $8.37 million was for the evaporation, fixation, and landfilling of mineral salts present at concentrations exceeding assumed discharge limits. (Of this amount, $5.03 million was for evaporation and $3.34 million for disposal-related costs.) The higher costs of evaporation, as compared with those for reverse osmosis and electrodialysis, were easily offset by the reduction in costs for solidification, fixation, and landfill disposal. It may be possible, however, for this operating cost to be reduced dramatically if markets can be found for products that can be recovered or reused, such as waste brines or salts.

Thus, banning deep well injection and requiring above-ground treatment and disposal for industries A, C, E, and F, would increase estimated total annual costs (operating costs plus annualized capital costs) by a factor of 16.3 to 40.0 times, resulting in an estimated annual economic impact of $24.0 million for the four industries whose wastestreams contain hazardous components. Industries B, D, and G would incur an estimated additional $2.9 million impact if above-ground treatment were required.

Only standard technologies (as discussed in this report) were used for these estimates; no innovative or emerging technologies were considered. In addition, the cost comparisons made do not reflect any fees collected under the authority of the Illinois Environmental Protection Act for injected hazardous wastes. Because the information used for the calculations is of general, not specific, nature, actual costs may be expected to range from 50 percent lower to 100 percent higher than the estimates.

The total amount of waste residue generated for disposal by alternative methods to deep well disposal was estimated to be about 57,500 cubic yards per year. Of this amount, 30,000 cubic yards would require direct solidification and fixation and 22,200 cubic yards would require chemical fixation of evaporated mineral salts. A volume of 5300 cubic yards would be generated by other treatment methods. An additional 274,000 gallons (5500 drums) per year of water and halogenated hydrocarbon solvents was estimated to result from the regeneration of a vapor-phase carbon system treating the off-gas from an airstripper. This water and halogenated solvent mixture would probably be incinerated.

SUMMARY: IMPACTS OF DISPOSAL OPTIONS

Societal and Environmental Impacts

The task of quantifying the impacts of various disposal options on society, human health, and the environment is extremely difficult and beyond the scope of this report; however, a qualitative assessment of these impacts was made. The greatest concern with deep well disposal is the possibility of contamination of fresh water aquifers by migration of waste constituents from the injection formation. This could mean human health problems, loss of the aquifer as a public drinking water supply source, or merely more stringent drinking water treatment requirements. Requiring removal of hazardous components or total treatment of wastes above ground might reduce the risk of aquifer contamination, but each method of treatment would have its own impacts. Those components that were removed but could not be destroyed would still have to be stored or placed somewhere and would always represent a potential contamination problem; however, incineration or catalytic oxidation processes can destroy organic components and leave little or no undesirable residue. Landfilling or other disposal at the surface may represent a more severe threat to water supplies and public health than does deep well injection because of the proximity of the surface disposal area to potable aquifers and human activities. Salt solutions are particularly costly to concentrate and difficult to fix in a manner that will prevent leaching after landfilling. Landfills themselves have a negative aesthetic impact.

Economic Impacts on Existing Users of Injection Wells

For the seven industries in Illinois currently using injection well disposal, the estimated impact of various treatment costs on total annual costs is between $3.2 and $26.9 million (March 1985 dollars). The lower figure represents the impact that would result from required pretreatment of hazardous components for three industries prior to injection; the higher figure represents the impact that would result from banning deep well injection. The corresponding capital investment for pretreatment and alternate treatment options ranges from $2.0 to $7.0 million. These figures are only approximate because of the simplified methods of cost estimation used and because actual deep well injection costs in Illinois may be higher than these current estimates reflect.

The information given in this chapter—only a first step in identifying technologies available for handling liquid industrial wastes—indicates that each disposal option available for hazardous and nonhazardous wastestreams has associated economic, environmental, and societal impacts. The risks, costs and benefits, and trade-off factors for each option must be identified and compared so that sound policy decisions can be made concerning the injection of industrial wastes (particularly hazardous wastes) in Class I wells. All steps taken to minimize the risk caused by generated wastes

have a cost that will ultimately be borne by the public; therefore, an effort should be made to increase public awareness of the fact that chemical waste generation is inextricably linked to the technology and resulting products that the public itself demands. Information on all aspects of disposing of hazardous wastes must be provided to allow the public to make informed decisions on acceptable levels of risk, commitment of economic resources, and the most appropriate disposal options that will minimize the risk to public health and the environment. In addition, research is needed to explore still other alternatives, such as waste minimization and water reuse/recycling. From this research and experience may come more suitable ways to handle wastes that are presently being injected. Until then, however, UIC must be regarded as one of the necessary options for waste disposal.

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8 CONCLUSIONS AND RECOMMENDATIONS

This legislatively mandated assessment of the Underground Injection Control program for Class I wells in Illinois focused on several major questions:

- Is underground injection of hazardous industrial wastes in Class I wells geologically, technically, and environmentally an appropriate disposal option for Illinois? Are the regulations and enforcement practices governing Class I injection adequate to protect the environment and public health?

- What is known and what is unknown about the ultimate fate of injected wastes in the disposal system?

- What are the comparative risks, benefits, and costs of deep well injection and alternative disposal options?

- What modifications in UIC regulations and regulatory practices and what type and level of research effort should be recommended to the legislature to increase the safety of the deep well injection disposal option?

The process of drawing conclusions to answer these questions was a complex activity. Well-established, tested principles of geology and hydraulics of fluid flow in earth materials provided the basis for evaluating available evidence and making reasonable assumptions about the processes affecting injection into a disposal system. The lack of data collection at all significant positions in a disposal system required extrapolation of data from known points and establishment of reasonable inferences to evaluate the fate of injected waste. Thus, any use of these conclusions must be made with the clear understanding that certain aspects of the input were based on reasonable assumptions and not on directly collected data. Recommendations have been made for increasing the available body of evidence for deep well disposal systems; this additional evidence is expected to support and refine the general conclusions reached in this assessment.

MAJOR CONCLUSIONS

The principal findings of this extensive review of (1) UIC regulations and regulatory practices, (2) geologic and hydrogeologic conditions critical to deep well injection in Illinois and hydraulic principles governing fluid flow in geologic materials, (3) test results obtained during well construction and operation, (4) limited (in-well) monitoring data, and (5) information and experience acquired during more than 20 years of disposal practice are supportive of continuing the practice of deep well injection under very strict compliance with the UIC regulations.

- Injection in Class I wells is concluded to be an acceptable option for hazardous waste disposal on the basis of: (1) prediction of fluid flow and containment in the subsurface disposal system using well established principles, (2) geologic conditions existing in certain parts of Illinois, (3) evaluation of testing and monitoring evidence from deep well injection activities, and (4) regulatory requirements placed on this disposal practice. However, limitations do exist with the currently available evidence and there is a limited degree of uncertainty associated with the geologic environment. Although acceptable estimates of waste and pressure distributions have been made, more rigorous (factual) delineation of these distributions within the disposal system may be desirable to verify that no migration into overlying aquifers or contamination of USDW is occurring. There is some uncertainty as to the character and degree of verification that would be adequate; this issue appears to be a concern at the national level.

- The current regulations—designed specifically to protect underground sources of drinking water and the near-surface environment—are adequate in basic concept and scope but deficient to

varying degrees in some areas noted in the report. In general, the regulatory practices of the IEPA carry out the intent of the regulations. However, some modifications should be made in both regulations and practices, particularly those concerning waste sampling protocol, chemical analysis of wastestream samples, and evaluation of well testing and monitoring data and procedures. These and other regulatory practices and procedures should be reviewed periodically and updated and strengthened to reflect developing technology, research results, and experiences of those responsible for carrying out the regulations.

- Although a great deal is known about the character of deeply buried geologic formations and the hydraulic principles governing movement of injected fluids within these formations, questions still remain as to the ultimate fate of injected wastes. There is an urgent need for additional research on waste/rock/fluid interactions occurring in the injection zone, the effects of these interactions on migration of wastes, and adequate monitoring of injected wastes.

- Deep well injection is not considered a primary disposal option for hazardous wastes, but is a potential option when waste reduction, recycling, and other disposal options are technically, environmentally, and economically unacceptable.

- Banning deep well injection appears to be an inappropriate option in the light of the increased risk resulting from disposal of some waste components in or near the surface environment. Placing limitations on deep well disposal may be much more protective of USDW and human health than banning Class 1 wells would be.

GEOLOGIC CONDITIONS AFFECTING DEEP WELL INJECTION

Extensive knowledge about the subsurface geology of Illinois has been gained from petroleum and mineral resource exploration, testing, and production, and data from numerous files and reports containing detailed information about regional and site-specific geologic and hydrogeologic conditions. Evaluation of these data indicates that deep well disposal of hazardous wastes is feasible in a number of saline aquifers (including those currently used at the seven industrial sites) across the central two-thirds of Illinois. Favorable conditions include adequate confining rock above and below the injection zone; permeable, porous rock to hold the wastes; presence of heavily mineralized water (more than 10,000 mg/L TDS) within and below the potential disposal zone; no known or potential hydraulic connections between units; and no significant risk from seismic events that could cause severe damage to the wells and possible compromise of integrity of confinement zones.

Earthquakes are infrequent events in Illinois, and most of those recorded in the state's history have been low-to-moderate magnitude and intensity events (Figure 2-19, 2-20). Minor and moderate magnitude and intensity seismic events offer little or no potential risk to maintaining the integrity of disposal wells and confining units. However, severe earthquakes may offer possibly significant risk to disposal systems in certain areas of Illinois, particularly in floodplain areas where there are loose, unstable surficial materials. Wells sited where significant seismic risk may exist should meet design earthquake requirements for planning and construction; no Class I disposal wells should be located in areas having a potential risk for severe earthquake damage (Region 3, Figure 2-20).

FATE OF WASTES IN THE DISPOSAL ZONE: KNOWNS AND UNKNOWNS

Fluid movement rates in deep subsurface environments range from much less than a few inches per year under natural groundwater flow conditions to much higher rates where injection occurs. During injection, the rate of movement is higher next to the well bore and decreases radially away from the well; the highest rates occur in the most permeable zones and adjacent to the well bore. Nonhomogeneous and anisotropic conditions that are typically present in the disposal zone rock affect both the rate and pattern of flow. A general picture of the flow characteristics and the radial uniformity of geologic conditions in the disposal zone can be obtained by evaluating monitoring and testing data; however, specific detailed information for these parameters is generally not available beyond the immediate vicinity of the well bore.

Waste components tend to move at different rates in response to flow characteristics of the disposal system and interactions with materials in it. Solutes in the waste tend to move at a slower rate

than the injected water because of chemical interactions and/or sorption. The distribution pattern of the waste in the disposal zone is controlled by many factors and can be roughly estimated, using currently available monitoring and testing data. However, detailed information on the fate and distribution of waste components beyond the immediate vicinity of the well bore cannot be determined from these data.

Pressure buildup in the disposal zone during injection produces a time-expanding area in which there is an upward hydraulic gradient. Currently available testing and monitoring data can be used to estimate the general pattern of this area and the general capacity of the overlying primary confinement to retain the waste affected by this upward gradient. These data cannot be used to determine the specific location and hydraulic character of each potential fracture present in the confinement interval, nor are such data detailed enough to verify waste and pressure distributions in the disposal zone or its primary confinement intervals. All Class I wells in Illinois are operated at injection pressures well below fracture pressure thresholds. Artificial fracturing of the disposal zone is not permitted.

The projected area in which a positive hydraulic pressure is expected to develop during the life of an operating injection well is known as the area of review. Past determinations for this parameter have been based on the larger of a fixed radial distance (Vi mile in the regulations, later increased in regulatory practice to 2V2 miles) from the injection well, or a calculated distance, using a simple flow equation. Since this equation and its assumptions are inadequate for describing actual flow conditions in most injection zones, a more rigorous flow equation with better defined assumptions is needed. Such an equation will provide more realistic estimates of areas of review and identify those injection operations in which an upward hydraulic gradient extends beyond a fixed, 2½-mile radius area of review.

The wastestreams at the seven sites are relatively homogeneous in composition and volume, and have not, for the most part, interacted adversely with fluid or rock of the disposal zone to reduce or limit significantly the capacity of the disposal zone to accept the injected wastestream. Changes in the character of wastes after injection can be expected but cannot be reliably monitored with current monitoring technology. First of all, the chemical composition of existing and candidate wastestreams has not been characterized in enough detail to (1) provide a baseline from which to evaluate subsequent changes occurring in the injection zone and (2) permit a thorough evaluation of solute-solid and waste fluid-groundwater interactions that affect injection operations. Compatibility studies conducted at the time of initial permitting of the nine disposal wells indicated that no significant incompatibilities existed, but those old studies are currently considered inadequate in scope and methodology. A review of monitoring data shows that injection rates have generally remained constant over an extended period of time; there has been little or no increase in injection pressure in most wells. More refined compatibility studies conducted to mimic in situ formation conditions and determine the full range of character of the injected waste are recommended to provide a better understanding of subsurface chemical interactions in the disposal zone.

Degradation changes in waste components, particularly organic compounds, have not been well documented for the subsurface disposal environment. Microbiological degradation of some injected organic compounds is expected, but this process has not yet been studied.

Much of what is known about the fate of injected waste is obtained by monitoring injection pressures and annular pressures at the wellhead of the injection well. In some instances additional monitoring at the injection site may be desirable or essential. Direct monitoring of the disposal zone through a monitoring well partly or fully penetrating the disposal zone would be the most reliable means of tracking waste movement in the subsurface; this method is not advisable, however, because each additional well penetrating the injection zone provides another avenue of escape for the injected waste (Warner and Lehr, 1977). The best position for monitoring would be in the first permeable zone above the primary confining unit. Monitoring at this position will intercept any leakage that might take place through the upper confining unit. An appropriate monitoring protocol has not been developed for designing and operating monitoring systems for Class I disposal wells. Additional research is needed to assist regulators and industry in determining optimum monitoring well design, density, and configurations. Thorough monitoring will be an important step in building public confidence in this disposal method.

At some well sites, more detailed information about the subsurface (i.e., hydraulic properties, areal extent of injection zone, geochemistry of injection formation and confining beds) than is now generally available must be obtained to improve modeling that is used to predict the ultimate fate of injected wastes. Models used to simulate pressure distribution and waste component transport are calibrated with field data collected during injectivity tests conducted as a routine part of the well completion process. Supplemental information is obtained in the laboratory by testing cores from the injection zone and the confining rock. The accuracy of predictions based on modeling studies improves as the quality and quantity of data used in the studies increases.

COMPARATIVE RISKS, BENEFITS, AND COSTS OF ALTERNATIVE DISPOSAL OPTIONS

Proven alternative waste disposal options are available for most hazardous and nonhazardous waste components found in wastestreams currently injected into Class I wells and those that are potential candidates for deep well disposal. Each option, including deep well injection, has its own economic, environmental, and societal impacts and poses a certain level of risk to public health and safety. For instance, landfill disposal of hazardous wastes and residual/indestructible, inorganic components may place surface waters, shallow potable aquifers and other USDW at greater risk than would deep well injection; on the other hand, any contamination that might result from deep well injection would be more difficult to detect and clean up.

Alternatives to deep well disposal must either destroy the waste components or reduce them to insoluble residues that can be stored in secure disposal sites. Water or gases generated by these disposal alternatives must be safely released into the surface/near surface environment. Some processes can convert most organic compounds to harmless combustion products, essentially eliminating the hazardous nature of these compounds; others can treat inorganic components and reduce these to residual/indestructible compounds that must be disposed of in a secure landfill.

Three possible disposal scenarios are possible for Class I wells in Illinois: (1) injection with no pretreatment (current practice), (2) injection with pretreatment required to remove, destroy, or reduce the concentration of selected components, and (3) a ban on deep well injection. Each option would have specific economic impacts for industries using Class I wells and generate specific impacts and risks for USDW and the surface environment. Requiring pretreatment of the hazardous components present in a wastestream prior to injection would increase the estimated annual cost of deep well disposal by factors of approximately 3, 5, 6, and 40 for the four industries producing waste classified as hazardous. The total annual economic impact for the first three industries is estimated at $3.2 million (in 1985 dollars). Pretreatment of the waste from a fourth industry would not be economically feasible and would force this industry to take some other form of action not considered in this estimate. The nonhazardous wastestreams of the other three industries would require no pretreatment.

Banning deep well injection completely would result in an estimated average 15-fold increase in treatment and disposal costs for the seven existing wastestreams in Illinois. The combined estimated annual impact on those seven industries would total $24.0 million (in 1985 dollars) based on cost estimates generated from standard cost curves published by the USEPA (1980) and deep well costs quoted by the U.S. Department of Interior (1970). The environmental risks associated with some waste disposal technologies other than deep well disposal appear to be significant but are difficult to quantify and are beyond the scope of this report. Other disposal methods involve very little risk.

It is estimated that banning deep well injection would generate 57,500 cubic yards of solid waste per year, requiring landfilling, and 274,000 gallons of water and halogenated hydrocarbon solvents per year, probably requiring incineration. Continuing deep well injection, with some requirements for pretreatment, may be much more protective of USDW and human health than banning Class 1 wells.

RECOMMENDATIONS RESULTING FROM THIS STUDY

Proposed Changes in Regulations and Regulatory Practices

- *Delete Section 704.193(b)(3) in Title 35 of the Illinois Administrative Code.* This section reads as follows:

  > The Agency may require as a permit condition that injection pressure be so limited that pressure in the injection zone does not exceed hydrostatic pressure at the site of any improperly completed or abandoned well within the area of review. This pressure limitation shall satisfy the corrective action requirement. Alternatively, such injection pressure limitation can be part of a compliance schedule and last until all other required corrective action has been taken.

  Injection could not be practiced under this permit condition because injection of any significant quantity of waste into an injection zone instantaneously causes a pressure front to move rapidly in a radial direction from the well toward the margins of the area of review. Therefore, the only appropriate "corrective action" to take for improperly sealed, completed, or abandoned wells that penetrate the disposal zone or its cap rock in the area of review is to perform the proper procedures for sealing, completion, or abandonment before injection commences. This preventive action is sufficiently set out in Section 704.193 (a):

  > Applicants for Class I or III injection well permits shall identify the location of all known wells within the injection zone. For such wells which are improperly sealed, completed, or abandoned, the applicant shall also submit a plan consisting of such steps or modifications as are necessary to prevent movement of fluid into underground sources of drinking water ("corrective action").

- *Request the Illinois Pollution Control Board to conduct a study evaluating the UIC regulations from the viewpoint of the IEPA* and establish a mechanism to ensure that the IEPA reviews proposed/needed changes, deletions, and additions to the regulations.

- *Define more narrowly the term radioactive waste, as used in Section 730.105(d) and Section 730.105(e)(11)* to specify clearly what levels or limits of radioactivity are intended, and determine what levels of radioactivity in process wastestreams constitute a hazardous waste. Injections of radioactive waste are currently allowed in Class V wells, but no mention of such wastes is included in the definition of Class I wells. The term "radioactive" waste, as used in the definition of Class V wells, is assumed to represent low-level radioactive wastes, but no intensity levels are identified.

- *Restrict injection of low-level radioactive wastes* (radiation intensity range specified) to Class I wells only, and regulate under Class I regulations.

- *Require applicants for Class I well permits to submit a well completion report* for evaluation by the IEPA before injection is allowed to begin at the well. Although the data supplied in the completion report act as a final verification of the subsurface conditions described in the permit application and feasibility report, submission of the well completion report is currently not required before well operation begins.

- *Require that the area of review be enlarged for some proposed well sites* at which it can be demonstrated that the larger area may be necessary to protect USDW. This recommendation would add a safety factor based upon knowledge of (1) the possible directional trend of formation permeability patterns, fractures, or crevices and (2) the effects this trend may have on the movement of the waste in the disposal formation. Currently, most Class I wells in Illinois observe a 2½-mile radius fixed area of review. The IEPA should have authority to extend a well's area of review if the added precaution is considered necessary. All references in the Title 35 Illinois Administration Code to a minimum V¼-mile minimum area of review should be changed to require a 2½-mile minimum area of review.

- *Require a comprehensive inorganic and organic chemical analysis of the injected wastes* at the time of well permitting and whenever the composition of the wastestream changes, and at

least annually thereafter. This comprehensive analysis should include: (1) specific analysis of all compounds connected with the manufacturing process and (2) comprehensive scan analysis, using acceptable techniques such as gas chromatography, mass spectrometry (GC/MS), and inductive coupled argon plasma spectrometry to provide a "survey" characterization of the wastestream rather than merely a test for targeted components.

Total organic carbon (TOC) and/or total organic halogen (TOX) should be determined to find out if all major organic constituents present in the wastestream have been identified. In cases in which TOC and/or TOX values are significant, complete characterization should be made of the organic fraction of the waste. If a USDW near an injection well should ever become contaminated, these chemical analyses would provide vital information for determining the source(s) and extent of contamination.

- *Require consideration of spill containment at the wellhead and any adjacent well components* covered by UIC permits in areas where moderate-permeability to high-permeability deposits overlie shallow aquifers or are adjacent to public water supply wells.

- *Limit acid (HCl) waste concentration injected into carbonate disposal zones* to a maximum absolute concentration, not a maximum average concentration, or neutralize the acid in the wastestream prior to injection, rendering it chemically inert.

- *Require that all injection pressures and the pressure exerted by fluids in the well not exceed design specifications* for the well during testing, injection, stimulation, and repair operations.

- *Maintain an adequate pressure differential between the annulus and tubing under all possible operational conditions.*

- *Require that mechanical integrity tests be conducted more frequently than every 5 years on wells more than 15 years old.*

- *Require that all new Class 1 wells in Illinois use a packer well design rather than a packerless well design,* except for certain narrowly defined geologic, operational, and waste type conditions.

- *Use batch mode injection in order to generate a more uniform wastestream* where contributing streams vary significantly in chemical character and volume.

- *Draft regulatory practices to specifically cover the commercial operation of Class 1 wells,* including mandatory compatibility testing of all wastes prior to injection and adequate maintenance of records of all wastes injected.

- *Limit injection parameters for wells utilizing geologic formations in which the natural hydrostatic head is either above that of the overlying USDW or above the land surface.*

- *Require new Class I well applications in Illinois to include plans for appropriate tests and data collection to conduct modeling of pressure distribution and solute transport of injected wastes.* Modeling results can be applied to verify the adequacy of the proposed area of review and to determine monitoring needs.

- *Recommend the following procedures for selecting a disposal option for industrial waste:* (1) make a comprehensive identification/evaluation of all significant risks, (2) establish guidelines for acceptable risk, and (3) determine the costs/benefits and environmental impacts associated with each disposal option or level of pretreatment. (In some situations, a combination of disposal methods, including recycling and reuse, might be the most effective way to handle wastestreams and reduce the risk and impact on USDW and the surface environment.)

- *Recommend that consideration be given to requiring monitoring outside the well* (beyond the well casing and borehole); making this type of monitoring mandatory would increase public confidence in deep well disposal.

Recommendations for Improving Management of UIC Programs

- *Provide opportunities for regulatory and scientific advisory personnel associated with UIC programs to maintain contacts with UIC staff in other state and federal agencies and the USEPA.* Such contacts permit exchange of ideas and updating on advances being made in (1) waste treatment technologies and management practices, (2) research and well testing technology, (3) handling of new regulations, and (4) adaptation of regulatory practices to local waste disposal conditions.

- *Retain a UIC program manager with a broad technical background in deep well technology* to enable this person to manage technical aspects of the program effectively and coordinate staff efforts.

- *Enter analytical results from monthly monitoring reports into a computerized central database.* Regulatory staff and technical advisory committee staff can then evaluate these data routinely to determine the condition of the waste disposal system and degree of compliance with permit and special condition requirements.

Recommendations for Research

To develop increased understanding of the fate of wastes in the disposal zone and thus increase public confidence in the injection of industrial wastes, the following research is recommended:

- *Determine chemical interactions of industrial waste components* with various types of formation fluids and formation rocks under in situ disposal conditions.

- *Determine permeability changes in the rocks* of the disposal and confining zones resulting from various chemical reactions.

- *Develop methods and equipment* for sampling and testing formation fluids under subsurface temperature and pressure conditions.

- *Conduct additional studies into the nature of fluid and solute transport* to quantify the magnitude and character of fluid movement in confining beds used for deep well disposal.

- *Develop a monitoring strategy for Class 1 injection operations* that includes determining the position of the monitoring site(s) in the waste disposal system, parameters to be tested, and frequency of testing.

- *Develop a methodology to improve monitoring of waste movement and behavior in the subsurface environment* in order to collect data required for testing models of subsurface disposal systems and verifying results obtained from model studies.

APPENDIX

Summary of injection waste composition for the seven injection well facilities ir Illinois, during 1983-1984 (concentrations in mg/L except where noted). Data were obtained on a monthly basis from various monitoring reports.

Site A

Summary statistics for 1983

Parameter	$\overline{X}^a$	S^b	$CV(\%)^C$	Minimum	Maximum	No. of spls^d	Yearly total
Acid(%HCI)	1.26	0.71	56.3	0.44	2.56	11	
Chloride	13,319	6,398	48.0	5,763	25,363	11	
pH (units)	0.65	0.18^e	82.3^e	0.34	1.37	11	
Specific gravity	0.990	0.004	0.4	0.984	0.996	11	
Suspended solids	145	50	34.5	77	242	11	
Viscosity (cps)	3.1	0.2	6.5	2.7	3.3	11	
Injection volume (gal.)							
Well #1	1.35×10^5	2.42×10^5	179	1.76×10^4	7.96×10^5	11	
Well #2	5.95×10^6	2.35×10^6	39.5	2.75×10^6	9.35×10^6	11	6.69×10^7

Summary Statistics for 1984

Parameter	$\overline{X}^a$	S^b	$CV(\%)^C$	Minimum	Maximum	No. of spls^d	Yearly total
Acid(%HCI)	0.77	0.33	42.9	0.31	1.29	11	
Chloride	9,918	3,451	34.8	4,538	15,400	11	
pH (units)	0.91	0.047^e	38.9^e	0.69	1.17	11	
Specific gravity	1.000	0.008	0.8	0.995	1.008	11	
Suspended solids	141	97	68.4	62	400	11	
Total dissolved solids	1,051	298	28.4	431	1,488	11	
Viscosity (cps)	2.8	0.61	21.8	2.2	4.4	11	
Injection volume (gal.)							
Well #1	$*2.29 \times 10^4$	6.44×10^3	28.1	1.62×10^4	3.70×10^4	11	
Well #2	5.84×10^6	1.11×10^6	18.9	3.90×10^6	7.44×10^6	11	6.55×10^7

* Average excluded one anomaly of 1,007,550 gal per 1-month period.

a: mean
b: standard deviation
c: coefficient of variation $(S/X) \times 100^2$
d: number of months
e: based on $[H^+]$
f: one analysis per month
g: samples analyzed quarterly
h: samples analyzed weekly

Site B

Summary statistics for 1983

Parameter	$\bar{X}^a$	S^b	CV(%)^c	Minimum	Maximum	No. of spls^d	Yearly total
Acidity (mg/L as CaCO$_3$)	278	345	124	53	1307	12	
Alkalinity (mg/L as CaCO$_3$)	228	323	142	29	973	8	
Anthraquinone Disulfonic Acid	17.4	21.5	124	<0.1	52	12	
Boron	1.6	0.4	25.0	0.7	2.3	12	
Calcium	84	30	35.7	47	145	12	
Chloride	1,161	275	23.7	734	1,578	12	
Fluoride	0.5	0.2	40.0	0.2	0.8	11	
Iron	4.1	1.5	36.6	2.0	6.7	12	
Magnesium	68	66	97.1	26	243	12	
Silica	17.3	4.4	25.4	13	26	12	
Sodium	2,593	2,559	98.7	439	8,169	12	
Specific gravity	1.003	0.003	0.3	0.999	1.010	12	
Sulfate	698	750	107	139	2,587	12	
Suspended solids	51	27	52.9	23	105	12	
Total dissolved solids	4,958	3,684	74.3	1,616	13,175	12	
Turbidity	28	20	71.4	12	77	12	
Vanadium	11.6	12.7	109	0.7	37	12	
Injection volume (gal.)	3.95×10^5	9.71×10^4	24.6	2.19×10^5	5.01×10^5	12	4.74×10^6

Summary Statistics for 1984

Parameter	$\bar{X}^a$	S^b	CV(%)^c	Minimum	Maximum	No. of spls^d	Yearly total
Acidity (mg/L as CaCO$_3$)	83	54	65.1	56	198	7	
Alkalinity (mg/LasCaCO$_3$)	114	72	63.2	37	258	7	
Anthraquinone Disulfonic Acid	13.0	7.0	53.8	12	25	7	
Boron	1.5	0.7	46.6	0.8	2.8	7	
Calcium	73	20	27.4	59	117	7	
Chloride	1,312	277	21.1	955	1,858	7	
Fluoride	0.8	0.2	25.0	0.6	12	7	
Iron	3.0	1.5	50.0	1.5	6.0	7	
Magnesium	55	17	30.9	39	92	7	
Silica	55	17	30.9	39	92	7	
Sodium	1,753	1,058	60.4	747	3,994	7	
Specific gravity	1.000	0.004	0.4	0.991	1.003	7	
Sulfate	347	161	46.4	194	682	7	
Suspended solids	39	15	38.5	22	60	7	
Total dissolved solids	3,714	1,253	33.7	2,461	6,411	7	
Turbidity	73	120	164	9	342	7	
Vanadium	7.0	5.2	74.3	1.1	17.1	7	
Injection volume (gal.)	5.41×10^5	7.75×10^4	14.3	4.35×10^5	6.26×10^5	7	3.79×10^6

Site C

Summary statistics for 1983

Parameter	$\bar{X}$[a]	S[b]	CV(%)[c]	Minimum	Maximum	No. of spls[d]	Yearly total
Acid(%)	3.43	0.51	14.9	2.48	4.11	10	
Chloride	230,230	39,625	17.2	196,611	321,202	10	
Chromium	0.10	0.12	120	0.04	0.11	10	
Copper	26.3	3.1	11.8	23	29	3	
Iron	134,747	17,342	12.9	112,817	166,742	10	
Lead[f]	0.40	0.07	17.5	0.32	0.44	3	
Manganese[f]	514	27	5.3	485	537	3	
Nickel[f]	18.3	1.1	6.0	17.4	19.5	3	
pH (units)	<1.0			<1.0	<1.0	10	
Specific gravity[f]	1.2598	.0323	2.6	1211	1.3058	10	
Total dissolved solids	318,786	43,223	13.6	262,484	411,176	10	
Viscosity (SSU)	150	21	14	124	180	10	
Zinc[f]	3.8	2.8	73.7	1.4	6.9	3	
Injection volume (gal.)	5.60×10^5	1.83×10^5	33.0	2.73×10^5	9.00×10^5	11	6.16×10^6

Summary statistics for 1984

Parameter	$\bar{X}$[a]	S[b]	CV(%)[c]	Minimum	Maximum	No. of spls[d]	Yearly total
Acid(%)	1.93	0.24	12.4	1.51	2.26	9	
Chloride	222,643	21,113	9.5	186,386	243,697	9	
Chromium	0.03	0.02	66.7	0.01	0.07	9	
Copper[f]	25.1	–	–	17.2	33	2	
Iron	137,629	12,427	9.0	115,638	151,912	9	
Lead[f]	0.34	-	–	0.18	0.50	2	
Manganese[f]	650	–	–	600	700	2	
Nickel[f]	22.9	–	–	17.8	28.0	2	
pH (units)	<1.0			<1.0	<1.0	9	
Specific gravity[f]	1.2489	.0246	2.0	1.2119	1.2844	9	
Total dissolved solids	332,159	40,718	12.3	261,909	384,685	9	
Viscosity (SSU)	130	20	15.4	104	175	9	
Zinc[f]	3.3	–	–	3.1	3.2	2	
Injection volume (gal.)	7.31×10^5	1.55×10^5	21.0	5.06×10^5	9.71×10^5	9	6.58×10^5

Site D

Summary statistics for 1983

Parameter	$\bar{X}^a$	S^b	$CV(\%)^c$	Minimum	Maximum	No. of spls[d]	Yearly total
Calcium	273	98	35.9	140	411	11	
Chloride	65	9	13.8	45	75	11	
Chromium	0.43	0.35	81.4	0.04	0.92	11	
Fluoride	182	70	38.5	40	198	11	
Magnesium	155	20	12.9	122	191	11	
Mercury (ppb)	0.15	0.04	26.7	0.11	0.21	4[g]	
pH (units)	2.8	0.001[e]	50.0[e]	2.4	5.9	11	
Phosphorus	609	130	21.3	357	758	11	
Potassium	46	21	45.6	28	69	4[g]	
Sodium	897	57	6.4	840	975	4[g]	
Specific gravity	1.011	0.001	.10	1.010	1.012	11	
Sulfate	2,192	508	23.2	1,603	2,988	11	
Suspended solids	36	9	25.0	17	49	11	
Total dissolved solids	6,056	928	15.3	4,506	7,296	11	
Total organic carbon	94	23	24.5	71	155	11	
Injection volume (gal.)	1.11×10^7	2.03×10^6	18.3	8.00×10^6	1.44×10^7	11	1.23×10^8

Summary statistics for 1984

Parameter	$\bar{X}^a$	S^b	$CV(\%)^c$	Minimum	Maximum	No. of spls[d]	Yearly total
Calcium	305	65	21.3	216	418	12	
Chloride	59	6.4	10.8	48	69	12	
Chromium	0.28	0.13	46.4	0.16	0.58	12	
Fluoride	182	25	13.7	144	227	12	
Magnesium	138	23	16.7	109	191	12	
Mercury (ppb)	0.19	0.06	31.6	0.11	0.24	4[g]	
pH (units)	2.62	0.001[e]	50.0[e]	2.3	3.0	12	
Phosphorus	533	65	12.2	428	679	12	
Potassium	48	28	58.3	19	74	4[g]	
Sodium	71	127	17.7	600	856	4[g]	
Specific gravity	1.010	0.001	0.10	1.009	1.011	12	
Sulfate	2,285	346	15.1	1,477	2,548	12	
Suspended solids	45	11	24.4	29	58	12	
Total dissolved solids	5,851	660	11.3	4,988	6,928	12	
Total organic carbon	121	21	17.4	96	175	12	
Injection volume (gal.)	1.03×10^7	2.19×10^6	21.2	6.10×10^6	1.28×10^7	12	1.24×10^8

Site E

Summary statistics for 1983

Parameter	$\bar{X}$[a]	S[b]	CV(%)[c]	Minimum	Maximum	No. of spls[d]	Yearly total
Acid(%HCI)	2.96	4.7	160	0	11.4	37	
Acid(%HF)	0.086	0.058	67	0	0.23	37	
Arsenic	30.3	29.3	96.7	4.5	117	51	
Chloride	7,300	8,300	110	1,000	59,000	51	
Nickel	1.7	0.9	50	0.2	4.7	51	
Sodium fluoride	930	570	61	20	3,100	51	
Total organic carbon	13	4	30	3	23	51	
Injection volume (gal.)	2.2×10^6	0.3×10^6	14	1.6×10^6	2.8×10^6	–	3.58×10^7

Site F

Summary statistics for 1984

Parameter	$\bar{X}$[a]	S[b]	CV(%)[c]	Minimum	Maximum	No. of spls[d]	Yearly total
Chlordane	0.5	0.1	20	0.4	0.6	2	
Chlorinated C_1,C_2 components	14	8	60	3.3	23.6	4	
Chlorinated C_5,C_6 components	230	208	90.4	6	493	4	
Hex	234	121	52	65	380	4	
Sodium chloride	27,100	21,100	77.9	900	118,600	52	
Total organic carbon	13	4	30	3	23	51	
Injection volume (gal.)	2.2×10^6	0.3×10^6	14	1.6×10^6	2.8×10^6	–	3.58×10^7

Site G

Summary statistics for 1983-1984

Parameter	X[a]	S[b]	CV(%)[c]	Minimum	Maximum	No. Of spls[d]	Yearly total
Anthraquinone Disulfonicacid	21	26	124	0	220	24	
Calcium	2,500	1,000	40	-	-	104	
Chloride	50,000	3,000	6	-	-	104	
Magnesium	1,200	200	20	-	-	104	
Sodium	29,000	3,000	10	-	-	104	
Sodium thiosulfate	-	-		6	280	17	
Suspended solids	300	200	66.7	-	-	104	
Total dissolved solids	83,000	2,000	2.4	-	-	104	
Injection volume (gal.)	0.6×10^6	0.4×10^6	70	1.1×10^6	0.04×10^6	23	1.08×10^7

Percentage of samples lying within the specified pH range for all sites.

pH range of injection wastes		0-1	1-2	2-4	4-6	6-8	8-10	10-12	12-14
Site	Year								
A	1983-84	74%	26%	—	—	—	—	—	—
B	1984	—	—	3.4%	93.1%	3.4%			
C	1983-84	100%	—	—	—	—	—	—	—
D	1984	—	—	100%	—	—	—	—	—
E	1984	6%	27%	48%	13%	2%	2%	2%	—
F	1984	—	—	—	—	4%	2%	4%	92%
G	1983-84	—	—	—	—	100%	—	—	—