International Association of Hydrogeologists

Philip E. LaMoreaux
Jaroslav Vrba
(editors)

Hydrogeology and Management of Hazardous Waste by Deep-Well Disposal

Volume 12
1990

Volume 12
1990

HEISE

International Contributions to Hydrogeology
Founded by
G. Castany, E. Groba, E. Romijn

HEISE

International Association of Hydrogeologists

Philip E. LaMoreaux
Jaroslav Vrba
(editors)

Hydrogeology and Management of Hazardous Waste by Deep-Well Disposal

A Report of the Commission on
Hydrogeology of Hazardous Wastes
of the International Association of Hydrogeologists

Volume 12 / 1990
International Contributions to Hydrogeology
Founded by
G. Castany, E. Groba, E. Romijn

Verlag Heinz Heise

Financially supported by UNESCO as a contribution to the International Hydrological Programme IHP-III Theme 8 ('Specific influences of man on the hydrological regime'), project 8.2: 'To consolidate information on hydrological aspects of liquid disposal by industry and mining, waste disposal on land and radioactive disposal'.

CIP-Titelaufnahme der Deutschen Bibliothek
LaMoreaux, Philip E.:
Hydrogeology and Management of Hazardous Waste by Deep-Well Disposal:
A Report of the Commission on Hydrogeology of Hazardous Wastes of the
International Association of Hydrogeologists/Philip E. LaMoreaux; Jaroslav Vrba.
Internat. Assoc. of Hydrogeologists. –
Hannover: Heise, 1990
(International Contributions to Hydrogeology: Vol. 12)
ISBN 3-922705-93-6
NE: Vrba, Jaroslav; GT

Volume 12, 1990
International Contributions to Hydrogeology
Founded by G. Castany, E. Groba, E. Romijn
ISSN 0936-3912
ISBN 3-922705-93-6
Printed by R. van Acken GmbH, Josefstraße 35, D-4450 Lingen (Ems), Germany

CONTENTS

FIGURES

APPENDIX A: CASE HISTORIES

TABLES

EXECUTIVE SUMMARY AND CONCLUSIONS

Philip E. LaMoreaux
and
Jaroslav Vrba

Situation at Present

The technology for managing hazardous waste has been slower to develop than the technology for generating it. The importance of properly managing hazardous waste commonly has been unrecognized until after the manufactured product has become an accepted "necessity" and the harmful effects of the by-products on the environment become evident.

Initially, hazardous wastes were sent along with the non-hazardous materials to streams, dumps, or municipal landfills. Treatment, incineration, storage and disposal are methods of managing hazardous wastes; each of these include different techniques for handling hazardous wastes. Injection of hazardous waste into deep wells is one of several alternatives.

The following generic recommendations apply to the selection of an appropriate hazardous waste management method:

1. Research to define risks associated with various management options including risks associated with specific wastes and management locations /sites/.

2. Establishment of criteria for evaluating and selecting various management options.

3. Research to develop incentives that would encourage the industry to move towards a waste reduction, recycle and reuse operation.

4. There is no practical level of engineering that can convert a poor geologic site into a favorable one.

The technology for deep-well injection evolved during the 1930s in the petroleum industry of the USA and the potash mining industry of Germany. By the 1970s deep-well injection had been adopted by other industries as a method of managing wastes.

Options available through deep-well injection should reflect both short- and long-term objectives. Short-term objective must provide current needs that encourages compliance and protects health and environment. Long-term objective should lead to a decrease in the production of hazardous wastes. Various studies / Reeder and Associates, 1977 and Brower and others, 1986/ have shown the economic advantages offered by deep-well injection. Brower and others /1986/ describe risks associated with treatment alternatives that could be greater than those posed by deep-well injection. Deep-well injection is a safe method of disposing of hazardous waste if the wells are properly sited, constructed, operated and maintained.

Deep-well disposal is an acceptable concept for waste management, considering that the earth has stored liquids, gases and solids /oil, gas, coal, minerals/ for millions of years. Some of these materials could be characterized chemically as hazardous wastes. Oil and gas, for example, are highly combustible and can contain lethal concentrations of hydrogen sulfide. Natural resource ocurrence demonstrates a safe containment, as migration of these natural hazardous materials has been prevented by impermeable cap rocks that have confined the materials for millions of years. The Commission believes, therefore that deep-well disposal should be considered after a very careful evaluation of many factors that include a detailed assessment of waste management alternatives, their cost, risk, physical and chemical character, geographic, geologic and geochemical setting. Risks associated with various options should be analyzed and compared. Potential impact on human health and the environment must be the deciding factor.

This monograph deals with deep-well disposal of hazardous liquid wastes; radioactive waste is not included in this report. No international standards provide guidelines for handling and management of hazardous liquid wastes; however, several countries regulate the injection of liquid waste by legislation. Some examples of deep-well disposal are presented in case histories in the second part of the monograph. This monograph was prepared as a reference source for decision makers, political representatives and citizens.

Geologic and Hydrologic Criteria

With respect to safety and efficiency aspects of the methods of hazardous waste managment, deep-well injection is the disposal method which depends the most on geologic conditions. The importance of geologic and hydrologic criteria is therefore stressed already at the stage of selecting a hazardous waste management method. Once deep-well injection is chosen these criteria play a decisive role in the design of the disposal system.

Lithology, permeability, storativity and structual conditions of the injection aquifer are the main considerations when assessing the technical and economic feasibility of a deep-injection project. To minimize environmental risks and assure safety of the disposal thickness, impermeability and coherency of all confining units of the injected hydraulic system, its structural position with respect to a water-supplying aquifer and other natural resources must be evaluated prior to the construction of an injection well.

Due to the great variety of types of geologic structures and hydraulic systems within the technically accessible part of the lithosphere, many of the proposed or recommended geologic and hydrologic criteria published so far, including those in this monograph, remain merely general ones. The optimum values of some of the criteria are stated, but definition of specific regulations is sensible only for a specific site where combined effects of all geologic and hydrologic criteria on environmental safety and economic efficiency of the disposal can be assessed.

The degree of specification of geologic and hydrologic criteria is closely related to the level of investigation for the site and the region.

Physical and Biochemical Compatibility

The host rock of a subsurface reservoir for a successful injection well should be physically and chemically suitable to accept and contain injected waste for an indefinite period of time. It is important to notice, however, that there is no technical level of engineering that can convert a less convenient geologic site into a convenient one.

Physical properties of host formation will control the direction and spatial distribution of the plume formed by the injected waste. These characteristics include porosity, permeability, storativity, isotropy, homogenity and the extent of porous media. Containment of injection waste within the receiving reservoir, however, is affected more by the confining layers.

All spatial, physical and chemical parameters that affect the rate of deep well injection and propogation of the waste within the aquifer can be assessed by the injectivity index. The injectivity index results from the quantity /volume/ injected per unit time /discharge/ and the pressure at a given aquifer. It is a specific characteristic of every injection well. It remains constant as long as the formation porosity and permeability and/or radius of influence of the well do not change. The injectivity may be increassed by acidification and/or by a more drastic measure of increasing the hydraulic fracturing with explosives.

The plot of injection ratio /discharge over pressure/ versus time indicates various types of aquifer behavior. With hydraulic fracturing within the host formation and/or the confining layers the line will show a marked gradient; the injection rate is higher in relation to pressure. On the other hand, a lesser gradient means clogging and plugging in the host formation.

It is for indispensable safety reasons and for cost reasons that it is recommended that testing of possible aquifer physical reactions be carried out on each injection before operation is begun.

There are two methods currently used in establishing the area of review; one, a fixed radius around the injection well and two, a calculated radius that reflects reservoir characteristics, injection rates, pressures and area of impact. The effects of injection pressures can extend for miles, depending on many variables. Therefore, a calculated area of review will more reliably reflect the zone of influence, or area that can be affected by deep-well injection.

Injection technology also requires comprehensive knowledge of chemical and biological reactions between liquid waste, host rock and native water.

Aggressiveness and solubility of injected wastes, chemical compostion of native water /mainly pH and redox potential/ and mineralogical composition of host formation - all these control the type and course of the reactions that take place in the waste-rock-water system.

Decomposition of the rock, cation exchange, sorption, membrane filtration, redox reactions - these should especially be studied before injecting liquid wastes, and carefully observed during operation of the deep well disposal.

Plugging of the pore space and gradual decrease in the permeability of the receiving unit is the most dangerous process that can occur during waste injection. Plugging is mostly a consequence of a high acid content in the injected wastes. However, highly alkaline wastes /pH 11 or more/ can be hazardous to the structure of the receiving unit as well, if silicates dominate. Control of pH of injected wastes and pH in the receiving unit environment is therefore strongly recommended.

Treatment of the wastes prior to injection is most desirable to avoid corrosion of the injection system by the waste material.

Certain bacteria accelerate chemical reactions, which may lead to plugging of the receiving formation. Some other bacteria /sulfate-reducing/ may cause corrosion of the injection well or other mechanical parts of the injection system. Therefore knowledge of the biological components present in the wastes to be injected or in native water is very important for the injection operation to be successful.

It is emphasized that physical, chemical and biological processes play an important role when the compatibility of waste to the host rock-water formation is studied and considered. The above processes affect each other, and therefore they should not be viewed in an isolated but an integrated way.

According to Gordon and Bloom /1985/, one major shortcoming of existing regulations is that they fail to prohibit the injection of wastes that are incompatible with the well materials, the injection zone, and the confining layers. The following recommendations were offered:

1. Requiring compatibility tests for each new waste stream prior to authorizing its injection.

2. Specifying the parameters needed to evaluate compatibility of the injected wastes with the well materials, injection zone and confining strata; the appropriate tests needed to measure these parameters, and the procedures for proper analyses of the test data. Such tests must be designed to demonstrate any incompatibilities that might occur under expected temperature and pressure conditions.

Research needs include:

- Characterization of constraints associated with the injection of acidic waste into carbonate formations.

- Identification of operating procedures to prevent gas-lifted eruptions.

- Evaluation of the effects of ion exchange, sorption, filtration, neutralization, and density on the reactions that occur between wastes and matrix and formation fluids.

- Evaluation of the potential for degradation and sorption of injected hazardous wastes into deep saline environments.

- Development of models that aid in prediction of the effects of reactions between wastes and formational waters and rocks.

Well Construction

The specifications for constructing an injection well must reflect the characteristics of the injection site and the waste stream to be injected. Most problems associated with well construction have not resulted from the construction itself but from failures to characterize adequately the site or waste stream.

Current technology for constructing hazardous-waste injection wells is adequate. Specifications must reflect types of sites and waste characteristics. These specifications should be formulated from an inventory of wells with successful injection histories. Construction manuals should provide updated technology. The resulting compiled data would be more valuable if construction procedures are standardized.

Proper cementing of all casings to surface is important. For example, if all cementing is completed in one operation, the pressures exerted on the formation and casing become great and can cause problems. Research is needed on cementing procedures and requirements.

A well completion report is an important final step in the drilling and design of the injection well. The report should include all aspects of the drilling, testing and completion methods used in constructing the injection well.

Monitoring

Monitoring of hazardous-waste injection wells must provide evidence that the injection well is operating correctly and that wastes are being contained. Monitoring devices must be able to detect problems as soon as they develop.

Four aspects of the injection process must be monitored:

1. the injected fluid; quantity and quality;

2. injection pressure, flow rate and volume, and the pressure on the annulus between the tubing and the long string of casing;

3. mechanical integrity of the well; and

4. selected wells within the area of review that are to be used to observe fluid migration.

Monitoring the actual injection well should include pressures in the annulus that exceed tubing-injection pressures. Pressure increases would indicate that the tubing or packer has failed. The absence of an adequate database regarding monitoring devices, recorders, gauges, failures, and types of failures precludes a quantitative assessment regarding the monitoring of the injection well.

The long string of casing is the safety system that ensures no injection into unpermitted zones if there is a tubing failure. There must be the assurance that the disposal system is intact. Frequent tests for mechanical integrity by pressurization of the annulus are necessary. Tests must be at a sufficient pressure to ensure integrity of the system. Consideration must be given to the effects on tubing, type of tubing, and on tension packers. Mechanical integrity tests are justified because they are not expensive, require minimal time, and provide crucial information on the integrity of the well.

Specific standardized methods for performing and reporting the results of mechanical integrity tests are needed, and any problems with mechanical integrity or significant fluid movement must be resolved immediately. All tests for mechanical integrity or significant fluid movement, workovers, construction, and so forth, should be witnessed by enforcement authorities.

Shallow groundwater monitoring for deep-well disposal projects is appropriate to detect leakage immediately adjacent to an injection well. Surface facilities should be inspected and certified and certification involves regular inspections.

Deep monitor wells are needed. The usefulness of the data that they can provide far outweighs the cost. Concerns that deep monitor wells could become pathways for fluid migration /either injected or reservoir/ need not be valid. If injection wells can be constructed for no leakage, then so can monitor wells. Pressure monitoring of the injection zone is a reasonable method for detecting anomalous changes within the injection reservoir. Reservoir performance is predictable and provides for methods of detecting migration or pressure drops that deviate from normal. Deviations from predicted pressures provide immediate information on possible problems. Pressure monitoring in the injection zone, in the confining zone, or just above the confining zone is needed.

Technology available from the petroleum industry is available to develop criteria for placement of monitoring wells and to evaluate the utility of pressure monitoring.

The following research is recommended:

- Development of specific methodologies for monitoring injection zones, confining layers, and adjacent aquifers.

- Evaluation of pressure monitoring within the injection zone versus periodic cessation of injection with shut-in and pulse-reservoir testing to evaluate reservoir performance and to compare actual performance with predicted performance.

- Development of specifications for using bottom-hole pressures rather than surface-injection pressures.

- Evaluation of the effects of stress on casing from high-pressure annulus monitoring versus zero pressure or fluid-filled annulus.

- Development of specifications for collecting and analyzing water quality samples from wells completed just above a confining layer.

- Definition of statistical methods that must be applied in determining sampling and data collection frequencies.

- Development of procedures to detect pressure differentials just above the confining layer and to identify and separate background pressure fluctuations.

- Development of non-invasive methods for monitoring waste migration.

- Definition of the extent and time required for unplugged and uncased holes to close due to overburden compression. For example, shales and clays compress in response to loading. The extent and time required for this closure needs definition for various depths and sediment types.

Environmental Impacts

A decision to ban deep-well injection of hazardous wastes should be made only if this method of hazardous-waste disposal has been found to be environmentally unacceptable and, also, only if more environmentally safe methods for managing hazardous wastes are available. Both the acceptability and feasibility of deep-well injection and alternative management methods provide the basis for different opinions.

A review of the performance record of deep-well injection reveals various problems that have been encountered during the siting, construction, operation and monitoring of injection wells.

For example:

1. Many criteria for siting, constructing, and operating an injection well are too general, and not specific enough to help the appropriate regulatory official to implement the regulations.

2. Permitting and inspection procedures have been insufficient in providing assurance that criteria and regulations for developing and operating a well have been met.

3. Failure to record and to compile data that could be used in assessing and providing proper direction.

4. Lack of adequate methodology and equipment to measure parameters and define necessary remedial action.

Problems, failures and environmental consequences of poor deep-well injection management are mostly related to the following general causes:

- Errors in well construction, particularly inadequate casing, casing seat, cement bond, casing head, tubing, packer.

- Pathways for fluid migration, particularly fractures or faults in the confining zone above the injection zone, improperly abandoned well, lithology changes, pressure-created pathways.

- Operational error, particularly failure to inspect and monitor equipment, excessive injection pressure, inadequate data management.

- Errors in compatibility calculations, particularly between waste stream and well materials, among waste stream components, between waste stream and formation, between waste stream and native fluids.

- Natural events, particularly earthquakes or seismic activity, lightning, vulcanism, tornadoes.

Aust and Kreysing /1985/ pointed out among the consequences of deep well injection activities the following environmental effects which must be considered as irreparable: ground and surface water contamination, raising of the freshwater/salt-water boundary, compromising the quality of usable mineral resources, subsidence or uplift of land, undesired heating up of reservoir rock and its environment, compromising thermal anomalies, changes in the injection unit /particularly with regard to permeability/.

Regulatory programs should be designed for compliance. An effective regulatory program provides assurance that standardized criteria and procedures are being followed and potential environmental impacts are minimized.

CHAPTER 1

PREAMBLE - UNDERGROUND INJECTION PROJECT

Philip E. LaMoreaux
and
Jaroslav Vrba

The Commission on Hydrogeology of Hazardous Waste (HWC) of the International Association of Hydrogeologists (IAH) was proposed at the 17th Congress of IAH in Tucson, Arizona January 8-10, 1985. Philip E. LaMoreaux was named Chairman. To insure coordination with the existing Commission of Groundwater Protection, Jaroslav Vrba was named Vice Chairman.

The Council of IAH met at Skaly, Czechoslovakia May 28-29, 1985 and advised that the Charter of the Commission should include radioactive waste management. In September, 1985 P.E. LaMoreaux completed the Charter of the new Commission and presented it to the Executive Council meeting of IAH in Cambridge, United Kingdom, at which time the Council approved the Charter and the Commission began its activities.

The Commission met for the first time during the 19th Congress of IAH in Karlovy Vary, Czechoslovakia in September 1986 and reviewed the general concepts of a worldwide study of underground injection of hazardous waste. At this meeting a draft outline for a report was completed and the contributing authors identified.

In the Spring of 1987, Jaroslav Vrba and Philip E. LaMoreaux met in Tuscaloosa and prepared a first draft of the report which was then reviewed by the Commission at the time of the 20th Congress of IAH at Rome, Italy, April 3, 1987.

On May 27 - June 3, 1988, the members of the Commission met at Skaly, Czechoslovakia, and on April 24-29, 1989, at Bilthoven, The Netherlands, and prepared the final draft of the report, "Underground Injection of Hazardous Waste". Subsequently this draft has been reviewed by some members of the Commission. Staff Scientists that contributed substantially to the report included: Jan Beba and Vladimir Houzim of Stavebni Geologie, Prague, Czechoslovakia; Tola Moffett, Laura Whitaker, Janet Smith, and Ann McCarley of P.E. LaMoreaux and Associates, Inc., Tuscaloosa, Alabama, U.S.A.

At the beginning of 1988, UNESCO and IAH signed a contract on the publication of the monograph "Hydrogeological Aspects of Deep Well Injection of Liquid Hazardous Waste" in the framework of the project 8.2 (6) Consolidation of Information Available on Hydrological Aspects of Waste Disposal on Land, in the third phase of the International Hydrological Program.

The permission for publishing the report in the IAH-UNESCO-IUGS series "International Contributions to Hydrogeology" was given by the IAH Council in 1989, after thorough review of the manuscript by H. Aust of the Federal Institute for Geosciences and Natural Resources, Federal Republic of Germany.

A final review of the contents of the manuscript was made by J. Vrba and P.E. LaMoreaux at the time of the 28th International Geological Congress (IGC) in Washington, D.C. on July 11, 1989. It was agreed by members of the Commission present at the IGC that owing to the time constraints for publication that the final report would contain the name(s) of the primary author or authors for each chapter. All members of the Commission participated in many ways as sources of information, preparation of text and discussion at the meetings. However, not all the members were able to review and approve the manuscript in its final form.

The 1989 membership list for the Commission on Hydrogeology of Hazardous Waste is as follows:

Philip E. LaMoreaux, Chairman
Hazardous Waste Commission
International Association of Hydrogeologists
P.O. Box 2310
Tuscaloosa, Alabama 35403
UNITED STATES

Eilon Adar
Ben-Gurion University of Negev
The Jacob Blaustein Institute for Desert Research
Sede Boqer Campus
ISRAEL 84993

Horst Aust
Bundesanstalt fuer Geowissenschaften und Rohstoffe
Stilleweg 2
3000 Hannover 51, P. O. Box 51 01 53
FEDERAL REPUBLIC OF GERMANY

Gunter Dörhöfer
Nieders. Landesamt für Bodenforschung
Stilleweg 2
3 Hannover - Buchholz
FEDERAL REPUBLIC OF GERMANY

Ron Hoffer
Guidelines Implementation
Office of Groundwater Protection (WH-550-G)
U.S. Environmental Protection Agency
Washington, DC 20460
UNITED STATES

Vladimir Kolaja
Stavebni Geologie
113 09 PRAHA 1
Gorkeho Nam. 7, Prague
CZECHOSLOVAKIA

John Moore
Environmental Strategies Corporation
8521 Leesburg Pike
Suite 650
Vienna, Virginia 22180
UNITED STATES

Stephen H. Stow
Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, Tennessee 37831-6038
UNITED STATES

Peter Vardy
Waste Management, Inc.
3003 Butterfield Road
Oak Brook, Illinois 60521
UNITED STATES

Jaroslav Vrba, Co-Chairman
Hazardous Waste Commission
International Association of Hydrogeologists
147 00 PRAHA 4
Korandova 32
CZECHOSLOVAKIA

Lars Anderson
Ministry of the Environment
Geological Survey of Denmark
Thoravej 31
DK-2400, Kobenhaven, NV
DENMARK

Larry Doyle
19926 Encino Moos
San Antonio
Texas 78259
UNITED STATES

Kenneth S. Johnson
Oklahoma Geological Survey
Office of Groundwater Protection
The University of Oklahoma
830 Van Vleet Oval, Room 163
Norman, Oklahoma 73019
UNITED STATES

Vladimir Kovalevsky
Institute of Water Problems
Academy of Sciences of the U.S.S.R.
Chernogriazskay 13/3,
Moscow-Sadovay
U.S.S.R.

Pierre Peaudecerf
BRGM, B. P. 6009
45018 Orleans - Cedex
FRANCE

Hubert G. van Waegeningh
Nat'l Inst. of Public Health and Environmental
Protection
Antonie van Leeuwenhoeklaan 9
P.O. Box 1
3720 BA Bilthoven
THE NETHERLANDS

Stanislaw Witczak
Inst. of Hydrogeology and Engineering Geology
St. Mickiewicza 30
30-057 Krakow
POLAND

CHAPTER 2

INTRODUCTION

Philip E. LaMoreaux
and
Jaroslav Vrba

Hazardous wastes for this report is defined as a waste which because of its quantity, concentration, or physical, chemical, or infectious characteristics may (A) cause, or significantly contribute to, an increase in mortality or an increase in serious adverse effects (direct or indirect) on human health, animals or plants, or (B) pose a substantial present or potential hazard to the environment when improperly treated, stored, transported, or disposed of, or otherwise managed.

Especially dangerous for human health, according to World Health Organization (WHO), are the following inorganic and organic substances and compounds: arsenic, asbestos, barium, beryllium, cadmium, chromium, cyanides, fluorine, lead, mercury, nitrates, nitrites, selenium, silver, sodium, chlorinated alkanes, chlorinated alkenes, cyclic hydrocarbons, pesticides, chlorbenzenes, phenol, chlorphenols and halomethanes.

2.1. Specification of Hazardous Wastes

No international criteria exist for the physical and chemical specification of toxic and hazardous wastes.

Wastes that occur in liquid, semi-liquid and solid states, depending on the chemical nature of the contaminants contained in them, are classified as inorganic and organic.

Liquid and semi-liquid wastes are those that contain contaminants in the liquid phase, in emulsion, or in a concentrated aqueous solution forming, together with the solid compounds, suspensions - slurry.

Examples of liquid inorganic hazardous wastes include:

A. Slurry produced by metal-plating technologies and surface-finishing of metals. It contains cyanides in concentrations greater than 1.0 g/l and may contain non-complex cyanides bound with heavy metals of different stabilities.

B. Slurry produced by ore mining and dressing.

C. Slurry produced by leather-processing and other types of industry.

The concentrations of certain heavy metals and toxic elements in wastes and their toxicological parameters are listed in Table 2.1.

Table 2.1. Toxicological parameters of heavy metals and other inorganic toxic substances in wastes

Metal or its compound expressed as metal	Concentration in wastes, mg/l	Maximum LC mg/l	Other toxic effects
Arsenic	500	5.0	K,M
Cadmium	100	1.0	K
Chromium VI^{+}	500	1.0	K,M
Lead	500	5.0	K
Copper	500 (LC 50)	3.3	
Nickel	134	5.0	K,M
Selenium	100	1.0	M
Thalium	130	1.0	K
Zinc	500 (LC 50)	8.4	
Cobalt	130	5.0	
Molybdenum			
Tungstan			
Vanadium	100	1.0	
Silver	500	5.0	
Mercury	20	0.2	
Cyanides	1.0 (LC 50)	0.1-17	

Note: M - Mutagenous K - Carcinogenic

In the USA the 1984 Hazardous and Solid Waste amendments include the following specification of hazardous wastes (commonly known as the California list):

A. Liquid hazardous wastes, including free liquids associated with any solid or sludge, containing free cyanides at concentrations greater than or equal to 1,000 mg/l.

B. Liquid hazardous wastes, including free liquids associated with any solid or sludge, containing the following metals (or elements) or compounds of these metals (or elements) at concentrations greater than or equal to those listed below:

1. Arsenic and/or compounds (as As) 500 mg/l
2. Cadmium and/or compounds (as Cd) 100 mg/l
3. Chromium (VI and/or compounds as Cr VI) 500 mg/l
4. Lead and/or compounds (as Pb) 500 mg/l
5. Mercury and/or compounds (as Hg) 20 mg/l
6. Nickel and/or compounds (as Ni) 134 mg/l
7. Selenium and/or compounds (as Se) 100 mg/l, and
8. Thallium and/or compounds (as Th) 130 mg/l.

Examples of liquid organic hazardous wastes include:

A. Oil-wastes - i.e. those produced during crude oil extraction and by the petrochemical industry, sludge from the processing of oil distillation fractions, wastes from the fat-processing industry, oil product mixtures from mechanical separators, wastes from the cleaning of cisterns and tanks and from the metal industry (cutting and cooling emulsions, oiled chips), sludge produced during the treatment of effluents containing oil and oil products, sludge from the washing and maintenance of motor vehicles and construction and farming machines.

B. Halogenated, particularly chlorinated aliphatic hydrocarbons (solvents), chlorinated mono- and disubstituted aromatics. They occur either separately, in the liquid phase, or in aqueous solutions, often in suspensions with solids at concentrations greater than 10 mg/l.

C. Organic solvents - aromatic and toxic aliphatic hydrocarbons and hydrocarbon derivatives.

D. Polychlorinated biphenyls are contained in transformer oils, dielectric liquids, hydraulic liquids, lubricating and cutting oils and plastifiers. They are 100 percent concentrated wastes, or with one to fifty percent admixture of PCB.

E. Pesticides - in the liquid phase or emulsions, or liquid and solid compounds dissolved in water and bound with solid substances or in sludge.

F. Phenols and phenol-containing waste products: residual of lignite and bitumen tars, sludge from phenol water treatment plants, wastes from oil refineries, wastes from the production of artificial resins.

G. Wastes from the production of organic chemicals and plastics, for instance aromatic amines and alkylating agents, alkylphtalates, monomers for the synthesis and from the processing of polymers, wastes from the production of varnishes and dyes, medicines, cosmetics and rubber.

H. Tenzides are usually bound with wastes from various industries, such as the textile, leather-tanning, food and pharmaceutical industries, and also with those from the processing of polymers and crude oil. They are abundant in municipal and household wastes (contained in detergents). Particularly hazardous are highly toxic cation tenzides, alkylpyridine and alkyltrimethylammonium compounds, non-ionogenic ethoxylated alkylamines and anionactive alkylbenzenesulphonates and acrylalkylsulphonates.

I. Organic wastes produced by the pulp and paper industry.

2.2. Hazardous Properties of Wastes

High-risk waste properties include: ignitability, corrosivity, reactivity and toxicity.

A waste is ignitable when it causes fire through friction, absorption of moisture, or spontaneous chemical changes, or burning vigorously and persistently when ignited. A solid waste also will have the characteristic of ignitability if it is an ignitable compressed gas or an oxidizer.

A waste is corrosive if it has in aqueous medium a pH that is less or equal to 2 or greater than or equal to 12.5, or it is a liquid that corrodes (by standard test methods) steel at a rate greater than 6.35 millimeters per year.

A waste is reactive if it is unstable and readily undergoes violent change without detonating; reacts violently with water; forms potentially explosive mixtures with water; generates dangerous toxic gases, vapors or fumes when mixed with water; is capable of detonation or explosive reaction if subjected to a strong irritating source or if heated under confinement; is readily capable of detonation, or explosive decomposition or reaction at standard temperature and pressure.

A waste is toxic if, by the specified test methods for toxicity, it contains any of the contaminants listed in Table 2.2. Toxicity of contaminants is characterized by:

- Lethal concentration (LC) for toxic effects (medium or maximum)
- A scale of 1 to 6, depending on the medium oral lethal doses /LD 50/ - Table 2.3
- Class of risk to man /O, A to F/ - Table 2.4.

The risk classes express the degree of danger to man in respect to acute and chronic toxicity and are designated as follows: O - no risk, A - very slight risk, B - slight risk, C - medium risk, D - great risk, E - very great risk, F - extremely great risk.

Contaminants are also described by other toxicological criteria, for example: carcinogeneity, mutageneity, teratogeneity and embryo-toxicity.

Table 2.2. Maximum concentration of contaminants for characteristic of EP toxicity (1988, Code of Federal Register - U.S. Environmental Protection Agency (EPA)

EPA Hazardous Waste Number	Contaminant	Maximum Concentration (Mg/l)
D004	Arsenic	5.0
D005	Barium	100.0
D006	Cadmium	1.0
D007	Chromium	5.0
D008	Lead	5.0
D009	Mercury	0.2
D010	Selenium	1.0
D011	Silver	5.0
D012	Endrin (1, 2, 3, 4, 10, 10-hexachloro-1, 7-epoxy-1, 4a, 5, 6, 7, 8, 8a-oxtahydro-1, 4-endo, endo-5, 8-dimethano-naphthalene	0.02
D013	Lindane (1, 2, 3, 4, 5, 6-hexachlorocyclohexane, gamma isomer.	0.4
D014	Methoxychlor (1, 1, 1-Trichloro-2, 2-bis [p-methoxyphenyl] ethane).	10.0
D015	Toxaphene (C_{10} H_{10} Cl_8, Technical chlorinated camphene, 67-69 percent chlorine).	0.5
D016	2, 4-D (2, 4-Dichloro-phenoxyacetic acid).	10.0
D017	2, 4, 5-TP Silvex (2, 4, 5-Trichlorophen-oxypropionic acid).	1.0

Table 2.3. Level of toxicity in relation to the lethal concentration /LC 50/

Degree	Level of Toxicity	LD 50 (mg/kg)
1	non-toxic	15.000
2	slightly toxic	5.000 to 15.000
3	moderately toxic	500 to 5.000
4	very toxic	50 to 500
5	extremely toxic	5 to 50
6	supertoxic	5

Table 2.4. Reference standards of risk classes with respect to toxicity

Class	Acute toxicity	Chronic toxicity
O	water, NaCl	water, $CaCO_3$
A	ethanol, KCl	glycerine, NaCl
B	benzene, $CuSO_4$	toluene, acetic acid, $AgNO_3$
C	CO_2, H_2SO_4, $NaNO_2$	ethanol, H_2SO_4, $HgCl_2$
D	anilin, HF, NaCN	benzene, trinitrotoluene
E	HCN, veratrin	CS_2, MnO
F	tetraethylpyrofafate, ricin	tetracarbonyl Ni, benzidine

2.3. Processing of Liquid Hazardous Wastes

Liquid hazardous wastes can be classified according to the methods of processing:

- wastes
  - recyclable
    - immediately
    - potentially
  - non-recyclable

- non-recyclable wastes
  - intended for disposal
  - intended for elimination by: incineration, catalytic oxidation, decomposition by radiation.

Hazardous wastes that can be recycled, i.e. returned to the production process or used for generating secondary raw materials for new products or energy include:

- Wastes containing heavy metals, i.e. from metal plating processes and surface finishing of materials, or dressing, as well as other wastes containing heavy metals
- Wastes containing degradable synthetic polymers and monomers
- Aromatic and halogenated alifatic solvents and halogenated aromatics with one to three chlorine atoms
- Used oils /lubricating motor oils, transformer oils, etc./
- Wastes from pulp processing
- Tars and wastes from crude oil processing
- Basic substances for organic synthesis; for instance, phenols and creosols, aromatic and alifatic amines, organic bases and acids, and alcohols.

Potentially unsuitable for recycling are, for instance, polychlorinated biphenyls, pesticides, wastes from the pharmaceutical industry, tenzides, and polyaromatic hydrocarbons. The reasons for this include above all: their low concentrations in wastes, and the difficulties associated with their isolation and concentration, as well as the great quantities of accompanying chemicals in the wastes, etc.

Wastes that cannot be recycled, or those that for some technical reason cannot be recycled immediately, must be eliminated from the environment. The quantity of the wastes to be eliminated or deposited depends on the situation prevailing in the country involved. The most widespread methods of hazardous waste disposal include: deposition of pretreated hazardous wastes in subsurface disposal sites, deposition in underground repositories, deposition in deep geological structures through injection wells, and in exceptional cases, composting.

CHAPTER 3

GEOLOGIC AND HYDROLOGIC CRITERIA FOR DESIGN OF A DEEP DISPOSAL SYSTEM

Stephen H. Stow
and
Vladimir Kolaja

3.1. Introduction

There are many types of injection wells that are used to dispose of different forms of liquid wastes. The geological and hydrological criteria that must be considered in siting the different types of wells are variable; for instance, wells that are used to dispose of brines from petroleum production are sited with minimal consideration of these factors as the brines are typically simply reinjected into the production horizon. In contrast, wells used for the disposal of hazardous wastes must be sited with maximum consideration of the geologic and hydrologic characteristics of the subsurface. Regardless of the type of well, the common factor for all is isolation of the wastes from the environment.

The selection of a site for a hazardous waste disposal well depends heavily on site-specific geologic and hydrologic criteria, in addition to certain non-technical considerations involving transportation and socioeconomic factors. There are also general technical siting considerations of a regional nature that can aid in locating an injection facility. We will briefly describe some of these regional issues and then will deal in more detail with the site-specific issues involving geology and groundwater hydrology. Suggestions will be offered as to how to proceed in acquiring the needed geologic and hydrologic data for siting. Regardless of the scale of any investigation leading to siting of a hazardous waste injection well, the focus of attention is on: 1) the nature of the host interval into which wastes will be injected, 2) the adequacy of the confining units that separate the wastes in the host interval from the environment and from drinking water supplies, and 3) potential pathways that could lead to inadvertent release of wastes into adjacent aquifers or to the surface. Warner et al. (1986) present a good summary of technical considerations related to the confining strata and Warner and Lehr (1977) review in detail the geologic and hydrologic issues associated with siting a well.

It is obvious that many data must be acquired in order to successfully site a hazardous waste injection well. These data relate, of course, to identifying an acceptable site for the well. Involved in this endeavor are not only geologic and hydrologic characterization activities, but also sophisticated engineering and hydrologic testing and modeling to allow prediction of the transport and fate of the injected wastes. The reader is referred to Warner and Lehr (1977) for a very complete overview of the types of data that will be required for the entire siting process and for ways in which to obtain those data. Depending upon the specific situations, there may be useful data that can be used prior to any drilling at the potential site; in addition, use of non-penetrative exploration techniques - principally surface geophysics - should be considered at an early stage in the siting program. Many data can be obtained during well construction and testing, and these will probably be the data that will be of greatest use in addressing regulatory issues that lead to permitting of the injection facility. Samples of the units should be obtained during drilling for description and testing, the formational waters from at least the injection interval must be characterized and compatibility tests run, and complete geophysical logging of all boreholes should be performed to acquire information on lithology, structure and hydrology. Testing of the injection and confining units must be undertaken to determine hydrologic parameters and predictive modeling of the fate of the wastes within the injection zone must be done.

3.2. Regional Criteria

Because injection wells require a host interval that can accept liquid wastes without excessive injection pressures, a porous and permeable sedimentary stratum is most ideally suited; therefore, on a regional basis, it is best to consider sedimentary rocks, rather than crystalline igneous or metamorphic rocks. There are certain types of sedimentary rocks, such as sandstone, that are better suited than others, and this will be discussed below. Regions where sufficient confining units occur, such as an area where a low permeability shale overlies a thick sequence of sandstone, are favorable with regard to stratigraphy. The rock units should be structurally simple with a horizontal or gently dipping orientation. Hydrologically, there must be lack of interaction among different groundwater systems and between groundwater and surface water, as maximum hydrologic isolation of the host interval is required; the groundwater in the injection interval should not be of good quality and often groundwater with more than 10,000 ppm total dissolved solids is sought. Regions that are seismically inactive and that do not contain existing or potential resources are preferable. For instance, in the United States, most hazardous waste injection wells are found in the Coastal Plain and Central Plateau Provinces; the Coastal Plain is characterized by gently dipping unconsolidated sands and clays of considerable thickness and lateral extent while the Central Plateau is underlain by thick sequences of Paleozoic carbonates and clastics with numerous structural basins that help the hydrologic isolation.

By using broad criteria such as those noted above, it is possible to screen large areas to identify potentially acceptable smaller areas for detailed geologic and hydrologic analysis; Fig. 3.1 represents a procedural flow diagram for evaluating large areas for injection well siting (Van Everdingen and Freeze, 1971). An approach such as this is advisable for regions of highly variable geology where little prior information is available that would aid in site selection. Once potentially acceptable areas are identified, then site-specific studies, as discussed below, can be undertaken. This approach represents an expeditious and cost-effective way to examine large regions, but it does not allow an acceptable site in an otherwise less desirable region to be located. For instance, there may be small, but perfectly acceptable injection sites in sedimentary rocks located in an area that is largely characterized by crystalline rocks. In order to locate all potential sites, rather than screen large areas to identify those with greatest potential, considerable additional work is mandated.

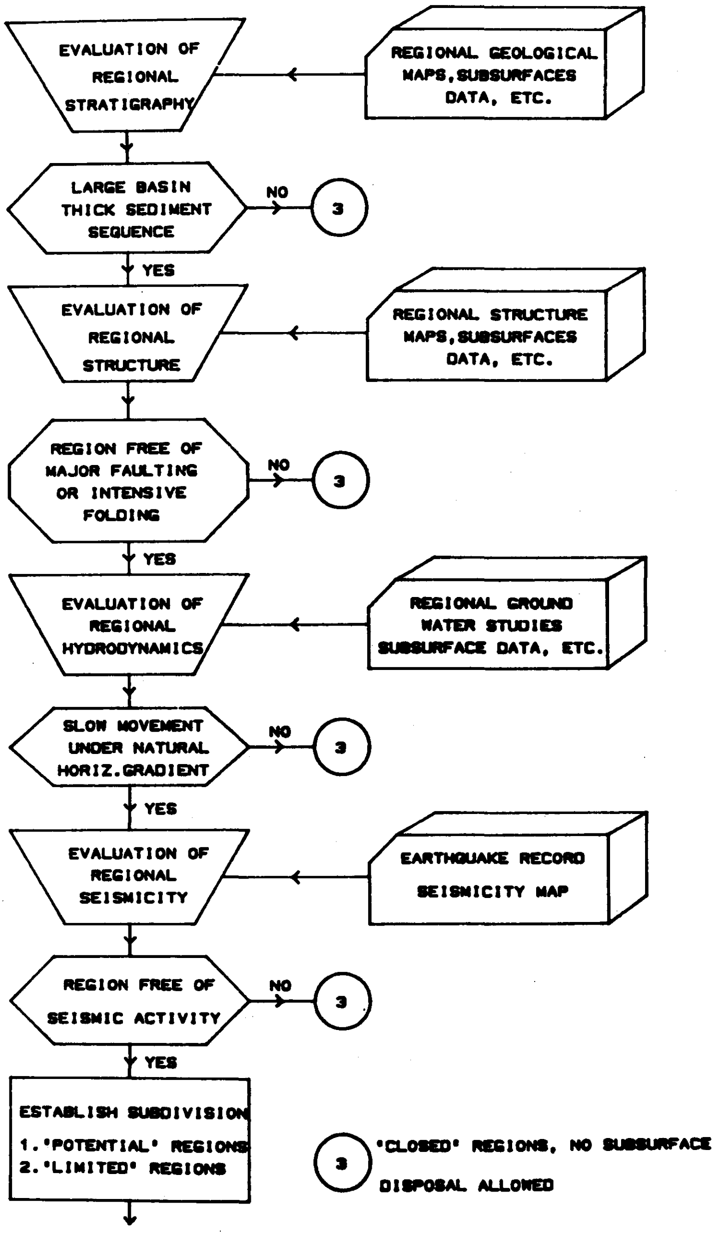


Fig. 3.1. Evaluation of regions for subsurface wastewater injection (Van Everdingen and Freeze, 1971).

3.3. Geologic Aspects

Site-specific geological considerations are of extreme importance as they represent essential factors in controlling hydrological characteristics and in helping to ensure proper operation of the well and waste isolation. Those that receive the most attention relate to the stratigraphic, lithologic and structural nature of the injection and confining intervals; others include the hydrochemistry, the seismic potential and the resource potential and history of the site. Fig. 3.2 represents a flow diagram for the evaluation of small areas for well siting.

3.3.1. Stratigraphic and Lithologic Criteria

A properly sited hazardous waste injection well will have the injection zone bounded at least at the top by a low permeability confining zone that prevents the upward migration of wastes toward fresh water aquifers. Depending upon the regulations that apply to the specific site, there may also be a requirement for a confining zone below the injection horizon (Fig. 3.1). Thickness and lateral extent are considerations that apply to all the zones. It is necessary that they extend laterally far enough so that the wastes remain in the injection zone and not reach discharge areas. This distance can be variable depending upon the area of influence of the injection, but the lateral extent and thickness of the rock units must be known for at least a kilometer (and perhaps much further) from the well; certainly the characteristics within the "area of review" must be well known. Homogeneity within the injection interval is favored so that there will be a more uniform distribution of wastes in the subsurface. There are many factors that determine the desired geometries of these two horizons, including the nature of the wastes, the permeability of the units, the existing hydrologic conditions, and many others; the reader is referred to the publications of Warner et al (1986) and Donaldson and Rezaei (1986) for more information.

Permeability and porosity are also factors that must be evaluated for both the injection and confining intervals, and these parameters help to dictate which rock types are best suited for each interval. Because the injection interval is expected to receive the wastes and house them without artificial fracturing by high pressures (except on occasion to stimulate the well prior to injection of wastes), it should have high porosity and a permeability in the order of at least 100 to 1000 millidarcies. Typically, sandstones and some carbonate rocks have sufficient porosity and permeabilities of this magnitude and one finds that these two lithologies serve as the most popular injection horizons, largely for this reason; the actual suitability of any specific horizon depends upon its reservoir capacity, however, which is principally a function of porosity and thickness. In contrast, the confining horizons must be of very low permeability, in the order of 10^{-3} to 10^{-6} millidarcies. Clay, shale, some evaporites such as anhydrite, and many dense and unfractured carbonates serve effectively as confining strata. It is possible to artificially decrease a weak section of a confining formation by injection of solidifying solutions, such as cement milk.

The chemical compositions of the injection and confining zone are of importance

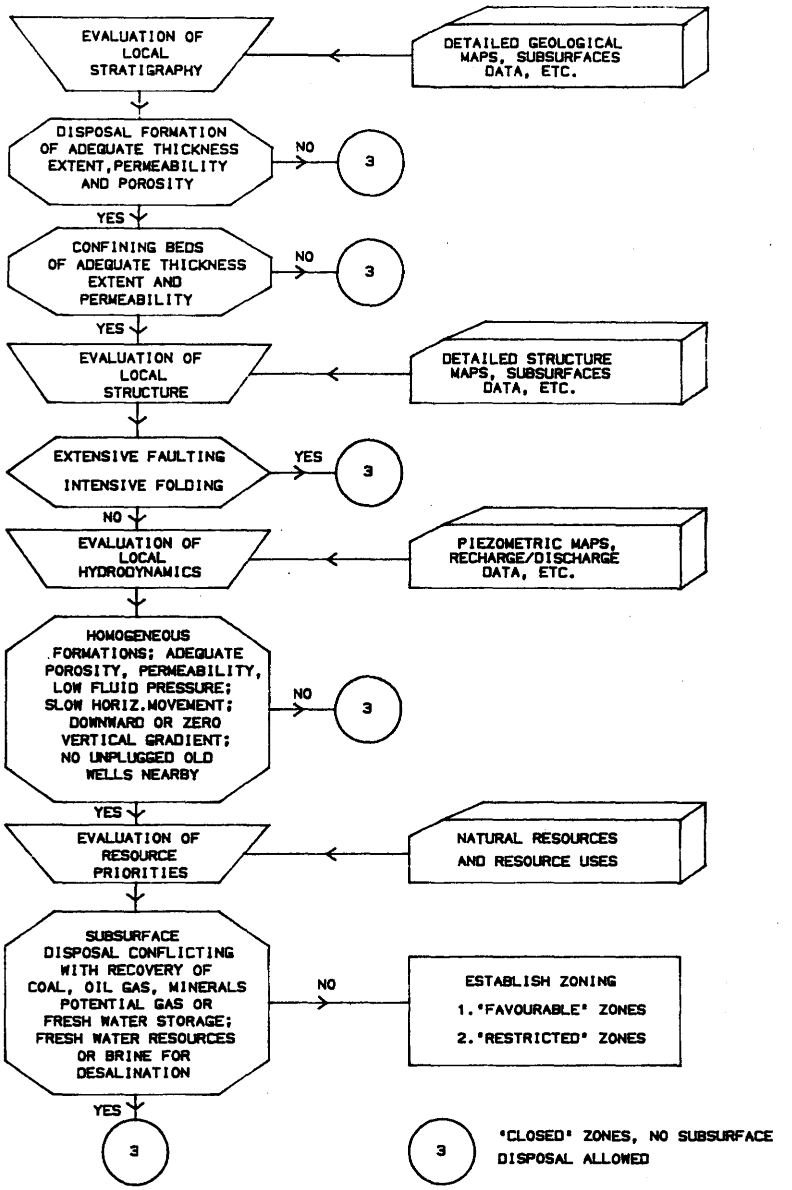


Fig. 3.2. Selection of formations and areas for subsurface disposal of industrial waste (Van Everdingen and Freeze, 1971).

also; this is discussed in more detail in Chapter 5, which deals with compatibility issues. For acidic wastes, which must be neutralized after injection in order to render them non-hazardous, a carbonate-rich injection zone is desirable and the disposal of such liquids into limestone and dolomite is documented (Kaufmann et al., 1973; Piskin, 1986). The reaction between the waste and the host rock helps create needed permeability and the carbon dioxide, which is generated during the neutralization, is generally dissolved in the groundwaters of the injection horizon. In the case of acidic wastes, it is not recommended that the confining strata be of carbonate composition, as the hydrologic isolation integrity of the system would be jeopardized; Kaufmann et al. (1973) and Vecchioli (1981) report cases where acidic waste reacted with a carbonate confining zone and may have migrated upward into an overlying aquifer.

3.3.2. Structural Criteria

In general, it is safe to say that the simpler the geologic structures of a site, the better that site is for hazardous waste injections. While it may be acceptable to inject into folded, faulted, and fractured stratigraphic systems in isolated cases, the potential for unsuccessful waste isolation dramatically increases in such a situation. Faults and other fractures can frequently represent pathways along which wastes may migrate; if they create desired permeability in the injection zone, that may be advantageous, but if the pathways lead into and through the confining units, this is not a permissible situation. Faults can also represent barriers to migration of groundwater (and wastes) if sealed with secondary materials, but sophisticated site characterization is needed to evaluate this situation; for a conservative approach to siting an injection well, it is advised that faults and other fractures be considered as potential pathways until proven otherwise, and that structurally deformed rock units be avoided to the greatest extent possible.

Artificial fracturing of the injection horizon is occasionally practiced under controlled conditions. Pre-waste injection hydrofracturing to stimulate the well and to increase permeability and acceptance of waste represents such a situation, but this must be performed after study of the in situ state of stress at the site and calculations as to the fracture extent and orientation. In the United States, injection pressures are not allowed to exceed specified limits that are calculated based on the depth of the injection, rock characteristics, etc., because the danger exists that hydrofractures will extend into the confining units and will create pathways out of the injection zone. There is, however, one unique well where injections of cementitious grout, containing wastes were made into a low permeability shale by hydrofracturing the structurally anisotropic shale along bedding planes during the injection.

A final aspect involving structural geologic considerations relates to seismicity. As indicated previously, avoidance of faults and other structures is recommended; this is especially true if a faulted injection horizon is under stress so that fluids enter the fault system, facilitating movement and seismic activity. A classic example of such a situation is the very deep injection of wastes near Denver, Colorado in the 1960s (see Chapter 7). A full investigation of structural and tectonic complexities is recommended during the siting of disposal wells, especially in areas of tectonic activity.

3.3.3. Hydrochemical Criteria

The compositions of the groundwaters in the injection interval, as well as in the confining units, are of extreme importance for a variety of reasons. One reason is that reactions can occur between the wastes and the natural waters present in the injection horizon; likewise, the composition of groundwaters can yield data on the history of the waters, information valuable to assessing the hydrologic isolation of the injection interval. Following are brief comments on each of these two aspects of hydrochemistry.

The reactions between wastes and groundwater can be either detrimental or beneficial, but they must be anticipated and assessed prior to injection. Consideration must be given to the potentially adverse reactions that might occur leading to precipitation of materials that cause loss of permeability and injection potential. It is virtually impossible to make valid generalized comments regarding this important issue, as it is highly specific to each waste stream and the site characteristics for each well. The need for complete testing is mandatory to avert incompatibility problems and the reader is referred to Chapter 5 of this report for more details. It is found that this entire issue of chemical reactions, either between waste streams, or between a waste and the rock units, including their contained fluids, is extremely important in all cases and very difficult to predict for commercial disposal wells which may accept a variety of different wastes (see Chapter 7).

The second aspect of hydrochemistry, assessing the composition of the groundwaters, can provide insight on the history, age, and mixing of groundwaters. For instance, use of various stable isotopes, chiefly of oxygen, hydrogen, and nitrogen, can aid in assessing the mixing history of groundwaters with surface waters (Fritz and Fontes, 1980). The use of radioactive isotopes, such as ^{14}C, ^{36}Cl, and others, has been documented for age dating of groundwaters (Davis and Bentley, 1982). Depending upon the half-life of the isotope, ages from tens of years to literally millions of years can be reliably obtained. Another aspect of natural water chemistry to examine is the basic cation and anion composition of the groundwaters. If groundwaters from the injection units consistently have a different composition from those of the adjacent confining formations, then this can be used as evidence of lack of mixing and of a high degree of hydrologic isolation; likewise, if the groundwater from any one stratum is highly variable in composition from place to place, this could be evidence of interconnections with adjacent units. Special attention might be given to looking for constituents that reflect anthropogenic input; for instance, nitrate and many organic compounds, if found in the groundwaters, would indicate a connection with surface systems.

3.3.4. Natural Resource Criteria

While the presence of a natural resource, such as hydrocarbons or minerals, may not, in itself, jeopardize the success of an injection well, it is strongly advised that injection wells not be placed where there is an existing or potential natural resource. The concern is quite apparent that attempts to extract the resource in the future might be made without adequate knowledge of the existence of the disposal system and there would be an inadvertent release of hazardous waste to the environment with attendant health and safety risks.

Therefore, a full assessment of the resource potential of a site and the surrounding area needs to be made during the siting process.

An aspect directly related to natural resources involves an assessment of the existence of abandoned wells in the area of review. There are many areas, especially in sedimentary terrains, where prior exploration for energy, water, or mineral resources was conducted by well drilling. In many cases, bore holes have been left abandoned and open; in other cases, boreholes were plugged, but the plugging did not provide a sufficient seal and there still exists open communication within the subsurface and with the surface. Identification of all boreholes in the area of review, specifically those that penetrate the injection horizon, is an essential aspect of siting an injection well. If boreholes exist that could provide a pathway for wastes to reach either the surface or a drinking water supply, they must be properly plugged. Plugging of a borehole to ensure no hydrologic communication between rock units is a very sophisticated endeavor and must be performed by someone who is expert at this activity.

3.4. Hydrologic Aspects

The hydrologic aspects associated with deep-well disposal siting are closely tied to the geologic aspects, discussed above; indeed, it is virtually impossible to separate discussion of the two. All hydrologic considerations must be based on and refer to a well defined hydraulic system in the region of the proposed well. The system must assure sufficient storage space and adequate permeability for the disposal and preclude contamination of groundwater in adjacent systems by natural restriction of the movement of the wastes.

3.4.1. Identification and Characterization of the Host Hydraulic System

The first step in identifying the hydraulic system is based on the available geologic information described above. The major hydrologic concerns in this identification process include geometry, hydrologic parameters, and relative positions of all permeable and impermeable units in the area of review. For economic purposes and to allow disposal of large volumes of waste, only units of sufficient permeability and/or large spatial extent should be chosen. For environmental safety, permeable units with maximum isolation from other permeable units are sought. This implies that only confined aquifers or confined parts of complex aquifers are suitable for deep well injection of wastes.

The aquifer and confining units represent a hydraulic system characterized by a certain degree of openness depending upon the completeness and impermeability of the confining units at the system boundaries. Larger amounts of waste can generally be injected into open hydraulic systems because the liquid within the aquifer can be displaced, but contamination can occur at the open boundries with adjacent hydraulic systems. Dilution or decomposition of the wastes during a lengthy path to these boundries can reduce the risk of contamination if the spatial extent of the host unit is large enough, but open systems should be avoided for injection of highly persistent and refractory wastes. Injection into more closed systems requires use of relatively high injection pressures to compress subsurface materials and to create storage space. Excessive injection pressures can fracture confining units and can open the system boundries, allowing uncontrolled contaminant migration. The geology of many regions of the world, however, does not provide for completely closed hydraulic systems and systems with more open characteristics must, therefore, be used; in such cases, the precautions noted above must be followed. For these reasons, it is necessary to acquire extensive knowledge about not only the injection system itself and its boundary conditions, but also about the adjacent hydraulic systems. This information is essential to allow assessment of the risks of potential contamination migration and to define properly the monitoring requirements.

The following sections summarize the essential characteristics of a host aquifer and the surrounding confining units for deep-well disposal and the basic hydraulic methods for calculating and evaluating parameters and the effects of the injection; this is based on the work of Aust and Kreysing (1985).

3.4.2. Hydrophysical Characteristics of the Injection Aquifer

In order to calculate the potential waste storage capacity of the injection aquifer, the following data must be determined:

A. The aquifer geometry parameters: thickness, areal extent, and form,

B. Hydrophysical parameters of the host formation(s): permeability, porosity, pressure, temperature, degree of fluid saturation, elasticity and compressibility, and storage coefficient (considering the pertinent waste),

C. Physiochemical parameters of the host formation(s) groundwater: chemistry (including total dissolved solids [TDS]), pressure, temperature, density, and compressibility.

Thickness, lateral extent, and form of the aquifer are determined by geological, geophysical, and drilling methods. Archived data available for the region can be used in the initial stage of the evaluation, but an extensive and complex survey for the specific injection system must be completed as part of the siting process and prior to initiation of any disposal operation to minimize environmental and economic risks.

Hydrophysical parameters of the host formation(s) heavily influence the operational and economic aspects of the injection system. The capability of the host formation to accept a unit volume of liquid waste essentially depends on its storage coefficient and coefficient of permeability. While the storage coefficient, which reflects the other mentioned parameters if properly calculated, influences the ratio of the volume of injected waste per unit column of the aquifer with unit change of pressure, the coefficient of permeability decisively influences the feasibility and velocity of the injection process. The values of the coefficient of permeability should be above 10^{-5} m/s. The values of the storage coefficient in confined aquifers of closed hydraulic systems into which an additional amount of liquid can be introduced only by an increase in pressure, lie between 10^{-4} and 10^{-7}: in semiconfined aquifers the values range between 10^{-2} and 10^{-4}.

For the reliability of quantitative evaluations, the knowledge of the spatial distributions of the principal hydrophysical parameters within the host formation (type of aquifer heterogeneity) and directional orientation of the measured values (type of anisotropy of the aquifer) is needed.

As with the geometric properties of the aquifer, rough values of the hydrophysical parameters, as well as their distribution and orientation, can be estimated by studying archived data and surface geological features, and by analogy. The more accurate evaluations will require surface geophysical measurements, core drilling and core analysis, borehole geophysical logging, and drill-stem hydraulic testing with formation fluid sampling and analysis.

Physiochemical parameters of the host formation(s) groundwater influence the flow velocity and compressibility within the injection system and, hence, the quantitative results of the injection. Viscosity, which has an inverse effect on flow velocity, increases with the TDS and decreases with increasing temperature (with a temperature change, e.g. from 20 to 40°C, the viscosity will decrease by one-third if the TDS remain constant). Pressure has an insignificant effect on viscosity.

The groundwater density can negatively affect the injection operation under specific structural conditions, (e.g. on the flanks of an anticline) if it is greater than the density of the liquid waste. Because the density increases with pressure and decreases with temperature, the influence of these two factors with increasing depth largely counter each other, however.

Knowledge of the groundwater pressure in the injection formation is of primary importance, principally for determining the appropriate injection pressure. The pressure of water in confined aquifers does not correspond to the hydrostatic pressure and it must be measured directly in the borehole at the injection depth by a drill-stem test. The pressure of the confined groundwater increases with the TDS, and it is dependent on the lithostatic load, the tectonic conditions, and the geologic characteristics of the host formation overburden.

In the case of closed hydraulic systems, where formation water cannot be displaced, groundwater compressibility must also be considered. According to Rottgardt et al. (1976), water compressibility is approximately 5×10^{-5}/bar, depending on the TDS content, temperature, and storage capacity. For instance, if 50 m^3 of water are introduced into an injection interval with a groundwater volume of 1,000,000 m^3, the pressure will increase approximately one bar.

3.4.3. Hydrologic Characteristics of the Confining Units

The host formation should be surrounded by extremely low permeability formations that will help to confine the waste. Structural, physical, and hydraulic parameters of confining and semi-confining formations adjacent to the host formation determine the boundary conditions of the host hydraulic system (i.e. the degree of waste confinement). Of these parameters, thickness, permeability, elasticity, and compressibility are very important.

Aust and Kreysing (1985) present a theoretical example of the influence of hydraulic system boundary conditions, expressed by values of thickness and permeability of the confining unit, on the injection process - chiefly pressure development within the injection interval. A quantity of liquid (0.1 m^3/s) is injected through a borehole, or a group of boreholes, within a small area into an aquifer with a coefficient of permeability of 10^{-3} m/s, a thickness of 30 m, and a storage coefficient of 10^{-3}. The host formation is overlain, alternatively, with: (a) a completely impermeable unit of sufficient thickness and (b) a semi-confining unit with a thickness of 200 m and a coefficient of permeability of 10^{-8} m/s. From theoretical calculations using groundwater hydraulics equations, one can follow the pressure increase in the injection zone at distances of one km and ten km from the injection borehole. The pressure values are given in Fig. 3.3 as a function of time. With the completely impermeable confining unit, the pressure increases constantly (broken lines) and, at a distance of one km, it reaches 30 m of hydraulic head after 30 years. The storage of injected liquid takes place exclusively through the compression of injected liquid, groundwater, and rock. In the case of the semi-confining unit, however, the pressure increases only for one year and then it remains constant. Thereafter, the injected liquid pushes the aquifer groundwater consistently upward through the low permeability semi-confining units; this is shown in Fig. 3.3 by arrows.

This example shows, therefore, that with low permeability semi-confining units, the compression process changes slowly into a displacement process; the pressures remain constant in time at each point and the pressure differences between points provide for steady state flow of the aquifer fluids. The related speed of propagation of the injection front, which can be calculated from the pressure gradient and coefficients of permeability and storage, is disturbed by complicated processes which have not been accounted for in the calculations; these are principally dispersion, differences in density, chemical reactions, etc.

The compressibility of the confining units can positively affect the volume of the injected wastes in a closed hydraulic system. Rock compressibility values range from approximately $7x10^{-7}$ to $7x10^{-10}$ 1/bar for unconsolidated and consolidated rocks (Warner, 1975). From these values it is evident that very high injection pressures are needed if one expects to gain injection volume by compressing the subsurface materials. Excessive pressures can cause fracturing of the confining units and diminish the effects of a closed hydraulic system. Confining strata with elastic characteristics, such as argillaceous rocks, can tolerate higher pressures without fracturing than can the more non-elastic rocks, such as carbonates.

3.4.4. Hydraulic Calculations for Evaluation of Injection Parameters

The design of a deep-well disposal system requires reasonable estimates of technical, economic, and environmental factors; this includes evaluation of the optimum injection pressures, the anticipated injection volume, and the range of influence of the injection. Several hydraulic equations, even though based on simplifications of natural conditions, can be used for these calculations which will indicate if a chosen host formation will receive an economically sufficient volume of wastes at a safe pressure and in an environmentally acceptable manner. If the calculations indicate that a proposed site is not feasible, resources of time, effort, and money will be saved.

The basic calculation is a mathematical expression of the flow phenomenon. The dynamics of the fluid movement within the injection zone are described by the following (the density of the fluid is similar to that of groundwater):

. The law of fluid flow (Darcy's law)

$$Q = K\ A\ \text{grad}\ h$$

(Q = quantity of flow per unit time,
A = area perpendicular to flow,
K = coefficient of permeability,
h = hydraulic head)

and

The continuity equation

$$\text{div}\ Q = S_s \left(\frac{\delta h}{\delta t}\right)$$

(S_s = specific storativity, t = time).

The last equation signifies that when a specific quantity of liquid waste flows into a specific volume of the aquifer it causes a pressure increase and related hydraulic gradient modification, both of which depend upon the storage capacity of the injected portion of the aquifer. Both equations can be combined into a differential equation which can be solved analytically for simplified hydrogeologic conditions such as simple geometry, hydraulic homogeneity, and impermeable boundries; this is then used for estimating injection volume, injection rate, and injection pressure. The divergence of the calculated and real values will depend upon the accuracy of the evaluation of hydrogeologic parameters of the injection system (aquifer permeability and storage coefficients; parameter homogeneity; aquifer pressure, thickness, and extent; confining unit permeability, etc.) used in the equations. The real quality of the data for the region under study must be considered when making estimates based on these calculated values. Experience with on-line injection systems shows that injection rates may vary according to the hydrogeologic conditions from 1 to 200 m^3/h (see Table 3.1) with injection pressure values measured at the surface ranging from 0 to more than 100 bars (Table 3.2).

Many references provide pertinent equations for calculating injection effects in simplified hydrogeologic situations; these equations are the basis for the estimation of the range of influence of an injection including the prediction of the magnitude and variation of variables within this range of influence. Particularly useful are the works of Ferris et al. (1962), Matthews and Russell (1967), Lohman (1972) and Warner and Lehr (1977); these references are the source of the following equations.

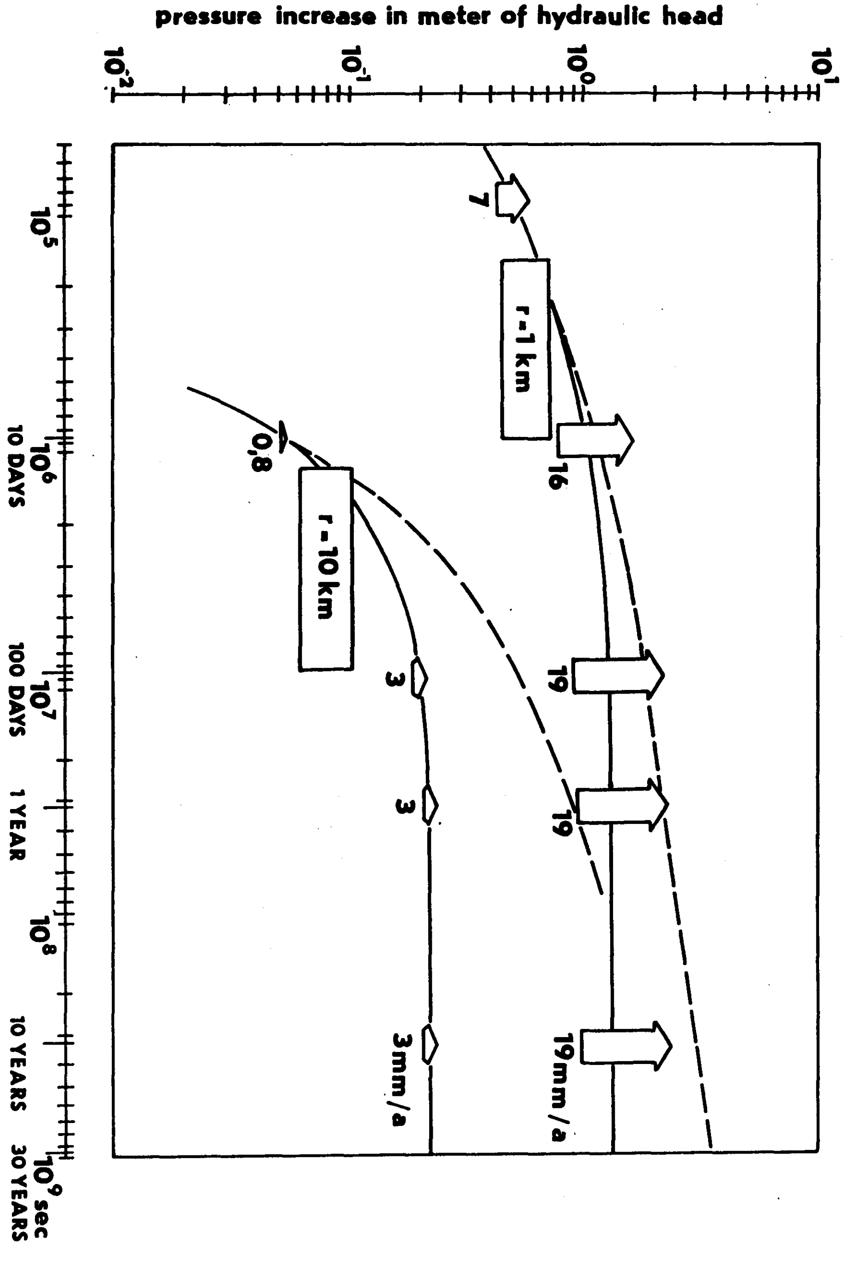


Fig. 3.3. Pressure development and penetration of pore-fluids into semi-confining units during injection (from Aust and Kreysing, 1985).

Table 3.1. 1973 average injection rates of injection wells in USA (from Conrad and others, 1975)

Injection Rate (m^3/h)	% of Wells
0 - 11	43
11 - 23	16
23 - 46	17
46 - 91	19
91 - 181	3
more than 181	2

Table 3.2. 1973 average injection pressure at the head of injection wells in USA (from Conrad and others, 1975)

Injection Pressure (bars)	% of Wells
less or equal to 0 (gravity wells)	21
0 - 10	19
10 - 20	21
20 - 40	17
40 - 100	21
over 100	1

One of the parameters to be evaluated is the distance of injected fluid transport by natural flow in an open hydraulic system. The velocity of propagation of the waste front must be calculated for this estimation; this involves a modification of the law of fluid flow (Darcy's law):

$$v = Q/A = K * (dh/dL)$$

(v = apparent velocity through entire area A
L = distance from the injection well)

To calculate average velocity of flow through pores (u), the value of effective porosity (n_e) must be included:

$$u = \frac{v}{n_e} = \frac{K}{n_e} * \frac{dh}{dL}$$

To estimate the minimum distance of the waste front from an injection well, the following equation can be used:

$$r = \mathrm{sqrt}\ (Q * t)/(\pi * b * n_e)$$

(r = radial distance of wastefront from injection well
Q * t = cumulative volume of injected waste
b = injected aquifer thickness)

The calculations above are simplified; the effects of dispersion, density, and chemical reactions are not considered and neither is the gradient of flow.

To compute the rate of pressure change in an injection interval of a closed or semi-closed system, Darcy's law must be combined with the continuity equation so that time and compressibility of the aquifer and its groundwater are taken into consideration. The appropriate partial differential equation and its derivation may be found in most modern texts on hydrogeology and petroleum reservoir engineering, along with numerous solutions. The solution first formulated and still widely used for predicting the pressure effects of an injection into an aquifer assumes the following conditions (Ferris et al, 1962; Kruseman and De Ridder, 1970; Lohman, 1972):

. The aquifer, for practical purposes, infinite in areal extent,

. The aquifer is homogeneous, isotropic, and of uniform thickness throughout the area of influence,

. Natural flow in the aquifer is negligible,

. The aquifer is sufficiently confined so that flow across confining beds is negligible,

. The well penetrates the entire aquifer thickness, and

. The well is small enough so that storage in it can be ignored and all water injected in the aquifer is taken in instantaneously, with change in hydraulic head.

The above is a formidable list of assumptions, which are obviously not completely met in any real situation. However, if one reviews the characteristics of many aquifers used for waste injection, it can be concluded, that for practical purposes, they probably comply sufficiently well with the assumptions. The equation that describes the response of such an aquifer to a single injection well is then:

$$\Delta h = \frac{Q}{4\pi T} * \left(-0.577216 - \log_e U + U - \ldots - \frac{U^2}{2.2!} + \frac{U^3}{3.3!} - \ldots\right)$$

where, $$U = \frac{r^2 S}{4Tt}$$

and,
Δh = hydraulic head change at radius r and time t
Q = injection rate
T = transmissivity
S = storage coefficient
t = time since injection began
r = radial distance from well to point of interest

One can easily enter the appropriate values into this equation. Tables with the series evaluated are available in the previously referenced publications on aquifer testing. A similar form of the equation above, as used in petroleum reservoir engineering, is given by Matthews and Russell (1967). For large values of time, small values of radius of investigation, or both, the equation can be reduced to:

$$\Delta h = \frac{2.30\ Q}{4\pi T} * \log \frac{2.25\ Tt}{r^2\ S}$$

Two very important characteristics of the equation presented above are that the individual solutions can be superimposed, and hydrologic boundries such as faults can be simulated by a properly located imaginary well, and the effects of multiple wells can be analyzed. These equations, and many other similar solutions that are available for different assumed conditions are used to generate potentiometric maps showing anticipated conditions at a selected future time.

Hydraulic equations used for the injection parameter evaluations can be solved analytically for simple hydrogeologic conditions. In settings that are less favorable for injection than are, for instance, the deep structurally undeformed sedimentary basins in the United States, one must deal with more complicated distributions of geometric and hydraulic parameters for the injection system; in those cases numerical methods with use of digital computers must be applied. Preliminary modeling for the predictive analysis may also be beneficial if analytical solutions prove to be inadequate. With the use of differential equations, numerical solutions of different approximations can be reached by mathematical modeling. For instance, questions of percolation through semiconfining formations, changes in aquifer behavior, effects of density differences and chemical reactions can be taken into account. It must be emphasized, nevertheless, that models can only solve problems that are clearly defined and that the available data from many regions are often insufficient to allow model development for satisfactory predictions. With increasing public awareness of surface disposal systems potential for accidents and the documented release of hazardous materials from many of these, safer deep disposal methods may be given priority, even in areas which are less favorable with regard to economic or technical factors. In such areas, in order to assure the main asset of deep-well disposal, i.e. its safety, a sophisticated and complete investigation based on a specifically designed borehole drilling and testing program must be undertaken to provide data for the evaluations described above and for predictive modeling.

CHAPTER 4

DRILLING, TESTING, AND COMPLETION OF A HAZARDOUS WASTE INJECTION WELL

Kenneth S. Johnson

4.1. Introduction

The primary concern in construction of a disposal well is permanent containment of the waste, in order to protect the biosphere and potential sources of useable water. To accomplish this, a well is drilled to the proposed injection zone, typically about 300-3,000 m deep. One or more strings of corrosion resistant casing or pipe are installed in the borehole. Corrosion-resistant cement is placed outside each string of casing to seal the casing into the hole and to provide extra protection for zones of potentially useable water. In most wells, another smaller-diameter pipe, called injection tubing, is installed inside the casing: it is sealed at the top with a wellhead and at the bottom with a packer. Waste is conveyed to the injection zone through this innermost tubing. The annular space between the tubing and casing is filled with noncorrosive fluid that is under higher pressure than the waste stream; thus a leak in the tubing can be detected by a pressure change, and the well can be shut down and repaired. Fig. 4.1 is a schematic diagram of a typical well designed for disposal of hazardous liquid wastes.

This chapter discusses the drilling of a borehole of the proper size and depth, and the development of a testing program that enables evaluation of rock and fluid characteristics of the injection zone and all overlying strata. It also addresses the methods of well stimulation that can increase the injection zone's permeability and receptivity to liquid waste. And finally, it describes completion techniques, such as the use of proper casing, tubing, cement, packers, and other materials, to ensure conveyance of the waste to the disposal zone. The discussion relies heavily upon data presented by Warner and Lehr (1981) and Moffett and others (1987). Other sources of information on injection-well construction are Geraghty and Miller and others (1982), Syed and others (1986), and UIPC (1987); recent books on conventional oil-well drilling and completion practices are by Bourgoyne and others (1986) and Moore (1986).

4.2. Drilling the Well

A well-planned program is needed for drilling a well to dispose of hazardous wastes. Equipment and procedures must ensure drilling a borehole of proper size and depth, and the casing and cement must assure protection of shallow, unpermitted zones against intrusion of wastes.

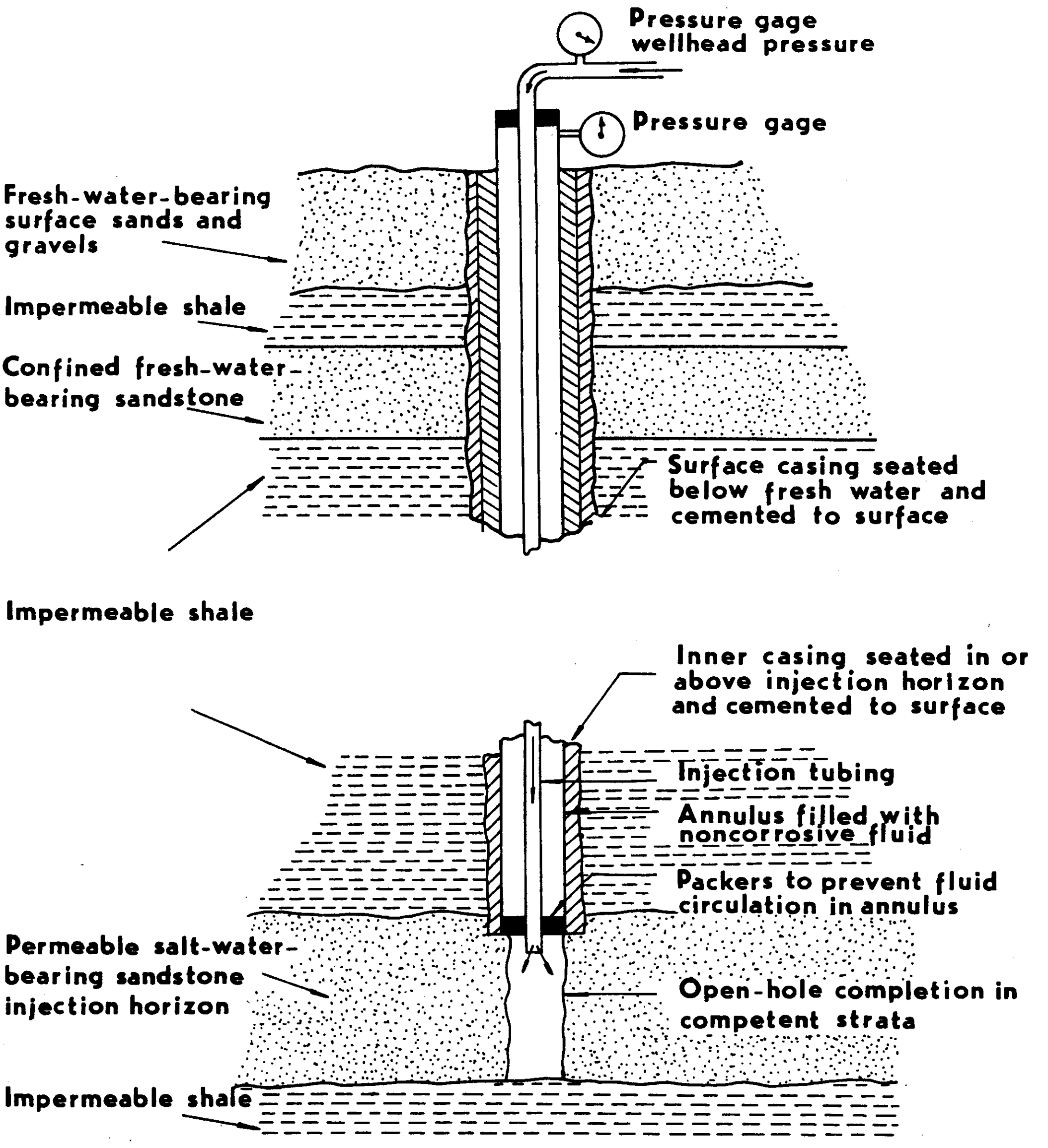


Fig. 4.1. Schematic diagram for a hazardous waste, deep-well disposal system (after Warner and Lehr, 1981, and Moffett and others, 1987).

4.2.1. Drilling Procedures

Selection of a particular drilling program is dependent upon the local geology and hydrology, the character of formations and fluids to be encountered, the depth of the well, the completion methods to be used, and the availability of equipment. The most common method of drilling injection wells is the rotary method, which is used extensively in drilling oil and gas wells (Fig. 4.2). In the rotary method, a rapidly rotating drill bit bores a hole downward through rock while drilling fluid or mud is circulated down the drill pipe to cool and lubricate the bit and to remove cuttings from the hole. Mud and cuttings flow out of the hole through the annulus between the wall of the borehole and the drill pipe; the cuttings are caught, studied, and retained as a record of rock formations drilled at the site. It is also possible to core the borehole and recover a continuous section (or core) of the material penetrated during drilling: it is especially desirable to core the proposed injection zone and confining layers to ensure complete characterization of these units. Fluids used in rotary-drilling operations can be plain water, "drilling mud" (water mixed with various additives), air or gas, or oil-base fluids: drilling mud is most commonly used.

Special drilling problems that can occur include deviation of the borehole from the vertical, loss of circulation of drilling mud, unintentional hole enlargement, sloughing of rock from the walls of the borehole, and sticking of the drill pipe in the borehole. These problems are discussed by Warner and Lehr (1981).

4.2.2. Casing

The wall of the borehole should be lined with a heavy steel pipe, called casing, for the following reasons: to prevent the hole from caving in, to prevent contamination of unpermitted zones, and to help control pressures in the borehole (Warner and Lehr, 1981). Several casing strings commonly used in injection wells are: surface casing to protect shallow ground water, one or more intermediate casing strings (depending upon well depth and geologic conditions), and, in some wells, an injection string to convey the waste to the injection zone. If injection tubing and a packer are to be used, most of the casing can be ordinary steel, except that the last few joints should be corrosion-resistant. If an injection string of casing is used, it must be corrosion-resistant throughout its length. Corrosion resistance can be realized by using carbon steel, stainless steel, fiberglass-reinforced epoxy, or specialized alloy metals.

When the borehole has reached a depth appropriate in casing installation, the borehole is conditioned by circulating mud, and then the casing is lowered into the hole. Casing cannot be properly cemented if it is not centered in the borehole, so casing centralizers are used. The annulus between the casing and borehole wall is then filled with cement, thus providing a barrier of steel and cement to protect fresh-water zones around the well and to protect the integrity of the well and its injection stream.

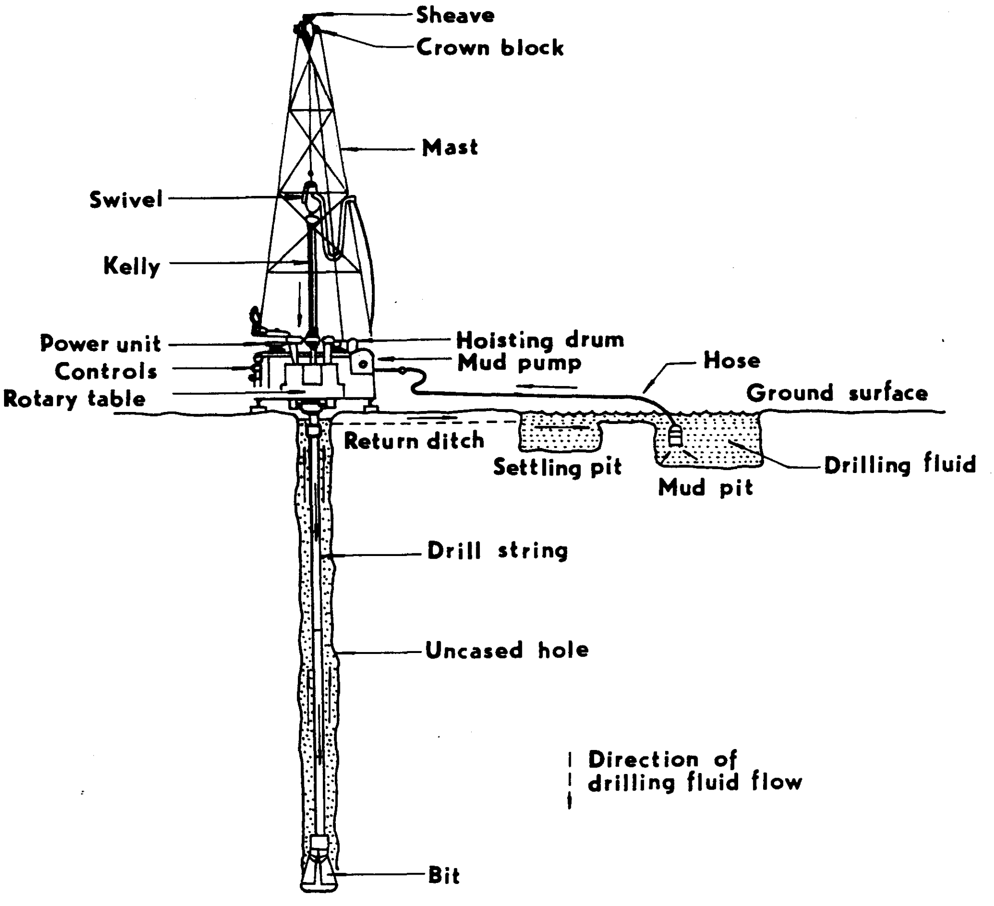


Fig. 4.2. Principal components of a rotary-drilling operation (after USEPA, 1985, and Moffett and others, 1987).

4.2.3. Cement

Cementing the casing in the borehole is a primary factor in assuring the integrity of the well. Cement holds the casing in place, prevents fluid movement between formations or from the surface to the subsurface, isolates zones of high pressure or lost circulation, and inhibits casing corrosion. A cement slurry is pumped down, usually inside the casing, and is forced up into the annulus between the casing and the borehole wall or the previously installed larger casing. The location and success of cement implacement behind casing must always be checked, typically by running temperature surveys, cement-bond logs, and radioactive-tracer surveys.

Selection of the proper cement depends upon the depth of the well, the physical/chemical characteristics of the waste, the formations penetrated, and the formation fluids. Chemical additives can change the cement's setting rate, density, strength, and corrosion resistance. Special epoxy-resin and plastic cements can be particularly resistant to chemicals and are recommended for cementing the bottom of injection casing, where injected wastes are in contact with the cement. Expanding cements are especially useful in disposal wells because of the especially tight seal they can form between the casing and borehole. More information is provided by Barlow (1972), Ostroot and Ramos (1972), and Smith (1976).

4.3. Formation Testing

The drilling program must include plans for a series of tests to be performed on the injection zone, as well as on overlying strata that are penetrated in the borehole. This characterization of the injection well includes collecting rock and fluid samples, running geophysical logs, performing injection tests, and determining waste compatibility.

4.3.1. Rock Samples

Samples of rocks penetrated during drilling are recovered either in the form of cuttings or cores. Cuttings are the small rock chips recovered from drilling fluids in a normal rotary-drilling process. They are routinely collected to represent intervals of 2, 3, or 5 m of drilling. Continuous cores provide the most accurate and reliable type of samples for determining rock characteristics. Coring generally is much more expensive and time-consuming: normally cores are taken only from the proposed injection zone and the confining intervals, although they might be obtained for the entire hole if there is uncertainty about the characteristics of overlying strata. With cores it is possible to perform more-precise laboratory analyses to determine porosity, permeability, fluid content, fractures, and waste compatibility. Sidewall cores can be taken from formations after they have been drilled, if it is later deemed necessary to obtain core samples from rock layers for which only cuttings are available. However, sidewall cores are less desirable than continuous cores, and in some cases attempts to collect them may fail. All cuttings and cores should be retained for future reference.

4.3.2. Fluid Samples

Samples of water and other in situ fluids can be selectively taken from various formations during or after drilling of the borehole. These fluids are recovered by drill-stem testing, swabbing, or air-lift methods. Drill-stem testing (DST), the most common method, involves temporarily completing the well and allowing formation fluids to flow into the cased borehole under natural conditions. Temporary completion of the well is accomplished by lowering an assembly of packers and valves on the drill stem to the depth of the formation to be tested, and then opening the valves to allow formation fluids to flow into the drill stem due to higher formation pressures. Such a test is used to collect fluid samples and to determine formation pressure, average effective permeability, borehole damage, and permeability barriers or changes. If the natural pressure on fluid in the tested formation is insufficient for a DST, the more time-consuming practice of swabbing is commonly required.

Swabbing is a method of recovering fluids, similar to pumping a well. Fluid is raised through the drill pipe, casing, or tubing by a swab on the upstroke, and by successive strokes the fluid is drawn out of the formation and eventually to the surface. Swabbing can be continued until all drilling mud is removed from the pipe, thus allowing a representative sample of formation fluid to be obtained. Swabbing can be used in conjunction with a DST to increase the volume of fluid recovered. Air-lift methods involve injection of air into the borehole under pressure, thus causing fluids in the well to rise to the surface.

4.3.3. Well Logging

A borehole log or well log is any tabular record or graphical portrayal of drilling conditions or subsurface conditions in a borehole. Well logs include sample logs, driller's logs, drilling-time logs, mud logs, and a wide assortment of geophysical logs. A sample log is prepared by a geologist from rock cuttings and cores, and usually is presented as a visual strip log or a columnar section. The driller's log is a daily record prepared by the driller or drilling foreman to document drilling operations, materials used, problems encountered and how they were resolved, and the basic progress of drilling activities. Drilling-time logs can assist in identifying formation boundaries and porous zones, even though the cuttings may not reach the surface for some time. Mud logs, which continually analyze for oil and gas in drilling fluid, can be used to identify these potential resources while drilling an injection well; mud logs help to avoid safety hazards that oil and gas may cause.

Geophysical logs are used to record the geophysical properties of penetrated formations and their contained fluids. A logging tool (probe or sonde) is lowered or raised in the hole on a wire cable while continuous measurements are made in the borehole and recorded at the surface. Measured geophysical properties include electrical resistivity and conductivity, sonic-wave velocity, natural radioactivity, density, hydrogen-ion content, temperature, and others. These properties are then interpreted in terms of lithology, porosity, fluid content, and chemistry. Other geophysical logs include a caliper log to measure borehole diameter, a dipmeter log to determine the inclination of rock layers in the borehole, a deviation log to measure deviation of the borehole from verticality, and a series of production-injection logs that can be especially useful in injection wells (Warner and Lehr, 1981). The combination of geophysical logs selected for use depends upon data requirements and the local geologic and hydrologic conditions.

4.3.4. Injection Testing

It is important to determine the performance characteristics of a proposed injection zone prior to completion of the well and startup of disposal activities. Injection tests can establish baseline data on the reservoir and on future well performance. Truck-mounted pumps are used to inject treated water into the injection zone. Commonly, injection begins at a fraction of the planned final flow rate and pressure, and then it is repeated at increasingly greater rates and pressures until the desired limits are reached. By recording pressures, time, and flow-rate data over a long enough period of time, it is possible to determine the formation transmissivity and storage coefficient (Warner and Lehr, 1981).

Injection tests can be valuable in evaluating potential problems that may arise during the lifetime of the injection operations. The tests also can be used to evaluate the proposed flow system and monitoring equipment, to estimate pressure buildup that might occur in time, and to determine electrical-power requirements. Injection tests also can be performed on the confining layers or zones by isolating them with packers, and thus the impermeability of these units can be further evaluated.

4.3.5. Waste Compatibility

Incompatibility of the waste stream with the solids and fluids in the injection zone can adversely affect the efficiency of the operation or can even cause failure of the system. Wastes that can be injected into a proposed reservoir without forming precipitates, plugging the reservoir, or otherwise adversely affecting the injection zone, are termed compatible; incompatible wastes may be made compatible by pretreatment. Physical, chemical, and biological characteristics of the waste that can affect compatibility are given in Table 4.1 and in details described in Chapter 5.

The volume of liquid wastes to be injected must not exceed the available reservoir space; otherwise, excessive pressures may be needed, and this may affect the integrity of confining layers. High-density waste water will tend to sink within the reservoir, whereas lighter waste water will tend to rise; thus, the density affects the migration path and mixing of waste water in the formation fluids. Viscosity (resistance to flow), which affects the mobility of waste water, varies with the temperature and the amount of suspended solids, and when the viscosity is high it is necessary to increase injection pressures. Temperature variations also may affect corrosion rates and some chemical reactions between wastes and the injection zone.

The potential for plugging an injection zone by suspended solids in the waste stream is inversely related to the size of pores in the reservoir. Suspended solids, such as mineral grains, metal particles, fibers, or plastics, can be removed from the waste by pretreatment. Gas bubbles in waste water can plug

Table 4.1. Waste characteristics to be considered in evaluating compatibility with the injection zone (modified from Warner and Lehr, 1981)

A. Volume

B. Physical Characteristics

1. Density
2. Viscosity
3. Temperature
4. Suspended-solids content
5. Gas content

C. Chemical Characteristics

1. Dissolved constituents
2. pH
3. Chemical stability
4. Reactivity
    a. with system components
    b. with formation waters
    c. with formation minerals

D. Biological Characteristics

---

the pores of the reservoir, and dissolved gases, such as oxygen, hydrogen sulfide, or carbon dioxide, may promote corrosion of equipment and may react with other chemicals to produce plugging precipitates; therefore, degasification of the waste may reduce corrosion or chemical precipitates.

Comparison of dissolved constituents in waste water with the analysis of formation water may indicate the potential for adverse reactions between the two waters. Precipitates that form due to such reactions may reduce the porosity and permeability of the injection zone: calcium, barium, strontium, and magnesium can be precipitated as carbonates, sulfates, orthophosphates, fluorides, and hydroxides; metals such as iron, aluminum, cadmium, zinc, manganese, and chromium can be precipitated as carbonates, bicarbonates, hydroxides, orthophosphates, and sulfides.

The potential corrosiveness of a waste stream to the mechanical system, the reservoir, and confining layers is indicated by the pH (acidity) of the waste water. Wastes with low pH (high acidity) have been the principal cause of injection-system problems and failure due to corrosion. Acidic liquids also can increase porosity and permeability by dissolving the reservoir and confining-bed materials, and may even cause partial collapse of the reservoir and failure of the injection system after extensive uncontrolled dissolution of soluble limestone or dolomite layers. Chemical stability of injected compounds is desirable, inasmuch as unstable compounds may precipitate during or after injection and may cause plugging.

Wastes can react adversely with the mechanical-system components, with the formation waters, and with the formation minerals. Knowledge of the chemistry of the waste stream and each of these other systems enables prediction of some potential reactions. Mechanical systems can be corroded or clogged by chemical, electrochemical, or microbiological reactions. Formation waters may interact with wastes and cause precipitates to reduce porosity and permeability. Reaction of wastes with minerals, for example, carbonates and some clays, can cause increases in porosity (dissolution of carbonates) or marked decreases in porosity (swelling clays that plug reservoir pores).

Bacteria and other microorganisms in waste water may cause corrosion or plugging of the injection system and reservoir rocks. The growth of bacteria or the precipitation of iron by bacteria can cause plugging, and sulfate-reducing bacteria can cause corrosion of mechanical parts and subsequent plugging of pores by corrosion by-products. The mere presence of bacteria does not mean that they will cause problems; it is their potential ability to flourish and multiply in the injection system that may cause major problems.

4.4. Completion Methods

After the well has been drilled and the various formation tests have been carried out, it is necessary to "complete" the well by making it ready for service. Completion practices may include stimulation of the injection zone, determination of the bottom-hole configuration, placement of injection tubing and packers, and preparation of a completion report. Although completion methods are discussed here at the end of this chapter, major decisions concerning well completion must be made before drilling even begins, in order to plan borehole size and the casing program that will accommodate the chosen completion methods.

4.4.1. Well Stimulation

Wells are "stimulated" to increase permeability of the injection zone in the vicinity of the well. Stimulation methods can be chemical or mechanical, and consist mainly of acidizing and hydraulic fracturing. Well stimulation can be used initially when the well is constructed, or later to alleviate plugging problems. Acidizing involves injecting acid into the potential reservoir to dissolve acid-soluble minerals and thus increase the porosity and permeability. Limestone, dolomite, or calcareous-sandstone reservoirs normally are treated with several hundred to several thousand liters of 15-percent hydrochloric acid that is pumped under pressure into the well. Hydrofluoric acid is commonly added to hydrochloric acid to form a mud acid that reacts also with silicate minerals.

Hydraulic fracturing is the injection of a fluid into the reservoir under sufficient pressure to open existing fractures and even create new ones. Care must be taken to prevent fractures from extending into or across the confining zone. Once the fractures are opened, they are kept open by propping agents, such as silica sand, injected with the fluid: the propping agents remain wedged in the fractures when the hydraulic pressure is reduced.

4.4.2. Bottom-Hole Configuration

Several bottom-hole configurations are commonly used for injection wells: open-hole completion in well-consolidated formations; screened, or screened and gravel-packed completion, used in poorly consolidated formations; and fully cased and cemented completion with perforated casing, used in well-consolidated or poorly consolidated formations. Barlow (1972) provides illustrations of the various completion methods (Figs. 4.3 to 4.5). The following discussion is mainly from Moffett and others (1987).

In open-hole completion (Fig. 4.3) the bottom of the casing is set just above the injection zone. There are several advantages to open-hole construction: the entire injection zone is exposed to the borehole; there is no screen and little casing subject to corrosion or deterioration; the method is less expensive; the borehole can be deepened easily; and the well can be converted easily to a liner or perforated completion. Open-hole wells often have a larger capacity than wells with other types of bottom-hole configurations (Barlow, 1972). They are especially effective in well-consolidated or indurated formations, such as limestone or sandstone.

Screened completion (Fig. 4.4) is commonly used in poorly consolidated formations, such as partly cemented or uncemented sands, to prevent collapse of formations into the borehole. Stainless steel, bronze, galvanized steel, or plastic screens can be used. The advantage of screened construction, in addition to supporting the formations, is that injection can occur only in those zones with screen. Packing the bottom part of the hole around the screen with gravel provides some control on the permeability and injection characteristics of the reservoir unit in the immediate vicinity of the borehole.

Perforated-casing completion (Fig. 4.5) may be utilized in both poorly consolidated and consolidated formations. In this method, the casing is fully installed and cemented prior to perforation. Perforation is accomplished by shooting small solid projectiles through the casing and cement, or by using small, shaped explosive charges. The perforations usually are about 1 cm in diameter and will penetrate 5-10 cm of rock. The major advantages of this method are the ability to inject waste into more than one zone in a well, control of collapse of poorly consolidated strata, and support of the formation walls. The main disadvantage is that since the entire well must be drilled prior to casing, the cement and other borehole fluids may damage the formations in the injection zone(s), thus impairing the permeability and porosity of the injection zone.

4.4.3. Tubing

Most disposal systems are constructed with injection tubing set inside the long casing string, and with a packer set near the bottom to keep waste from circulating up the annular space between tubing and casing (Fig. 4.1); the waste stream is then injected down this inside tubing. Tubing size is usually determined by the rate of wastewater injection, with larger tubing requiring less energy for injection. Tubing materials normally used include steel or stainless steel, fiberglass, and fibercast. The selection of an appropriate material depends on the type of waste to be injected. Metal tubing is harder and more resistant to collapse or bursting. Fiberglass tubing is resistant to corrosion but is subject to collapse if annulus pressures become too great. Special types of tubing include metal tubing coated with plastic and bimetallic tubing.

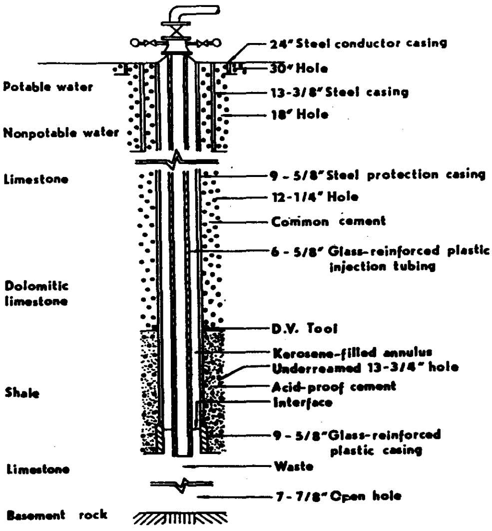
4.4.4. Packers

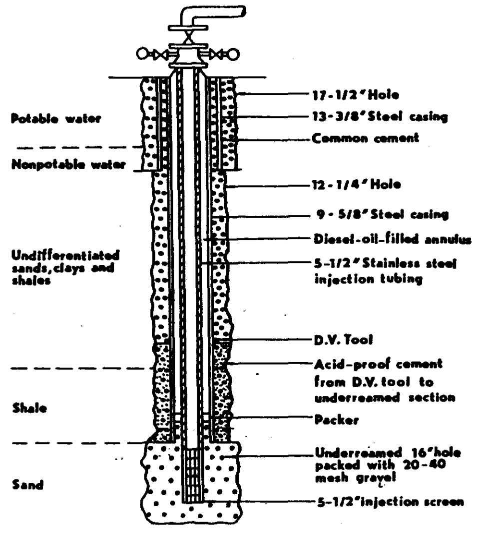
Packers are placed between the injection tubing and the well casing to seal off, or "pack off," certain intervals in the disposal well (Fig. 4.1). Packers commonly utilize expandable seals that can be expanded mechanically or hydraulically. The packer "anchors" the injection tubing and commonly is located at the top of or in the injection zone near the bottom of the long string of casing. Packers can be used to separate multiple injection zones, to protect casing from formation pressures and fluids, to isolate specific injection zones, and to insure subsurface safety. A packer also allows the pressure in the well annulus to be monitored. The chosen packer must withstand the pressures, temperature changes, tubing movement (for example, expansion due to temperature changes), and waste corrosion of the injection system. Packers are either removable or permanent; the permanent ones normally are nonretrievable, but they will withstand high pressure differentials.

Once a packer has been seated, pressure testing should be performed to assure that it is seated properly. This testing is usually performed by pressurizing the annulus and noting whether the pressure declines within a specified time. Such pressure tests are part of the "mechanical-integrity" test for injection wells.

4.4.5. Completion Report

Preparation of a well-completion report is an important final step. The report should describe in detail all aspects of the drilling, testing, and completion methods used in constructing the injection well, and should discuss all geologic and hydrologic observations made. Such a report normally is required by agencies that regulate waste-disposal operations, and furthermore it is necessary for interpreting the cause of any operational problems that may arise in the future.





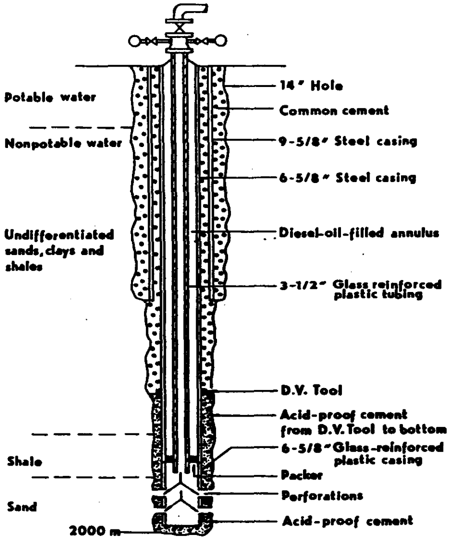


Fig. 4.3. Schematic diagram showing open-hole completion of an injection well (after Barlow, 1972, and Moffett and others, 1987).

Fig. 4.4. Schematic diagram showing screened and gravel-packed completion of an injection well (after Barlow, 1972, and Moffett and others, 1987).

Fig. 4.5. Schematic diagram showing perforated-casing completion of an injection well (after Barlow, 1972, and Moffett and others, 1987).

CHAPTER 5

PHYSICAL AND BIOCHEMICAL COMPATIBILITY OF WASTE TO HOST FORMATION

Jaroslav Vrba
and
Eilon Adar

5.1. Introduction

The physical effects pressure, density, and transport (spreading of injection and chemical compatibility between the injected wastes and the strata and native fluids must be evaluated for design of an injection system. The injection pressure should not exceed a certain level so that hydraulic fracturing of the confining strata will not occur to preserve the integrity of the confining layer. The liquid waste must not react with the host rock or native fluids: 1) to form precipitates or gases that can reduce permeability or generate blowouts; and 2) to increase the permeability of the confining layers. Conversely, the beneficial aspects of physical effects and chemical interactions must also be considered. The discussion of these aspects of siting and operating a deep injection well are described in Chapter 4. In the following text some chapters and paragraphs are from Aust and Kreysing (1985).

Possible aquifer reactions during actual injection procedures form a source of danger for the injection project itself and occasionally even the danger of compromising the useable mineral and groundwater resources. On the other hand, physical, chemical and biochemical reactions in the aquifer can accelerate the decomposition or conversion of pollutants (without the appearance of adverse damage resulting from injection). It is for safety reasons indispensable and for cost reasons recommendable that testing of possible aquifer reactions be carried out before each injection operation is begun.

The following sections offer a description of basic knowledge and data gained in the laboratory, attention to which has proven justified in injection practice and various isolated incidents and experience gained from injection projects.

5.2. Physical Effects

The principal physical reactions are pressure and density. Pressure is to be understood here in its broadest sense, ranging from the injection pressure to be used during injection and the original fluid and rock pressure in the aquifer. Also the tectonic pressure or stress which should be estimated according- to strength, but which can also partly be obtained through measurements. If no attention has been paid to the physical component "pressure" this can lead to failure in an injection project such as hydraulic fracturing in a confining unit or blowouts.

The physical parameter "density" is also partly responsible for the success of an injection operation. When the proper geological structure is chosen, and a favorable relationship exists between the density of the formation water and that of the waste liquid, these wastes can be introduced into the aquifer, such that their escape under natural conditions can practically be excluded for secular periods of time.

5.2.1. Effects of Pressure

The injection of liquid wastes into deep aquifer reservoirs cannot, as a rule, be accomplished without pressure. The pressure which is to be applied must, nevertheless, be higher than the natural fluids pressure. From the bottom of the borehole the pressure decreases almost proportionally with the radial distance from the borehole. The level of the necessary excess pressure and the range of its influence are dependent on the aquifer parameters, the type of native fluids, and on the required discharge of waste injection.

For injection procedures with liquid wastes, knowledge of the fluid pressure in the injection unit with overlying confining units is of primary importance. This is the pressure under which the pore contents actually stand. It must not correspond to the hydrostatic pressure. Its determination can be done directly in the borehole at the depth of the injection unit by means of a drill-stem test.

Pressure increases with an increase of dissolved salts. Warner (1975) quotes the example of a solution with 65,000 ppm components and a density of 1.05. The pressure increase here amounts to 0.102 bar/m. This means that at the bottom of a 1,000 m deep well, there would be a pressure of 102 bar, as long as one proceeds from a static water level in the borehole.

The pressure changes in the aquifer caused by injection are to be determined by knowledge of the potentiometric surface. This gives a rough area overview of the range of influence. Since the probable dispersion of the waste liquids can be calculated, the corresponding potentiometric-surface maps can be drafted. They are to be checked and modified as the project proceeds using test data from monitor wells (see Chapter 6). A further question of great importance is, which maximum injection pressure is admissible?

For obtaining reasonable injection discharge, 50-80 percent of the hydrostatic or bottom-hole pressure can be used as an empirical value for the excess pressure applied in injections. In Texas approximately 0.1 atm/m is allowed not only for the reintroduction of formation water, but also for the injection of liquid wastes. Density values must be known. According to Mayerhofer (1977), a pressure factor of 1.2 compared to the prevailing hydrostatic pressure (plus fluid pressure) may not be exceeded during the injection of waste liquids. Sufficient distance from the threshold of hydraulic fracturing, which generally lies at 1.9, is therefore taken into consideration. Ellison (1976) points out that pressures up to 136 atm (137 bar) have recently been used in deep-well injections. The flow behavior produced by this, however, can no longer be compared with the conditions in aquifers which are normally influenced by pressure. For numerous experts, therefore, accurate observation and recording of pressure appear to be more important than following the subsurface waste front.

For determination of total pressure when injecting liquid wastes, pump pressure must be added to hydrostatic pressure. Abnormal pressure conditions may depend on the following:

- Compacting of sediments
- Tectonic factors
- Osmotic effects
- Intense withdrawals or injections of liquids

The first three causes plus strong injections may cause abnormally high pressure. Extremely low pressure may be created by osmotic effects and intense draw-offs.

Healy (1976) points out that the determination of the original fluid pressure is absolutely necessary, not only for technical reasons, but also because of possible seismic influences.

5.2.2. Stress and Hydraulic Fracturing

The increase of pressure in the injected formation leads to developing of stress and hence, to deformation of the host rock. A continuous injection of fluid under high pressure may finally end with reverse hydraulic fracturing in the confining layer which could lead to the closing down of the injection site.

The determination of actual stress conditions in the rock, i.e. particularly at the injection level, should form one of the necessary bases for the injection projects.

The zones near the earth's surface, one from a total of three existing stresses or (tectonic) principal stress alignments, runs practically perpendicular to the earth's surface in areas of balanced topography. The two other alignments are, in general, at right angles to each other and horizontal to the surface.

Deeper zones (ca. 700-1,000 m), if they are in a tectonic unstressed state, are usually characterized by the vertical alignment of the largest principal pressure component. This is usually identical with the overburden pressure. Reeder et al. (1977) give data for this:

The increase in the overburden pressure varies between 0.158-1.24 atm./m (0.16-1.26 bar/m) at a depth of 600 m, and between 0.128-0.197 atm./m (0.13 to 0.2 bar/m) at a depth of approximately 2,400 m (data from different regions). The extreme values determined in boreholes amount to 0.08-0.34 bar/m.

These figures are almost representative of the injection pressures which are to be applied in injection projects. The average indicated reduction of the quotients with greater depth may be considered an indication that tectonic pressure components and/or pore-water pressures (fluid pressure) are increasing to the debit of the overburden pressure.

Hydraulic fracturing, also called artificial fracturing is a process which occurs during the injection of liquids under pressure. Hydraulic fracturing in the host formation can lead to a short- or long-term increase in permeability in underground rock. Hydraulic fracturing may be deliberately accomplished to increase formation receptivity or apparent permeability. It may occur during injection testing or wastewater injection if the fracture initiation pressure is exceeded.

This method was first used by the petroleum industry as a measure to improve oil extraction in oil fields. It is also practiced in waste-injection technology to raise the storage volume of an injection unit. Simultaneously, the limits of this method can be recognized by exceeding the critical fracture pressure during injection, the interfaces in the rock can widen into fractures, joints, and cracks which can continue on into the biocycle even through the confining units.

As long as the process of hydraulic fracturing is limited to horizontal interfaces, there are basically no problems with safety if attention is paid to certain requirements. According to Reeder et al. (1977), this concerns zones which lie deeper than 300 m.

As a rule, hydraulic fracturing at greater depths leads to the tearing apart of planar structures. Wolff et al. (1975) state that this happens when the bottom-hole pressure is roughly two-thirds that of the overburden pressure. The fracture elements created continue vertically as long as the injection pressure exceeds the sum of the lowest horizontal main pressure and an existing tensile strength. If the overburden pressure represents the lowest main pressure component, the horizontal interface system will open.

The magnitude of the hydraulic fracturing in relation to the injection pressure can be determined by the injection of tracers.

In the USA, the fracturing of horizontal interfaces was tested on shale: in Oak Ridge, Tennessee, and West Valley, New York, mixtures of radioactive liquid with cement were deposited into opening cracks (de Laguna et al. 1968; Sun, 1973; Sun and Mongan, 1974). The advantage of this method is that the mixtures bond very quickly after injection and remain fixed in place in the storage bed. Sun (1976) proved the success of his tests by the subsequent taking of core samples, by determination of the gamma radiation in the borehole, and by high-precision levelling of the land surface.

Regulatory policy may or may not allow short-term hydraulic fracturing operations for well stimulation, but continuous injection at pressures above the fracture point are prohibited by most, if not all agencies. This is because of danger of damage to well facilities and because of the uncertainty about where the fractures and injected fluids are going if fractures continue to be extended. In order to produce and propagate a hydraulic fracture that will achieve increased well receptivity, large amounts of pump power, effective fluid loss control additives, and propping agents such as sand, are desirable. Fractures may not propagate in normally permeable rocks unless the fracture surfaces are continually sealed by the injected fluid. In practice a fluid loss control agent that later breaks down and becomes inoperative is employed to assist fracture propagation.

In estimating the fluid pressure at which hydraulic fracturing will occur, one of two conditions is usually assumed:

- That the least principal stress is less than the vertical lithostatic stress caused by the rock column. In this case fractures are assumed to be vertical.

- That the vertical lithostatic stress is the least principal stress. In this case fractures will be horizontal.

In the first case, the minimum bottom-hole pressure required to initiate a hydraulic fracture can be estimated from (Hubbert & Willis, 1972):

$$P_i = (S_z + 2\ P_o)/3$$

where

Pi = fracture initiation pressure
S_z = total lithostatic stress
P_o = formation fluid pressure

The hydraulic fracturing gradient, that is, the injection pressure required per meter of depth to initiate hydraulic fractures, can be estimated by entering representative unit values into the equation. The unit values for S_z and P_o are, respectively, 0.0207 and 0.0096 atm/m. This yields a Pi gradient of 0.0133 atm/m as a minimum value for imitation of hydraulic fractures. This situation implies a minimum lateral earth stress. As the lateral stresses increase, the bottom-hole fracture initiation pressure also increases up to a limiting value of 1.0-0.0207 atm/m. Actually, fracture pressures may exceed 0.0207 Atm/m when the rocks have significant tensile strength and no inherent fractures that pass through the well bore.

In any particular case, injection tests can be run on the well to determine what the actual fracture pressure is. Operating injection pressures are then held below the instantaneous shut-in pressures measured immediately following injection of fracture pressures. In the absence of any specific data, arbitrary limitations of from 0.0104 to 0.0207 atm/m of depth have been imposed on operating injection wells. Regional experience should be used as a criterion in establishing an arbitrary limit, since regional tectonic conditions and fluid pressure gradients dictate what a safe limit will be.

A series of field experiments were performed in the Piceance Basin of northwest Colorado to test the validity of the concepts discussed above and to determine the state of rock stress in that area (Wolff, et al., 1975; Bredehoeft, et al., 1976). The conclusions reached were consistent with theory.

5.2.3. Porosity and Permeability

Porosity and permeability controls the capability of the host formation to transmit the injected fluid. Hence, it affects the rate of discharge into the injected well.

Permeability, which substantially affects the rate of spreading of injected liquid wastes, is usually much lower in vertical than in horizontal direction. The permeability in unconsolidated materials depends on pore diameter and possible pore filling by clay, silt, lime, limonite and quartz. In consolidated materials, permeability due to fractures predominates over the permeability due to pores. Continuity and frequency of fractures greatly control fracture permeability. The secondary permeability and porosity of karst in limestone and dolomite can provide great areas for storage of wastes compared to porous reservoirs. Liquid wastes can be injected either without pressure or under only limited pressure (often open hydraulic system). Because of the uneven flow paths in karst, monitoring the spread of injected liquids is more difficult than in porous reservoirs (Aust and Kreysing, 1985).

The specific permeability, K, should be as high as possible for the rock of the receiving unit ($>10^{-5}$ m/s) and as low as possible for the overlying confining unit ($<10^{-8}$ m/s). In simple problems, the specific permeability is included in the transmissivity, which is the product of the horizontal permeability and the thickness of an aquifer. Permeability is based on the flowing water in the rock pore space and is, therefore, determined by rock properties, as well as by the dynamic viscosity of the fluid medium. Viscosity decreases with the temperature so that an increased rock temperature and, therefore, higher permeability favors the steady transport of the substances. Permeability of $K = 10^{-5}$ m/s at normal temperature corresponds to $k = 1$ Darcy, a value which is determined only by pore structure, not by the properties of the flowing medium.

Porosity and permeability of a potential reservoir can be estimated in a number of ways. Porosity and permeability values can be obtained from prior studies of the rock unit in question by field survey and laboratory measurements of newly collected samples of the reservoir. State, private geology or petroleum-related agencies commonly maintain libraries of cuttings and cores. Porosity can be estimated by studying such cores and cuttings with a petrographic microscope.

Sonic, density and neutron geophysical logs can be used to estimate porosity. Permeability may also be determined by analyses of drill-stem or injectivity tests. The availability of drill-stem or injectivity tests, however, is highly variable. Much reliance must be placed on evaluation of cuttings, cores, and borehole geophysical logs in the area near the potential site.

The permeability of a zone is in part dependent on the chemistry of the permeating fluid. Variations in permeability because of fluid chemistry are a reflection of the fluid's viscosity and its chemical interaction with the formation (Warner and Lehr, 1977). These factors must be considered when estimating the effects of injection on the reservoir.

Information can also be gathered from many sources and correlated with others for interpretations of trends in porosity and permeabilities in the area. Such trends are established more easily for noncarbonate rocks since carbonate rocks (for example, limestones and dolomites) have secondary porosity, which can be highly variable. If no attention has been paid to the physical parameter "PRESSURE," this can lead to failure of the injection project such as hydraulic fracturing in the confining layers and a blowout near the injection well.

5.2.4. Storativity and Compressibility

The specific coefficient of storage, S_s, indicates the ability of the rock to accept water. In completely water-saturated rocks, into which an additional amount of water can be introduced only by an increase in pore water pressure, the coefficient of storage lies between 10^{-4} and 10^{-7} 1/m. The specific coefficient of storage is dependent on the compressibility of the pore filling and on the rock matrix. In many simple problems, the specific coefficient of storage, S_s, is included in the non-dimensional coefficient of storage, S, which is the product of the specific storage coefficient and the thickness of a water-saturated rock sequence, which is covered by a nearly impermeable layer. In water-table aquifers, S is basically identical with the effective porosity, P, which lies between the values of 10^{-2} and $3*10^{-1}$. The compressibility of an aquifer encompasses not only the rock itself but also the contained liquids.

Rock compressibility with values between ca. $7*10^{-10}$ up to $7*10^{-7}$ 1/bar, shows a relatively larger range of variation, whereby the first value is the standard quality for consolidated, the second for unconsolidated rock (Warner, 1975). The figures emphasize the small compressibility margin for the injection of liquid wastes in consolidated rock. Compressibility and the coefficient of storage are combined with each other as a function of the aquifer thickness:

S' (compressibility)

S (coefficient of storage)

$S' = 7 * 10^{-7}$ 1/bar $= 7 * 10^{-8}$ 1/m

Following this, a 100 m thick aquifer with this compressibility has a storage coefficient of:

$S = S' * 100 \text{ m} = 7 * 10^{-6}$

Not only rock compressibility, but also water compressibility must be considered if a confined groundwater reservoir has to take up liquid water as the contained formation water cannot be displaced but must be compressed. One must, therefore, be careful that the aquifer and its overburdens are not fractured by applying too high pressure.

Rottgardt et al. (1976) claim that water compressibility will be approximately $5*10^{-5}$ bar^{-1} depending on the concentration of dissolved salts, on temperature and on storage. If, for example, 50 m^3, the pressure will increase approximately 1 bar.

In addition to the pressure, temperature also influences water compressibility. In this case, the water compressibility will decrease within the range of approximately 20°C to 50° and will further increase with steadily rising temperatures. Simultaneously, a pressure increase will lower the compressibility in all temperature ranges.

5.2.5. Isotropy and Homogeneity

If the physical property of the aquifer such as hydraulic conductivity, transmissivity and porosity are independent of the direction of measurement at a point in the host formation, the formation is isotropic at that point. In a case where it varies with the direction, the formation is anisotropic at that point. Similarly, if that physical property (i.e. hydraulic conductivity) is independent of the position within the geologic formation, the aquifer is homogeneous. When it depends on the spatial position, the aquifer is heterogeneous (Freeze and Cherry, 1979).

Both heterogeneity and anisotropy affect the spatial and time distribution of injected fluid in the host formation. The extent of homogeneity will control the change in the rate of waste discharge with time. Change in spatial porosity for example, will affect the spatial flow velocity and hence, also the propagation rate of the injected waste. On the other hand, the anistropy of the porous media will control the preferential flow direction of the fluid in the aquifer. Therefore, isotropy or anistropy essentially induce the magnitude of lateral versus longitudinal distribution of the contaminated plume.

Isotropy and homogeneity are essential properties of the host formation that should be embedded in flow and/or mass transport equations to be used for the quantitative assessment of the aquifer. Any attempt to predict the spatial flow velocity or the direction and the propagation rate of the contaminated front must consider the magnitude of anisotropy and the extent of homogeneity. Otherwise, the expected flow system under waste injection will not fit the real conditions.

5.2.6. Temperature

The influence of the aquifer temperature and the fluids temperature is of great importance to the subsurface behavior of the injected material, specifically:

- Chemical aspects (acceleration of reactions with increasing temperature)
- Physical aspects (e.g. decrease in viscosity with higher temperatures and therefore greater mobility of liquids).

The preparation of regional isothermal maps in geothermal increments of °C/100m is recommended where there is sufficient data material so that areas with greater temperature gradients, which accelerate chemical reactions in an undesired fashion, can, if necessary, be eliminated from the injection project.

5.2.7. Viscosity

In porous rock, the dynamic viscosity (units: centipoise, cp = g/s * cm) of the water as well as that of the liquid wastes, influences the flow of velocity.

Temperature of the fraction of dissolved material influence the viscosity in inverse proportions.

- Increasing temperature = decreasing viscosity, and increasing flow velocity
- Increasing salt content in the liquid = increasing viscosity and decreasing flow velocity.

In a temperature range between 20° C and 60° C, the viscosity will already be reduced by half, whereas the salt content remains constant.

Pressure has only an insignificant effect on the viscosity.

Viscosity influences the diffusion of the liquid wastes when the injection is carried out in greater depths (1,000 m) at higher temperatures. A certain compensation for the anticipated more rapid spreading is obtained here by the higher salt content from the formation water and/or injected waste.

5.2.8. Density

Before liquid wastes can be injected underground, one must collect basic data, details about the density of the natural liquid reservoir contents and about the liquid wastes which are to be injected.

The density ($g * cm^{-3}$) of liquids increases proportionally to the pressure and falls with increasing temperatures. Changes of this type, however, have little effect on fresh water. The case is different if the dissolved materials increase greatly. Pirson (1963) uses NaCl as an example:

Density = ca. 1.0 $g * cm^{-3}$, fresh water (100 mg/l) at 15°C

Density = 1.1 $g * cm^{-3}$, with ca. 165,000 mg/l dissolved materials at 15°C

The problem of the density of the liquid wastes in relation to the native fluids is very important for the diffusion of the waste liquid in the injection unit. The density of the waste liquid can hereby be higher than, equal to, or lower than that of the native fluid.

The theoretically simplest case is the one in which the density of the native water and the waste liquid are equal, so that by eliminating other effects (dispersion, intermixing), an homogeneous, cylindrical displacement of the native fluid is possible (a horizontal aquifer is assumed). In this same aquifer, the waste liquid would spread out in the bottom of the aquifer if the waste has a higher specific gravity than the native water. The consequence of having a specific gravity lower than that of the formation water is that the waste will migrate along the roof of the aquifer. In both cases, after a certain injection period and with equal injection rates, a certain maximum will have developed on the roof or bottom and the diffusion of the waste liquid proceeds, owing to the specific gravity, only on the aquifer roof or bottom. The diffusion of the waste accelerates quickly in inclined aquifers, in the case of which heavy waste liquids sink to the bottom, lighter wastes extend upwards on top of the native waters.

5.2.9. Hydrodynamic Dispersion

By dispersion is understood the process by which a liquid penetrates another liquid, on the condition that both are miscible. The mixing of the liquids is, thereby, a result of the different flow rates of the individual fluid particles based on a specific path length in porous rock. Things which affect this are different forms, cross-section, sizes, and branchings of the flow paths.

It is important for the estimation of the flow processes underground, and therewith the diffusion of liquid wastes, to recognize that the coefficient of dispersion is inversly proportional to temperature, porosity, and grain form; whereas an increase in grain size, grain roundness and the degree of irregularity promote dispersion.

5.3. Chemical and Biological Effects

The chemical and biological compatibility between the injected waste and the host-rock formation, including native fluids, should be considered and assessed as it influences significantly the design of an injection system. The course of chemical reactions is also strongly affected by physical factors. Special attention should be devoted to biochemical processes. An inadequate insight into the chemical and biological processes and the waste-rock-native fluid system may lead to a loss of control over these processes and their products, and subsequently to a reduction of the permeability, and thus also a drop in the deposition capacity, of the receiving injected unit. Treatment of liquid waste to reduce or remove the hazardous constituents is therefore strongly recommended.

5.3.1. Chemical Reactions

Aust and Kreysing (1985) mention the following principal causes of natural changes in the chemistry of native formation water: compaction, reactions between minerals in the rock, organic substances and pore solutions, filtration due to electrically charged clay membranes, sorption and exchange of bases and biochemical reactions.

The same authors point out the following reactions between wastes and the native rock-fluid material in relation to temperature, pH and the redox potential:

A. Decomposition of the rock, particularly carbonates, by acids, that of clay particles by organic acids and silicates (especially feldspar and amorphous silicic acid) by strong bases having a pH greater than 11.

B. Attack on rock or rock components, for instance pyrite attack by O_2 in waste water, and the resulting $Fe(OH)_2$ or $Fe(OH)_3$ precipitates. Similar reactions occur with Ca^{2+} available from gypsum.

C. Cation exchange, e.g. Ca^{2+}, Mg^{2+}, K^+, Na^+ contained in waste water with H^+ from clayous minerals (according to Faust and Vecchioli, 1974); Ca^{2+} and Mg^{2+} in waste water in exchange with Na^+ in clayous minerals. In general (according to Wedepohl, 1967), the exchangeable cations are Ca^{2+} in clays containing lime and H^+ in lime-free clays.

D. Sorption, e.g. sorption of Sr^{2+} and Cs^+ onto clayous minerals (e.g. vermiculite). Sorption of Cu^{2+} onto kaolinite, illite and montmorillonite increases with rising pH, as does sorption of Cu^{2+} onto ferric oxides (Wedepohl, 1967); sorption of Zn^{2+} onto clayous minerals.

   The above reactions also apply to other minerals.

E. Metasomatic processes, for instance reactions of phosphate containing waste water with $CaCO_3$ and Al, with compounds containing Fe, the latter particularly in areas containing clay, with a logical greater elimination of phosphate in the liquid contents of reservoirs (Ku et al., 1975).

F. Redox reactions pertain especially to sulfur and nitrogen compounds particularly under the influence of microorganisms (bacteria); see Matthess (1973).

Permeability may be reduced with the injection of liquid wastes containing metals. Complications arise especially in the aquifers with a reductive environment and high pH as this supports the formation of metallic sulfide- and metallic hydroxide precipitates, and thereby a decrease in rock permeability as a result of pore plugging. Henby et al. (1973) describe some specific chemical reactions among wastes (particularly when they contain $FeCl_2$ + HCl or $FeSO_4$ + H_2SO_4) and aquifers composed of carbonate rock or calcareous sandstones. Initially, the permeability will be increased by dissolution of rock, H_2O, CO_2 and $CaCl_2$ being the reaction products; later, when pH rises, the pore space of the injection zone becomes plugged as a result of $Fe(OH)_3$ precipitates:

$Fe^{3+} + 3(OH)^- = Fe(OH)_3$ (gel precipitate)
$Fe^{2+} + 2(OH)^- = Fe(OH)_2$ (precipitate)

The reaction of sulfuric acid with carbonates leads to re-precipitation of Ca in the form of $CaSO_4$ (anhydrite) or $CaSO_4 x 2H_2O$ (gypsum). In a liquid waste high in Fe, $Fe(OH)_3$ gel precipitates are possible with an increase in pH.

The plugging of the pore space can be avoided by injecting liquid wastes with low acidity. Rocks with fissure permeability are more suitable for acid-containing injections than a porous reservoir because a smaller surface and shorter time are available for the reactions taking place between wastes and rock material.

According to Hanby et al. (1973), reaction of HCl with salaquifers causes fewer problems than in the case of H_2SO_4, particularly in the presence of Fe. Reaction of liquid waste containing H_2SO_4 can produce results comparable to HCL.

Sandstones are the preferred reservoirs for injection of liquid wastes. Kell and Perry (1975, 1976) have determined that feldspars' and amorphous silicas' (as binding agents) solubility depend heavily on the pH of the injected fluids. The solubility of silicates is relatively constant at a pH less than 9.5 (140 mg/l). With a higher ph (11), their solubility increases rapidly up to 6,000 mg/l, exposing the aquifer to the risk of collapsing. On the other hand, strong acids may cause a decrease in rock permeability through the formation of silica gels, and consequently a constriction or blockage of the flow paths in the aquifer.

According to Kell and Perry (1975, 1976), complex organic acids, e.g. asparagic, citric, salicylic, tartonic or tannic acid have a 5 to 75 times greater dissolving power than distilled water.

Solutions with a high pH generally cause impairments to the injection process, especially in clayey sandstones. The best pH value of the wastes that are to be injected ranges from 6 to 8, and therefore neutralization of the wastes prior to injection is recommended. A low value of pH may lead to corrosion of the material of the well casing. On the other hand, highly alkaline wastes may be corrosive to iron, and form soluble sodium ferrite (Ostroff, 1965).

It is also generally known that the permeability of clayous host rocks and aquicludes can be increased by injection of fluids at a high temperature with high levels of dissolved solids in an ionic state (Goldberg, 1983; Bresler, 1983).

Membrane filtration is another very important process that takes place underground between wastes and the receiving unit which contains clayous material. The electrostatic forces of the clay, and the simultaneous presence of kerogen make this function possible. Membrane filtration is influenced significantly by the following factors: temperature, pressure and the chemical concentration of the aqueous solutions (Berry, 1969).

Permeability of clay depends on the salinity, chemical composition and temperature of waste water. It can increase several times with an increase in the concentration of chloride solutions (Goldberg and Skvortsov, 1986). When clay within the injection zone comes into contact with waste water of lower salinity, the clayous minerals tend to re-arrange their stacking pattern to accept and absorb the additional water on their surfaces. This new pattern of clays can decrease permeability (Hower et al., 1972). Clays are, above all, cation exchangers. Their low anion-exchange potential is limited only to the OH^- ion.

An important role is played by the organic substance kerogen - a dispersed, inextractible organic substance. Amino acids can promote anion exchange in connection with kerogen. With rising temperature, however, these catalytic effects are diminished.

Apart from the influence of temperature and pressure, the permeability of clay membranes to chemical substances depends on the following conditions: solubility of the chemical substance in question, dissociation, non-ionic sorption, preferred sorption of bivalent cation exchange, filtration of various dissociated substances, influence of atomic weight on transport processes, and pH.

Dissociation is important with respect to the above processes. The more dissociated substances indicate a stronger tendency to pass through the membranes. On the other hand, non-ionic sorption is of minimal importance.

According to Berry (1969) a strong sorption affinity of bivalent elements can be observed with clay. For instance, during membrane filtration, a prominent preference for Ca^{2+} versus Na^{+} is evident. But also inside a group of elements having the same valency, a sorption affinity to Na^{+} versus Li, Ca^{2+} versus Sr^{2+} has been confirmed.

Among the halogenes, the degree of membrane filtration drops from chlorine to fluorine: Cl > Br > I > F.

The processes triggered by temperature lead to increased dissociation and decomposition of the organic components which are determinant for the exchange properties of kerogen, progressive reduction in the exchange capacity of clay, and metamorphosis of clayous minerals into more stable variations with a lower ion exchange capacity.

Chilingarian and Rieke (1969) observe that increased pressure of overburden helps lower the salinity of displaced solutions.

According to Dickey (1969) reverse osmosis and salt sieving are common in connection with changes in concentration during the formation of salt-containing solutions. These terms are basically related to the effects of membrane filtration. However, molecular and thermal diffusion and ion separation due to gravity are also significant factors. The osmotic effect can build up pressure that acts against the pressure gradient of injected fluids.

5.3.2. Biochemical Reactions

The type and intensity of the reactions produced by biological components vary with the composition and quantity of the liquid waste injected.

According to Kell and Perry (1975, 1976), only lower organisms such as fungi and bacteria are capable of living underground at depths of hundreds of meters. According to Ehrlich (in Leenheer et al., 1976), ten to one thousand microorganisms per millilitre live in unpolluted groundwater.

Kuznetsov et al. (1962) report that bacteria can withstand high pressures (300,000 to 400,000 kPa) and temperatures of up to 75 to 80°C.

Under oligotropic conditions, bacteria and viruses can survive in a groundwater system for several months (Matthess et al., 1985). Elimination of bacteria is accelerated by higher temperatures (37°C), at a pH value of about 7, a low oxygen content and a high level of dissolved organic substances. Persistance of bacteria varies in relation to the physical, chemical and biological conditions and the kind of bacteria (Figs. 5.1 and 5.2).

Hall (1974) and Hutchinson (1974) suggest that the existence of microorganisms underground is possible since in nature many non-equilibrium oxidation-reduction systems are used by different types of microorganism for energy generation (respiration), with highly effective enzymes acting as catalysts. The following processes are especially emphasized: purification when pollutants, including those of biologic origin, are transformed into harmless products of decomposition (including pathogenic substances); cyclic transformations of carbon, nitrogen, phosphorus and sulfur compounds; and decomposition of chemical pollutants such as pesticides, herbicides, detergents, and other synthetic compounds.

Goolsby (1972) introduces the following transformation process which occurs frequently with the injection of liquid wastes:

$$\text{reduced organic substance} + NO_3^- \xrightarrow[\text{bacteria}]{\text{denitrifying}} \text{oxidized organic substance} + 0.5\ N_2 + OH^-$$

Nitrate, whose higher content which is hazardous for drinking water supplies, is reduced to nitrogen.

Desulfurizing bacteria are especially important, above all when ferric sulfide is present:

$$2FeS_2 + 5H_2O + 15(O) \rightleftharpoons Fe_2O_3 * H_2O + 4SO_4^{-2} + 8H^+$$

Under fully aerobic conditions, this conversion equation can be quantitatively controlled by Thiobaccillus thiooxidans. This reaction does not take place in deeper aquifers overlying confining units because of oxygen shortage. Favorable conditions for this reaction are also set when the injected pollutants contain oxygen or when the aquifer system (particularly a karstic one) is not overlaid by a confined bed.

According to Kaufman and McKenzie (1975), methane fermentation as a reduction of CO_2 to CH_4 has been observed in the injection installations in Florida. The fermentation is affected by dissolved carbon dioxide which is a source of oxygen for the anaerobic oxidation of organic substances by bacteria in the waste material.

Kell and Perry (1975, 1976) point out the danger of polymerization of the receiving unit, with reduced permeability as a result. On the other hand, however, such effects can purposely be generated in order to block-off underground a solution containing hazardous wastes, and so prevent their reentry

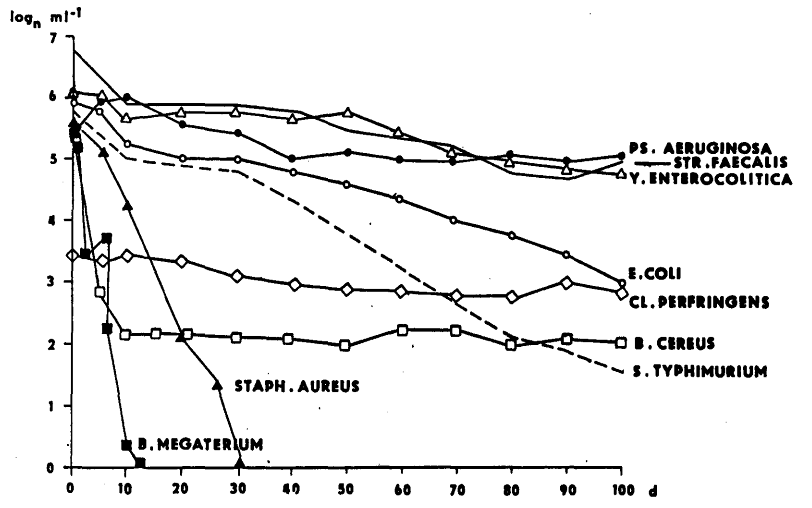


Fig. 5.1. Persistence of bacteria in sterilised groundwater (Filip et al., 1983).

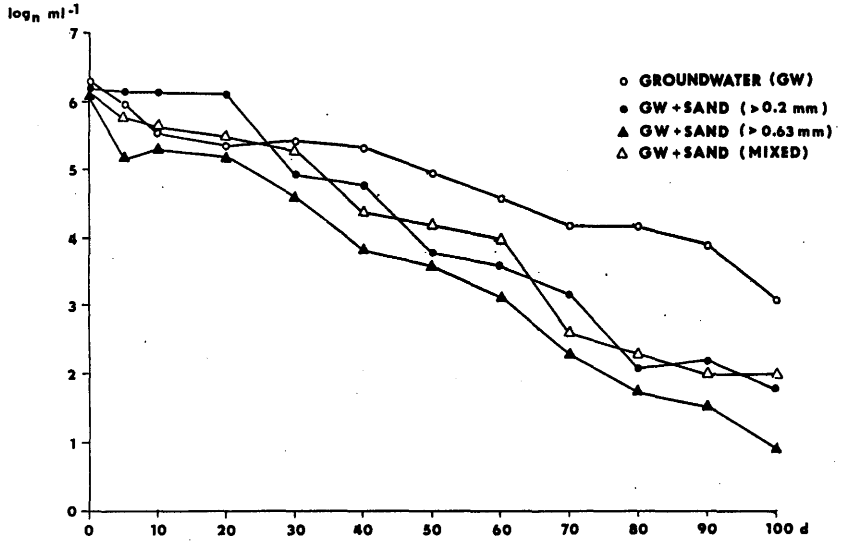


Fig. 5.2. Persistence of E.coli in groundwater in the presence of solid substances (Filip et al., 1983).

into the biological cycle.

Sharply (1961) describes aquifer blockage by sticky polysaccharide excretions of bacteria which form mucilaginous impermeable masses as a result of their binding together. Aquifer blockage is frequently caused by filamentous bacteria, particularly the genera sphaerotilus and lepothric.

Table 5.1 lists the type of substances required by microorganisms and bacterial growth in relation to the type of injected liquid waste.

The problem of bacterial contamination was recognized largely during exploitation of oil fields. As a preventative measure, the following media were injected: Cl_2 solutions, formaldehyde, carbolic acid, fatty acids, heavy metal compounds (e.g., cupric sulfate, acrolein).

5.4. Interactions of Waste, Rock Formation and Native Water

Prior to the injection activity the natural composition (background) of native aqueous solutions should be determined and all macrocomponents (Na, K, Ca, Mg, Fe, Mn, Cl, HCO_3, CO_2, SO_4, NO_3), heavy metals, pH, conductivity, alkalinity, total dissolved solids (TDS) content, biochemical and chemical oxygen demand (BOD and COD), as well as gases (O_2, CO_2, H_2S) should be analyzed. These analyses help assess native water's compatibility with the injected wastes, and the pretreatment scheme can be established. Neutralization, reverse osmosis, evaporation, distillation, electrodialysis, ion exchange, chemical precipitation, chemical oxidation, activated carbon adsorption - all these are the most frequently used treatment techniques for liquid wastes before their injection. Sampling requires implementation of a high-pressure sampler to prevent leakage of dissolved gases during the transport of a water sample to the surface, thereby preserving the natural state of the sample, native water and waste water.

The physical, chemical and biological properties of liquid wastes also affect their compatibility and reactivity with the host rock formation. It is therefore particularly necessary to know the following data on the wastes to be injected: injected volume and pressure, specific gravity, temperature, viscosity, suspended solids content, effective particle size, pH, conductivity, chemical and biological composition, gas content and corrosivity.

It is especially the temperature of the injected wastes which influences the reaction rates, viscosity, corrosivity and biological activity. An increase, due to geothermal gradient, in the temperature of the waste injected into a receiving unit, and thus also waste water's greater reactivity in respect to native water, should always be considered in the injection scheme. Viscosity, which varies with temperature, and the amount of suspended dissolved solids both affect the mobility of waste water.

The potential plugging of the injection zone by suspended solids in waste water is related inversely to the size of the pores of the receiving reservoir. If the suspended solids content or particle size is too great, pretreatment of the waste is desirable. Alverson (1970) reported that the Indiana Geological Survey (Hartman, 1960) found that a particle size greater than 2.5 microns

Table 5.1. Type of substances required by microorganisms and bacterial growth in relation to the type of injected liquid waste.

1)	generally required energy sources	organic substances inorganic substances
1a)	electron recipient	oxygen, organic materials nitrate (NO_3^-), nitrite (NO_2^-) nitrous oxide (N_2O), sulfate (SO_4^{2-}) carbon dioxide (CO_2)
1b)	elements	nitrogen, phosphorous, potassium, magnesium, sulfur, iron, calcium, manganese, zinc, copper, cobalt, molybdenum
2)	stage or constituents of growth	
	amino acids	alanine, asparagic acid, glutamic acid, etc.
	vitamins	thiamine, biotin, pyridoxin, riboflavin, nicotinic acid, pantothenic acid, paraminobenzoic acid, folic acid, thioacid B12, etc.
	other	purines, pyrimidenes, inosites, peptides, etc.

would clog the injection wells completed in Mt. Simon sandstone near Protage, Indiana. Plugging of the injection zone may also occur due to the formation of chemical precipitates. Plugging of the pores of an injection unit is most frequently a result of precipitation of alkaline earth metals and metals, their compounds, and products of oxidation-reduction reactions. Dissolved salts of metals (above all alkaline metal salts and acid salts) are also considerably corrosive.

The volume of waste stream, the size and density of solids, and the reservoir permeability and porosity must be considered when evaluating the ability of a particular zone to accept injected liquid wastes. Acid flushes, backwashing and cleaning using high-pressure jets can be employed to eliminate certain problems caused by plugging.

The potential corrosiveness of waste water in respect to an injection system and confining layers of an injection reservior is indicated by its pH. Extended contact between the injection equipment and wastes with a low pH can cause corrosion and failure of the injection system. Acidic liquids can increase porosity and permeability by dissolving the material of the injection rock. However, dissolution of confining materials can affect adversely the integrity of the confining layer as mentioned above. In general, changes in the pH of native water, as a result of reaction with injected waste, frequently lead to precipitation of dissolved substances and consequently to plugging of the receiving unit pores. Corrosion of the injecting equipment and injection reservoir is accelerated by dissolved gases, mainly oxygen.

As explained above, the reactions between the injected fluid and the formation minerals occur upon injection. Many of these reactions cannot be reversed by subsequent treatment.

Bacteria can cause chemical reactions leading to the formation of precipitates or gases that plug the injection zone. Bacterial growth, or precipitation of iron by ferrous bacteria can also cause plugging. Sulfate-reducing bacteria in waste water, or formation water, cause corrosion of the mechanical parts of the injection system, and subsequent plugging of pores by the corrosion by-products.

To maintain the stability of especially chemical compounds contained in the injected liquid wastes and native water is a desirable but complex task that affects decisively the life span of a deep injection well, or the whole injection field selected for waste disposal.

CHAPTER 6

MONITORING REQUIREMENTS

Gunter Dörhöfer

6.1. Introduction

The scope of monitoring a project of hazardous waste injection is to provide evidence that the injection well or well-field is operating correctly and that the wastes are being kept under long-term isolation within the chosen host rocks. Comprehensive monitoring at frequent intervals should detect problems as soon as they develop.

For each injection project a monitoring concept must be developed prior to operational begin which takes the specific hydrogeological characteristics of the area of potential influence /API/ into consideration. The construction of monitoring devices and the choice of monitoring procedures must follow the regulations of a monitoring plan that must be laid down in the permit.

Basic monitoring requirements include:

Monitoring the injection process. This includes analysis of the injected fluids with sufficient frequency to yield representative data of their characteristics. Continuous recording instruments are installed to monitor injection pressure, flow rate and volume as well as the pressure on the annulus between the tubing and the long string of casing.

Monitoring the injection devices. Demonstration of the mechanical integrity of the injection devices must be anticipated periodically depending on the type of injected fluid and inserted pressure.

Monitoring the area of potential influence. The integrity of the host reservoir must be controlled. This requires the installation and observation of a groundwater monitoring network sufficiently covering the entire potential area of influence. The monitoring network usually incudes monitoring wells, which are frequently observed. Preventive groundwater quality monitoring mainly concentrates on the observation of potentially affected near-surface drinking water resources. Pressure relief monitoring wells should always complement the monitoring system.

The monitoring concept must center on the possibility to predict long-term behavior of injected wastes in the underground and should be able to allow early detection of malfunctions of the system.

"Past failures that have occurred generally fall into several distinct categories:

A. Leakage from the well, including backflow at the surface.
B. Upward migration through nearby wellbores.
C. Upward migration through channels in the cement adjacent to the casing or borehole.
D. Upward migration through faults or fractures, or waste-induced deterioration of the confining beds, and
E. Generation of seismic activity" /Kent & Bentley, 1985/

6.2. Monitoring the Injection Process and Devices

"The principal means of surveillance of wastewater injection that is presently practiced is monitoring at the injection well of the volume, flow rate, chemistry, and biology of the injected wastewater and of the injection and annulus pressures" /Warner & Lehr 1977/. With adequate evaluations during the planning, construction and testing of the well, this monitoring concept would be sufficient to control the short-term effects during the injection process itself as the greatest potential for loss of injected fluids occurs in the vicinity of the well.

Injection data as well as pressure fall-off data after extended continuous operation must be available to interpret predicted versus actual reservoir performance. Deviations of actual from predicted performance are indications of malfunctions of the system.

The following review of monitoring techniques is mainly based on the publication of Warner & Lehr (1977).

A common technique to detect leaks is the continuous recording of the pressure in the annulus. Anomalous pressure changes must trigger immediate testing in order to localize the leaks. Coupons can be used to monitor corrosive effects of wastewater on the well casing. The coupons are composed of the same metal as the casing and are placed in the injection well. By careful weighing before and after exposure to the waste stream, the corrosion rate can be determined.

A conductivity probe can be used to monitor the composition of the annular fluids in both packerless wells and wells with fluid seals wherein shifts of the fluid interval can be detected. During continuous cycling of the annular fluid analyses for specific contaminants are advised.

When the injectivity index increases rapidly near the injection well it might be attributed to a leak that has been created as a result of corrosion in the borehole construction and the waste liquid is escaping into an overlying aquifer with a lower pressure. This faulty behaviour can be prevented by installing a double-pipe construction containing a control liquid between the tubular and the injection casing and by continually monitoring the control liquid for constant pressure by means of a manometer.

It is useful to periodically inspect and test the injection well. The tubing and packing can be removed and be inspected physically and mechanically. Geophysical logging techniques are particularly useful to evaluate the condition of tubing and casing. Caliper logging for instance can detect changes in the tubing or casing diameters.

Pressure tests and radioactive-tracer surveys are the most current and common methods to monitor the integrity of injection wells. Pressure tests are performed by pressurizing the annulus and observing for changes in pressure for a specified time. Radioactive tracer surveys can be used to detect tubing leaks, packers, and fluid movement along the outside of the casing. Short-lived tracers commonly are injected into the well with the wastewater and are subsequently carefully observed during their flow. Detection of residual tracer at a depth from which the tracer was flushed by injection would indicate a tubing leak.

Monitoring the injection well is of primary importance. There is logic for maintaining pressures in the annulus that exceed the tubing-injection pressures as a part of a monitoring system. High-annulus pressures, however, have the disadvantage that they increase the stress on the casing. There is also logic in using an unpressurized annulus that is filled with fluid. In the former method, leaks in the tubing or casing would result in immediate drops in pressure. In the latter, pressure increases would be noted if the tubing or packer fails. The absence of an adequate database regarding monitoring devices, recorders, gauges, failures, and types of failures precludes quantitative assessments of the monitoring process.

6.3. Monitoring the Area of Potential Influence

An unrenouncable prerequisite for the planning of the concept to monitor the area of potential influence is a sound understanding of the geological and hydrogeological conditions. This requires collection of all pertinent data. It is important to know of all deeper boreholes and wells (including abandoned ones) within the API. For each injection project a hydrogeological report should be required for permitting. That report must compile all structural and hydrogeological information and must state under which conditions and risks the geological structure qualifies as a host reservoir for hazardous waste liquids. In general, risk assessments should be undertaken using groundwater models to simulate the contaminant transport under regular (expected) conditions. In addition probable scenarios for malfunctions should also be simulated and evaluated.

The main qualifying criterion for a suitable injection structure is the presence of thick, laterally extensive and intact confining beds. Natural passages through these confining beds "include structural features such as faults, fractures, joints, or depositional features such as pinch-out and replacement by a more permeable lithology" (Kent & Bentley 1985). The absence of depositional features that could furnish vertical passages can sometimes be predicted to some degree if the sedimentary rocks were deposited over wide areas under uniform conditions. However, rapid lateral facies changes are not uncommon features of near-shore and fluvial deposits. It is almost impossible to gain sufficient certainty on the absence of higher conductive layers within such strata.

"Structural discontinuities such as faults and joints tend to be concentrated in areas which have undergone regional deformation due to tectonic forces. The likelihood of waste migration up along faults or fractures is thought to be restricted to areas of competent rocks" (Kent & Bentley 1985).

It is extremely difficult to adjust a monitoring concept to single tectonic elements. Therefore the siting investigations should demonstrate the absence of such structures or at least reduce the probability that they are present. Geophysical surveys (seismic, geoelectrical etc.) are helpful to back up the geological findings.

The most common devices for monitoring the hydrodynamic conditions within the groundwater bodies are observation wells. The basic principles for the siting of these wells are shown in Fig. 6.1. Several types of observation wells and monitoring objectives can be distinguished (Table 6.1.).

Advantages and problems of the different types of observation wells are discussed extensively by Warner & Lehr (1977: 310-314). They note that it is often sufficient to monitor pressure in the receiving aquifer only at the injection well. However "special monitor wells may be desired where pressure at a distance from the injection well is of concern because of the presence of known or suspected faults or abandoned wells that may be inadequately plugged. The pressure response in a monitor well would indicate the extent of danger of flow through such breaches in the confining beds and possibly also indicate whether leakage was occurring".

Wells within the receiving aquifer have the advantage of directly measuring the rate and direction of wastewater movement. Yet, a fair number of wells would be necessary to sufficiently describe the spatial development of the waste plume within the receiving groundwater body. This would be even more critical in cases where porosities and permeabilities are not uniform.

Wells to monitor hydrochemical changes within the receiving groundwater body should be close to the injection well within a reasonable radius of travel time. Also, the influence of dilution should be considered.

An example of a comprehensive system of observation and monitoring wells is shown in Fig. 6.2.

A special monitoring objective can be the observation of the location and possible shift of the fresh water/saline water interface.

Disadvantages of monitoring wells within the receiving aquifer can be that they might act as conduits for the escape of injected wastewater. A monitoring well completed within or just above the confining bed "has the potential for acting as a very sensitive indicator of leakage by allowing measurement of small changes in pressure (or water level) that accompany leakage. A well of this type is best suited for use where the confining unit is relatively thin and well defined" (Warner & Lehr 1977: 311), or where stratigraphical discontinuities are present (Fig. 6.1, Type 5). Hydraulic situations where a quick pressure response in the case of system failure is to be expected, are most

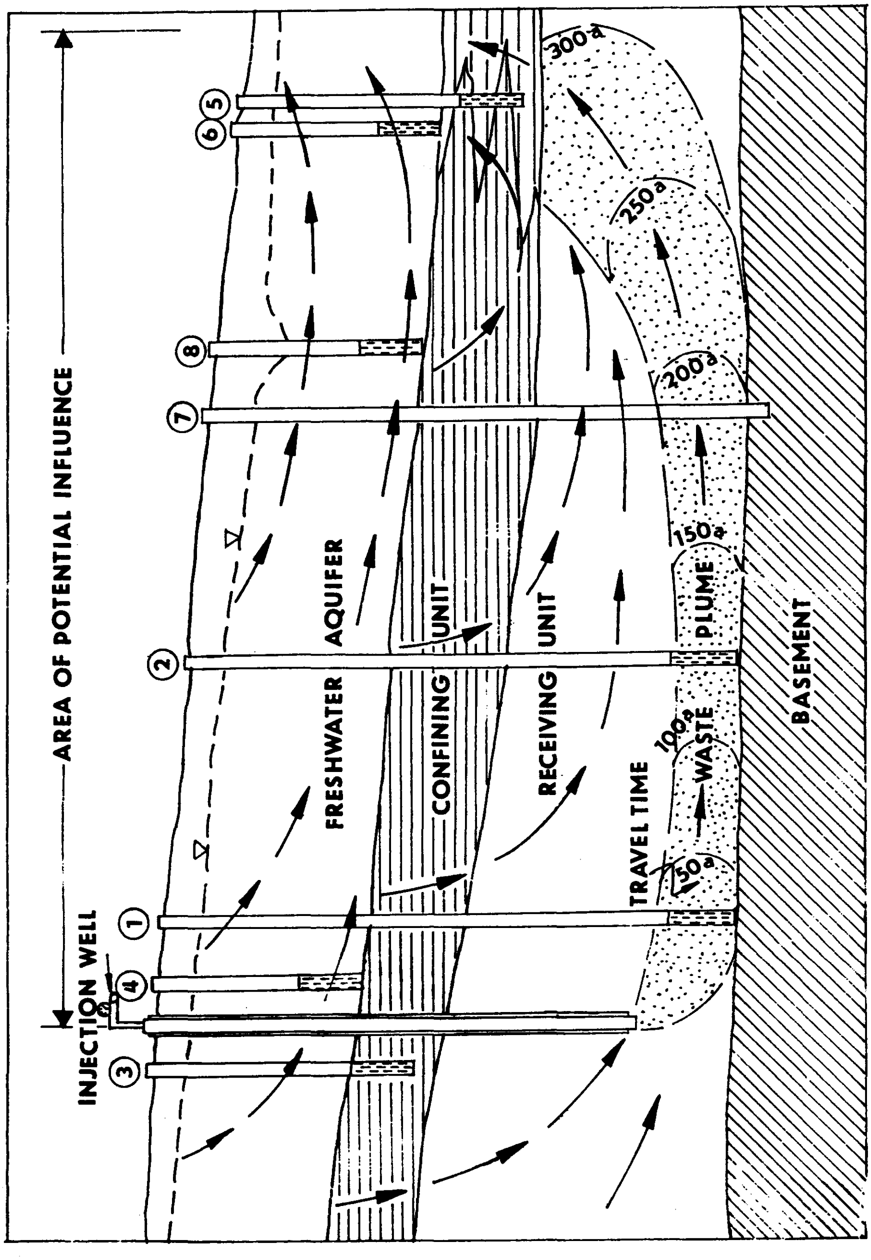


Fig. 6.1. Principles for the siting of observation wells for a deep-well injection project (for numbers refer to Table 6.1).

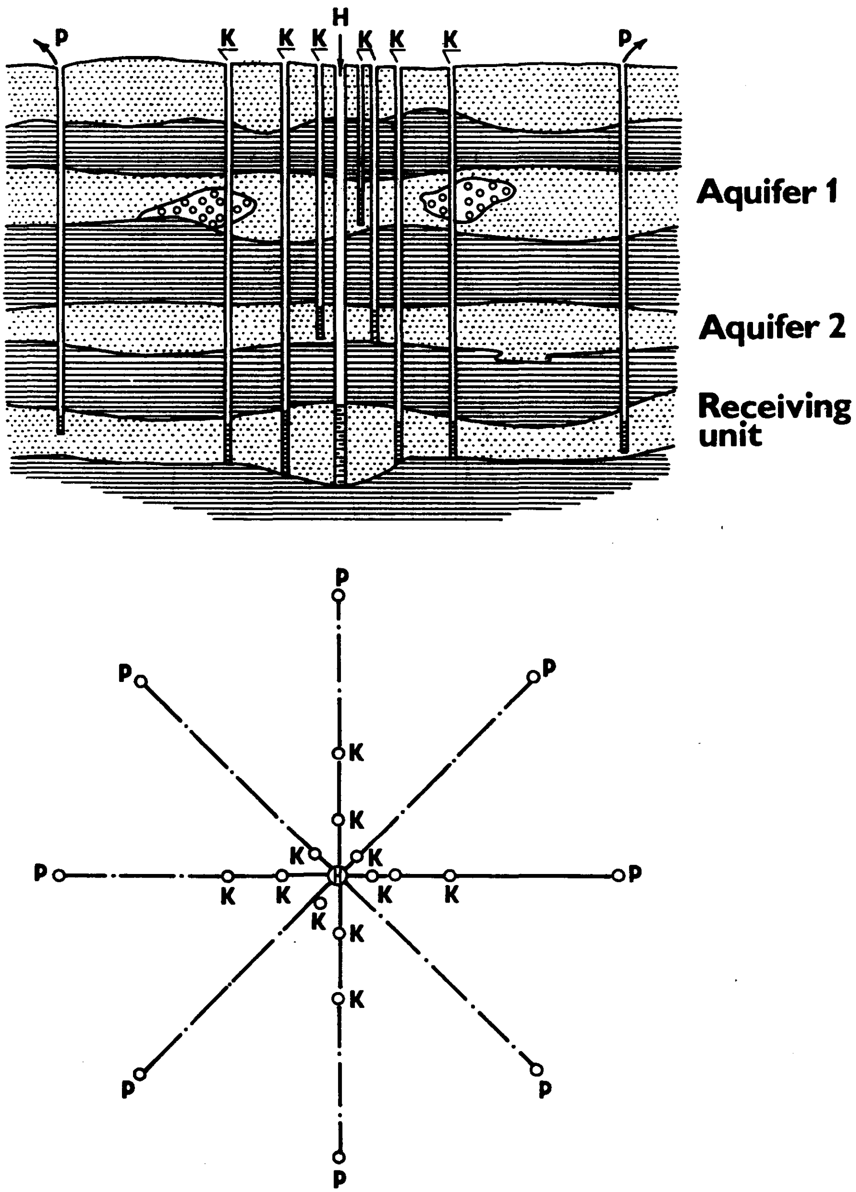


Fig. 6.2. Comprehensive system of monitoring and observation wells: central injection well (H), a ring-shaped pressure-relief system (P) and monitoring or observation wells (K). (from Spitzyn and Balukowa, 1977 and Aust and Kreysing, 1985).

Table 6.1. Types and objectives of observation wells for the groundwater monitoring of deep well injection projects (modified after Warner & Lehr 1977: 310). For types (1,n) refer to Fig. 6.1.

POSITION	TYPE	OBJECTIVE
A. Receiving aquifer	1,2	- obtain geologic data - monitor pressure in receiving aquifer - determine rate and direction of wastewater movement - detect geochemical changes in injected wastewater - detect shifts in fresh water/saline water interfaces
B. In or above confining unit	3,4,5	- obtain geologic data - detect leakage through confining unit
C. Fresh water aquifer		- obtain geologic data
- nondischarging	4,6	- detect evidence of
- discharging	8	fresh water contamination
D. Undefined stratum (abandoned borehole)	7	- obtain geologic data - detect evidence of fresh water contamination

suitable for this type of monitoring. However, the success of such a concept strongly depends on the uniformity of the confining unit.

Whereas alterations in the quality of deep groundwater are often considered acceptable, contamination of the fresh water unit on top of the confining layer in most cases cannot be tolerated. Therefore the fresh water aquifer is the main object of concern and monitoring must be directed to the task to gain evidence of contamination as early as it occurs.

The use of non-discharging wells that allow only the sampling of groundwater that passes through the borehole can be of limited use, because point sources of contamination would hardly be detected. Discharging wells would have the advantage to allow sampling a wider area within the cone of depression, yet at the same time would propagate a wider spread of contaminants. The wells within the fresh water aquifer should be as close as possible to the anticipated or potential source or route of contamination.

The implementation of a sufficient number of monitoring wells in most injection projects has not taken place. Economic aspects were the main reasons, but also the specific benefits of the installation of these devices could often not be demonstrated. It can therefore be concluded that monitor wells should not be arbitrarily required, but should be used where local circumstances justify them. On the other hand, if the uncertainties about the hydrogeological situation within an area of potential influence are so large that a comprehensive surveillance of the system is not possible, the project should not be permitted, as remedial actions can hardly be undertaken in cases of system failure.

The following processes should be observed and recorded (Aust & Kreysing 1985):

A. Leakage in the casings or grouting
B. Appearance of waste liquids in abandoned or operating wells
C. Seepage of waste liquids along faults, fractures, or layers in the confining unit
D. Horizontal and vertical diffusion of the waste liquid within the receiving unit
E. Decrease in permeability in the receiving aquifer caused by plugging
F. Regional changes in groundwater quality and effluent behaviour.

To achieve the rquired information, the recording of the following parameters (among others) is generally recommended: electrical conductivity, pH, eH, temperature, pressure.

The monitoring of surface water from springs, streams, lakes, which could be affected by wastewater leaking from the reservoir, in some cases might be advised. Especially springs are often associated with faults that might conduct deep groundwater to the surface. "Also, springs and gaining streams act similarly to discharging wells in that they provide a composite sample of groundwater over their area of influence" (Warner & Lehr 1977: 314).

Limited possibilities offer seismic reflection or electrical resistivity methods to detect escaping wastewater from the surface.

6.4. Evaluation of Monitoring Data

The information gathered from the monitoring systems is used to evaluate the following:

A. Assessment of the effects of stress on casing from high-pressure annulus monitoring versus zero-pressure or fluid-filled annulus
B. Assessment of performance standards for all used monitoring techniques
C. Definition of statistical considerations to be applied for determination of sampling and data collection frequencies
D. Assessments of the validity of previous assumptions and predictions regarding waste plume development and distribution, as well as physical parameters and boundary conditions.

CHAPTER 7

ENVIRONMENTAL IMPACTS ASSOCIATED WITH DEEP-WELL DISPOSAL

Stephen H. Stow
and
Kenneth S. Johnson

7.1. Introduction

The disposal of liquid hazardous wastes by deep-well injection is a controversial practice, due chiefly to perceived and well publicized environmental impacts. It is clear that under certain hydrological, geological, and technical conditions, deep-well disposal is a viable process. Risks from using this disposal method result almost entirely from human errors in siting, constructing, or operating a facility. In this chapter we shall examine some of the factors that can lead to adverse environmental impacts and review a small number of specific cases where there have been adverse effects from injections. The reader is referred to Gordon and Bloom (1986) and Moffett et al (1987) for reviews of some of the adverse impacts associated with hazardous waste wells, and to Lehr (1986), Hanby (1986), Davis and Hineline (1986), and Velde (1986) for reviews of successful injection wells. A recent review (CH2M Hill, 1986) of hazardous waste injection wells in the United States represents an excellent assessment of the nature and extent of operational and environmental problems associated with this disposal technology.

In spite of unfavorable publicity associated with injection well failures, it should be pointed out that the actual number of documented cases where there have been detrimental impacts is quite small compared to the number of injection wells in operation, and that essentially all problems have been associated with older injection wells that were constructed and operated prior to the enactment of enforcing legislation, at least in the United States. Paque (1986) summarizes the CH2M Hill (1986) survey of 106 wells at 45 sites and points out that there were adverse environmental incidents at 17 of the sites. At all of these sites there was injection into strata other than those that were intended, or permitted; in most cases this was due to failure of the well casing. Five of these had leakage into an underground source of drinking water, but contamination was localized around the well. At four sites there was surface contamination directly associated with the injection system. He notes that there were no documented health problems at any of the 45 sites and most had no adverse environmental problems; in some cases operator error was very clearly the cause of a problem. It is important to point out that properly designed monitoring of the injection process does serve as an indicator of problems and that corrective measures can be taken to rectify a failure.

In general, the factors that can lead to environmental problems or system failure can be placed in one of the following categories:

A. Errors in well construction,

B. Operational errors,

C. Incompatibility of waste with the host formation,

D. Presence of pathways for unplanned fluid migration, and

E. Natural events.

The adverse environmental impacts can be discussed, using examples, under the following four broad categories:

A. Contamination of an unpermitted zone,

B. Plugging of the injection well or the host formation,

C. Initiation of seismic events, and

D. Other impacts

In the following discussion we shall basically assume that a disposal well has been properly sited with regard to the hydrologic and geologic criteria, as any number of hypothetical situations leading to adverse impacts could be visualized otherwise. Discussion will be presented, however, of seismic events associated with a deep disposal well at a site that presumably would not meet all siting criteria today.

7.2. Possible Causes for Problems or Failure

Problems or failures of deep-well disposal systems commonly are related to one or more of the following five general causes. Case histories of some of these adverse results are discussed in Section 7.3.

7.2.1. Errors in Well Construction

Major problems in a well system may be introduced in the initial design and construction of the well. There is no single design or construction, inasmuch as each well must reflect the local hydrogeologic and reservoir conditions, specific types of waste, and anticipated chemical reactions. All wells require, however, that casing, tubing, and cement be used in the borehole, and many wells require the use of a packer to produce a fluid-tight seal between the tubing and the sides of the borehole or the casing (Fig. 7.1). It is these items (casing, tubing, cement, and packers) that are most likely to fail if not properly designed and emplaced to deal with local conditions.

Casing failures are commonly attributed to the casing being corroded or ruptured due to lack of strength. By not using corrosion-resistant casing, such as those made of carbon steel, stainless steel, or fiberglass-reinforced epoxy, acidic wastes can corrode and weaken the casing, thus allowing its failure and leakage of wastes to the area around the borehole. This is especially true if wastes are injected directly down the well casing without use of the injection

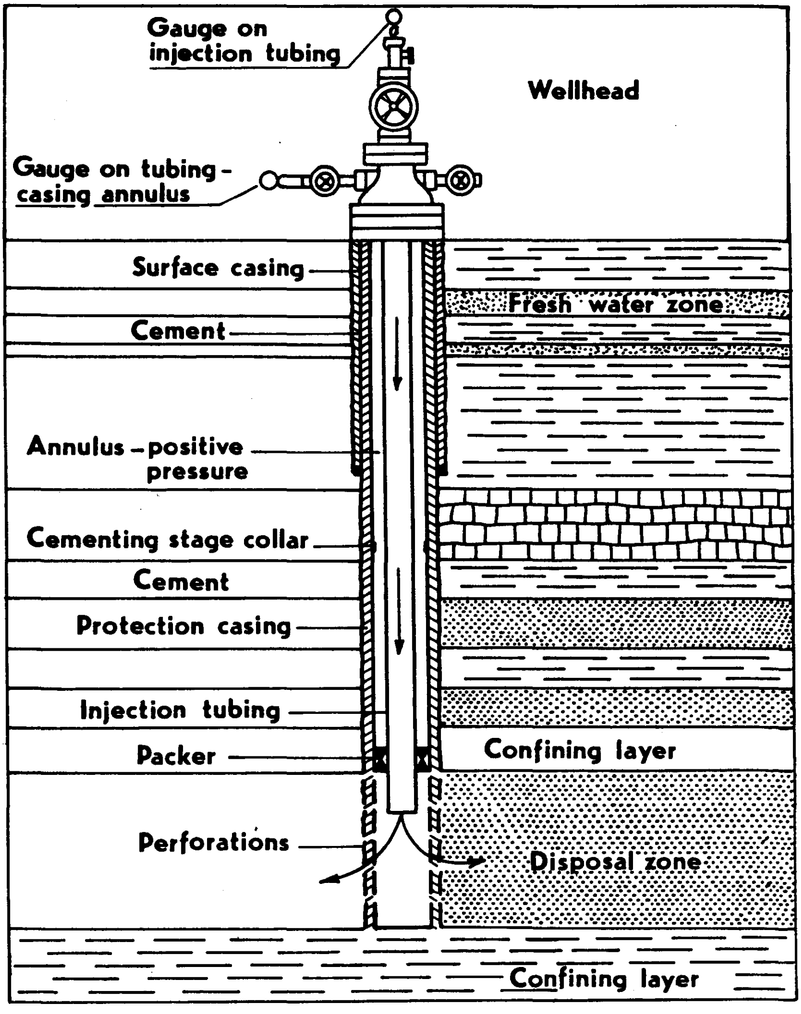


Fig. 7.1. Typical construction features for a deep-well disposal system (modified from Texas Water Quality Board, 1972).

tubing. The threading of casing joints also is a potential site for corrosion and (or) leakage.

Tubing (or injection tubing) that carries the waste stream from the surface to the injection zone must also be corrosion resistant and of sufficient mechanical strength to prevent failure. It should be made of stainless steel or fiberglass to resist corrosion. Failure of the tubing can allow leakage of waste fluids into the annular space between the tubing and well casing.

Cement used in seating the casing and tubing, or used to fill the annular space in the borehole, must be compatible with the waste streams that are to be injected; thus, the common types of oilfield cements are not generally suitable for this use. The most likely pathway for upward migration of wastes to shallower zones is at the wellbore itself, so selection of the proper cement is critical. Epoxy-resin cements, used in conjunction with corrosionresistant casing and tubing, should provide a barrier to waste migration. If the cement is not properly chosen, mixed, and (or) emplaced in the borehole, it can deteriorate and allow vertical migration of wastes to unpermitted strata or to the land surface.

Packers, often used to form the hydraulic seal between tubing and casing, must be selected to withstand anticipated pressures and the chemical/physical effects of the waste stream for each well. If the packer is not the correct size, does not expand properly, is not corrosion resistant, or in any other way malfunctions, wastes may bypass it, enter the annular space in the borehole, and migrate upward to shallower zones.

Several other aspects of well design and construction must also be properly tended to in order to avoid problems. Annular fluid should be a noncorrosive and nontoxic liquid kept at higher pressure that the waste injection pressure; thus, if there is a leak in the tubing, annulus fluid would flow into the tubing rather than waste flowing into the annular space. Pumps, flow lines, and pressure controls must be designed for each operation, and a solids-separation system is needed to prevent damage to equipment and the host formation.

7.2.2. Operational Errors

Operational procedures must be designed to maintain the operating status and to detect any abnormalities and problems as soon as possible. Although operational errors would seem to be the most preventable causes of all injection well problems, they are, unfortunately, among the most prevalent. These problems can generally be prevented by checking equipment in the injection system routinely and frequently, thus enabling a "problem" to be solved before its results cause a "failure" of the system.

The CH2M Hill (1986) survey, as noted previously, identified 45 sites in the United States where one or more waste-injection wells had some sort of operational problem during their histories. It should be noted that there were no documented health problems at any site and at more that half the sites there were no adverse environmental impacts related to the well. Injection of wastes began at six of these sites in the 1980s, at 19 sites in the 1970s, at 17 sites in the 1960s, at one site in 1957, and no date was given for two sites;

thus, the wells at nearly half of the sites were constructed prior to 1970, when construction and operating standards were not as stringent as they are today.

Testing and monitoring of pressures, equipment, casing, tubing, packers, waste streams, disposal zone, and unpermitted zones are critical and necessary to ensure that potential problems are identified early and are corrected before they lead to adverse results. Pressure surges or higher-than-anticipated injection pressures can cause failure of weakened or corroded materials, or can accelerate the failure of previously undamaged equipment and cement. Injection pressures that exceed the fracture gradient at the disposal site can cause fracturing of the confining zone and allow loss of waste to an unpermitted zone. Injection of some mixed incompatible waste streams, or of waste more corrosive than anticipated, can cause rapid corrosion of casing, tubing, packers, and other equipment. By not screening solid particles (sand, metals, plastic, or fibers, for example) from the waste stream before injection, these materials can significantly decrease the porosity of the injection zone or tubing, thus leading to increased injection pressures or even to loss of the well.

Most of the operational problems reported in the CH2M Hill study stemmed from corrosion and leakage of casing or tubing, allowing waste to enter the annulus of the well or an unpermitted zone. By early detection and repair or replacement of damaged casing, tubing, or other equipment, most wells can be returned to service without adverse consequences. Other operational errors reported include excessive pressures, extremely cold waste stream (causing contraction of the packer and expansion joints), and the introduction of solids, bacteria, or incompatible wastes that decrease the porosity of the injection zone. Specific examples of some of these are discussed in section 7.3.

7.2.3. Incompatibility of Waste with the Host Formation

Effective and continuous operation of a deep-well injection system depend heavily upon the chemical compatibility of the waste with the mineral and fluid components of the host rock. Chemical reactions can produce precipitates that can plug pore spaces in the rock, reducing permeability and storage capacity. Also, clay minerals among larger grains may swell owing to injection of certain wastes and thus reduce pore space. As a result of such plugging, the operator may be tempted to increase the injection pressure to a dangerous threshold, which could cause failure of tubing, packers, and other equipment, or could induce fractures in cement and confining strata.

On the other hand, chemical reactions may increase the porosity and permeability by dissolving certain minerals and opening new passages that were not anticipated in the original design. Such channeling may enable toxic materials to escape. Therefore, the mineral and fluid content of the reservoir must be analyzed carefully, and laboratory studies of the interaction between these materials and the waste must be carried out before injection is started. Problems of incompatibility may often be minimized or overcome by treatment of the waste before injection.

7.2.4. Presence of Pathways for Unplanned Fluid Migration

Potential pathways for unplanned migration of injected wastes include faults, joints, fractures, caves, mines, and unplugged or poorly plugged boreholes that come near to or intersect the injection zone. If liquid wastes were to enter any of these natural or man-made openings, they could pass through the confining zone and reach an unpermitted stratum or the land surface. All of these features must be identified during geologic and engineering screening of a potential site, and the presence of these pathways should be the basis for abandonment of the site unless they can be sealed or it can be shown that they will not allow waste migration.

In many cases, poorly plugged or unplugged boreholes are the most likely avenue for fluid migration; this includes both abandoned boreholes and those still in use, especially those that are close to the injection well. Boreholes may have been drilled for petroleum, water, mineral exploration, or a variety of other purposes. Such boreholes may have been left open with no casing or cement plugs, or they may have been poorly plugged and still permit vertical migration of fluids. Areas of early-day drilling are probably more risky than areas drilled recently, because they are more likely to contain boreholes that have been forgotten or that have been improperly plugged. It is essential that all these boreholes be plugged and sealed effectively.

Confining beds around the injection zone must not contain open fractures if wastes are to be contained. They may be fractured by excessive pressure caused by injection, by release of carbon dioxide, or by thermal expansion (Reeder and Associates, 1977). Therefore, pressure buildup or drawdown tests must be made and maximum operating pressure must be established to prevent fracturing of the confining beds.

7.2.5. Natural Events

A number of natural events, such as tornadoes, hurricanes, lightning, vulcanism, and earthquakes, could cause serious problems at an injection-well facility. Any of these could disrupt surface receiving, handling, and storage operations and might result in release of waste materials in an unwanted manner. Earthquakes or seismic activity pose the greatest threat to an injection well itself. Therefore, the entire disposal system, including surface and subsurface facilities, must be designed and constructed in a manner consistent with the seismic risk of the site.

7.3. Possible Adverse Results from Injection

Following are examples of cases where there has been an adverse environmental impact from hazardous-waste injections; many of these examples are taken from the literature references and they are intended to indicate the nature of the documented problems.

7.3.1. Contamination of an Unpermitted Zone

The possibility of contamination of aquifers below or above the injection zone represents the greatest environmental threat associated with deep-well injection and, indeed, this is the most common problem. In most cases, however, the aquifer that unintentionally receives waste is not a current supply of drinking water. There are numerous reasons why aquifer contamination can occur; these include grout-seal failures around the injection well, failure of the casing, failure to plug abandoned boreholes that penetrate the injection zone, excess injection pressures that lead to fracturing of the confining horizons, dissolution of confining horizons due to reactions that occur between injected wastes and strata, and improper siting or maintenance of the injection well. Ward et al. (1986) provide an assessment of many of these failure mechanisms.

One example of aquifer contamination resulting from design and operational errors and reactions involving the waste are the seven commercial injection wells (ca. 600-825 m depth) at Vickery, Ohio. From 1976 to 1983, leaks occurred around the well casings due to damage during cleaning of the wells and to corrosion of the casings by waste water. Due to an inadequate design of the monitoring system for the fluid levels in the annulus, in some cases the leaks were not detected immediately and waste materials entered the groundwater system above the injection zone, but did not contaminate any drinking-water supplies. It is estimated that between 180 and 240 million liters of waste were lost.

Deterioration of the well casing, tubing, and packer by corrosive wastes also occurred in two commercial injection wells at Ranger, Texas, and wastes entered strata other than the injection zone; a nearby oil field was contaminated in the subsurface. These same wells also experienced pressure build-up and blowout of wastes due to unanticipated reactions that occurred between the waste solutions and the injection formation; surface contamination resulted. There is documented evidence of non-compliance at this facility leading to some of the problems.

Leakage out of the injection zone into adjacent strata may have occurred at an injection well in Mulberry, Florida, when acidic wastes were injected approximately 1500 m below the surface and reacted with carbonate rocks in the injection zone. A large cavity was formed in the injection zone and there was loss of the integrity of the well casing; contaminants may have entered the underlying confining beds. Growth of the cavity was directly related to the injection rate.

A further example involving aquifer contamination due to leaks from an injection-well casing occurred in 1982 at Lake Charles, Louisiana. A factor leading to this failure appears to be the fact that multiple waste streams were used at this commercial facility, thereby complicating the understanding of the chemical reactions that could occur in the subsurface. As a result, the well integrity was lost and an overlying aquifer was contaminated. It has become apparent that a disposal well must be designed to accept a known waste stream and that multiple types of wastes should not be disposed of in any one well; this is especially true for commercial wells.

It is difficult in many cases to accurately predict the potential lateral extent of wastes within the injection zone; this is especially true if there are reactions that occur in the subsurface that can increase the porosity. Therefore, there may be contamination within this zone beyond the expected extent. Miller et al. (1986) have examined analytical modeling methods for predicting waste movement and pressure increase in the injection interval. A situation involving migration of wastes and elevated pressures is represented by two wells in Pensacola, Florida, where wastes were injected into a saline part of a limestone aquifer; clay-rich confining beds occur above and below the injection horizon. About ten years after injections started, wastes were detected in the aquifer some 2.5 km from the injection wells, a distance greater than initially expected. It was also noted that pressure effects associated with the wells extended more than 65 km from the site. There is, however, no evidence that any contamination or pressure increases have occurred in the drinking-water aquifers above the injection zone. This problem may have arisen due to the possible presence of an undetected high permeability zone.

7.3.2. Plugging of the Injection Well or the Host Formation

This impact is less common than that described above, but it can be extremely detrimental to a disposal operation. In general, a plugging phenomenon occurs when chemical reactions and precipitation occur at depth due to incompatibility between waste streams or between wastes and the host formation or its fluids. Also, solid particles (sand, metals, plastics, fibers, etc) not screened from the waste stream, or natural materials from the injection formation may plug the system.

An example of the former situation is shown by a commercial injection well in Odessa, Texas, where two incompatible waste streams were injected in 1979. It is speculated that the formation of precipitates caused the blockage of most of the pores in the injection zone and perhaps even the perforations in the well casing. As a result, injection pressures monitored at the surface exceeded specified limits. Corrective measures, involving acidification to improve porosity, were taken before a dangerous condition developed.

The repeated plugging of seven injection wells in Orange County, Texas, by unconsolidated sands from the injection zone represents the latter situation noted above. These wells experienced loss of porosity for almost 20 years due to sand from the unconsolidated injection horizon entering the well bore; in addition, permeability was reduced by precipitation and viscosity changes associated with some organic wastes that were injected. Pressure monitoring of the wells allowed this problem to be identified and corrective measures, such as acidification and hydrojetting, were taken.

An example of injection formation damage due to injection of an incompatible fluid is cited by Davis and Funk (1974). During construction of a plant, transfer lines to the disposal well were pressure tested with fresh water, which was inadvertently left in the lines. When the well was put into service the water was pumped into the well where it caused damage through hydration and expansion of water-sensitive clays in the formation.

The consequences of inadvertent plugging of an injection well or the host formation, coupled with continued attempts to inject waste, can lead not only to loss of the well itself, but, perhaps more importantly, to induced fracturing of confining strata and the creation of pathways for wastes under excessive pressure to move vertically into fresh water aquifers. In addition, the build up of pressures in the subsurface can lead to blowouts at the well head with the spread of contamination and compromised safety. To avert situations such as this, it is mandatory that compatibility tests be performed for all components of the system, that pre-injection treatment of wastes be performed when necessary, and that maximum permitted injection pressures not be exceeded.

7.3.3. Initiation of Seismic Events

If liquid wastes are injected into fault systems that are under stress, the lubricating effect of the wastes and the increase in pore pressure can result in fault movement and seismic events. Perhaps the best known site with such a cause-and-effect situation is the injection of highly toxic chemical manufacturing wastes at Rocky Mountain Arsenal, northeast of Denver, Colorado in the 1960s (Evans, 1966; et al., 1968). Wastes were injected through a 3671 m deep well at a rate of 15-30 million liters per month into Precambrian gneissic rocks below flat-lying sedimentary rocks. Injections started in March 1962 and seismic activity started within months. The frequency of earthquakes corresponded almost perfectly with the volume of wastes injected (Fig. 7.2), with the largest earthquake registering 4.3 on the Richter scale. Injections ceased in 1966 with a corresponding decrease in seismic activity, which continued for well over one year, but which eventually ceased after some earthquakes with a rating of over 5.0 occurred. Prior to the first injection, seismic activity at the site had not occurred since 1882. Drill-stem tests and core samples from the injection well indicated that the host gneissic rock was characterized by high-angle fractures capable of opening and closing, and containing a fluid at a preinjection pressure of some 900 psi less than hydrostatic. This example represents a situation where the injection well was apparently improperly sited with regard to geologic conditions. In the United States, current regulations now prohibit injections within 60 m of a fault and require that the structural geology (and other aspects) within a radius of 0.4 km around the well be fully understood.

7.3.4. Other Impacts

There are other detrimental impacts that injections can theoretically have on the environment, but these are much rarer and have been documented much less than those discussed above. One of the impacts involves raising the fresh water-saline water interface by injections at depth into a saline system; in theory, this should not occur, however, if adequate measures are taken to ensure that the well is properly sited and operated and there is not upward hydrologic communication through the overlying confining strata. However, due to the potential effect that injections might have laterally at distances beyond their anticipated zone of influence, this impact can not always be fully quantified. In addition, injection wells should be sited so that there will not be future exploration for resources that could be jeopardized by the presence of the injected fluids (see Chapter 3); it is possible that a future resource might be rendered unavailable due to an injection disposal operation because we cannot fully predict the future resource picture in all cases. There has been consideration of using abandoned oil and gas fields for injection of wastes (Rottgardt et al., 1976); such a move would render these fields unavailable for enhanced recovery in the future as technological and economic situations change. Most injections occur at sufficient depth so that overlying

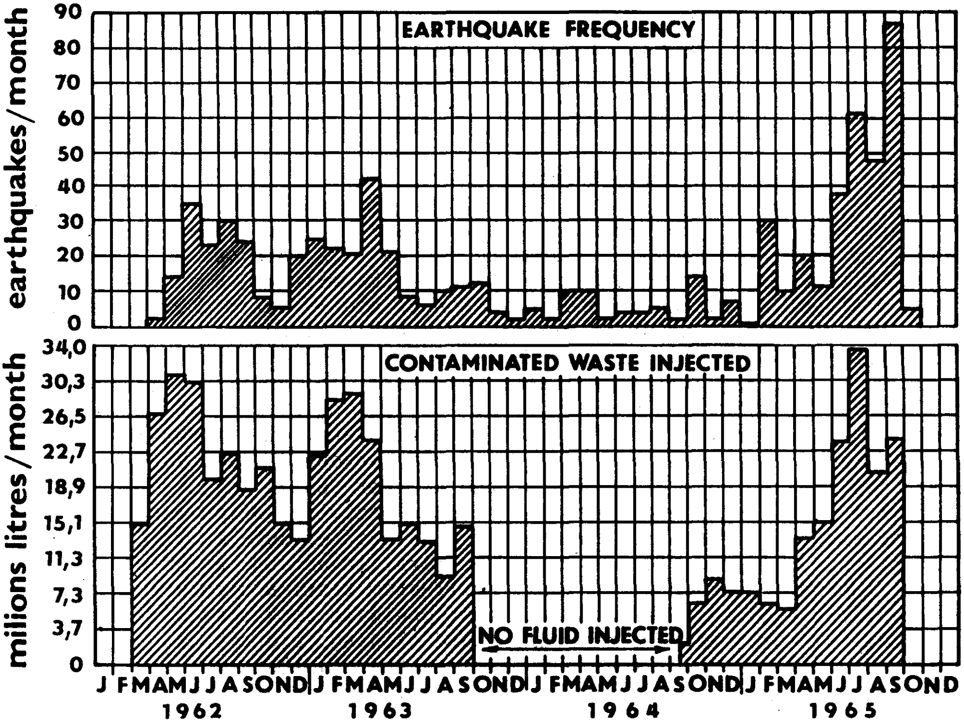


Fig. 7.2. Histograms showing relation between earthquake frequency and volume of waste injected into the Rocky Mountain Arsenal well (after Evans, 1966).

strata can maintain their integrity even though dissolution may occur at the injection depth. It is possible, however, that subsidence could occur at an injection site if the injection depth is not great enough, if the host rock is highly soluble, or if the overlying strata are not competent. Proper siting of the facility should help prevent this situation, however. Finally, surface contamination could occur at a site if pre-existing boreholes open to the injection horizon are not properly plugged; again, proper siting can prevent this occurrence.

SELECTED REFERENCES

A comprehensive list of references was compiled from a number of international data banks. The comprehensive list contains many times the references given in this section. This is a selected bibliography as referenced by the contributing authors, plus some additional references that individual members of the Commission felt should be given.

Alexander, I. and Seiler, K.P., 1983, Lebensdauer und Transport von Bakterien in typischen Grundwasserleitern: Münchener Schotterebene. Schrift. R. Wasser 35, Frankfurkt/Main/ZfGW/, p. 113-126.

Alverson, R.M., 1970, Deep-well disposal study for Baldwin, Escambia, and Mobile Counties, Alabama: Alabama Geological Survey: Circular 58, Tuscaloosa, AL, 49 p.

American lnstitute of Chemical Engineers Hazardous Waste Task Force, 1986, Technical needs for improved management of hazardous waste: Government Programs Steering Committee, Washington, D.C., 70 p.

American Institute of Professional Geologists, 1984a, Hazardous waste: issues and answers: Arvada, CO, 24 p.

Anonymous, 1984, Hazardous waste: Compressed Air Magazine, June, p. 8-16.

Aust, H., and Kreysing, K., 1985, Overview of Deep-Well Disposal in Europe.

Aust, H., and Kreysing, K., 1985, Hydrogeological Principles for the Deep-Well Disposal of Liquid Wastes and Wastewaters. Federal Institute for Geosciences and Natural Resources, Hannover, Federal Republic of Germany.

Baffa, J.J., 1965, Experience with injection wells for artificial recharge: Journal American Water Works Association, v. 57, no. 5, p. 629-639.

Barlow, A.C., 1972, Basic disposal-well design: American Association of Petroleum Geologists Memoir 18, Tulsa, OK, p. 72-77.

Bates, R.L., and Jackson, J.A., editors, 1980, Glossary of geology: American Geological lnstitute, second edition, Falls Church, VA, 751 p.

Belitskii, A.S., 1976, Protection of natural resources in the case of underground industrial liquid waste disposal: Nedra Publ., Moscow, 145 p. (in Russian).

Berry, F.A.F., 1969, Relative Factors Influencing Membrane Filtration Effects in Geological Environments. Chem. Geol., Volume 4, p. 295-301.

Billings, N.F., 1952, Control of underground waste disposal: Journal American Water Works Association, v. 44, no. 6, p. 685-689.

Billings, N.F., 1953, Findings and recommendations on underground waste disposal: Journal American Water Works Association, v. 45, no. 12, p. 1295-1297.

Booth, A.N., 1972, Watch for boomerang in pollution control: U.S. Chamber of Commerce, Washington, D.C. 1 p.

Boraiko, A.A,, 1985, Storing up trouble. . . hazardous waste: National Geographic, v. 167, no. 3, p. 318-351.

Borevskaya, V.A., Gavrilov, I.T., Goldberg, V.M., Krivosheev V.P., Tarasova, N.V., and Titov, N.A., 1972, Hydrogeological and hydrochemical studies for solution of the problem of industrial wastewater disposal to deep-seated carbonate rocks: MGU Publ., Moscow, 350 p. (in Russian).
Borevskaya, V.A., Gavrilov, I.T., Goldberg, V.M., Krivosheev V.P., Tarasova, N.V., and Titov, N.A., 1976, Hydrogeological studies on industrial wastewater disposal to deep aquifers: Nedra Publ., Moscow, 311 p. (in Russian).
Borevskaya, V.A., Gavrilov, I.T., Goldberg, V.M., Krivosheev V.P., Tarasova, N.V., and Titov, N.A., 1978, Assessment of changes in hydrogeological conditions under the effect of economic activities: Nedra Publ., Moscow, 264 p. (in Russian).
Bourgoyne, A.T., Jr., Millheim, K.K., Chenevert, M.E., and Young, F.S., Jr., 1986, Applied drilling engineering: Richardson, Texas, Society of Petroleum Engineers, 502 p.
Bouwer, H.R., 1974, What's new in deep-well injection: Civil Engineering, v. 44, no. 1, p. 58-61.
Braunstein, Jules, editor, 1973, Underground waste management and artificial recharge, vols. 1 and 2: Preprints of papers presented at the Second International Symposium on Underground Waste Management and Artificial Recharge, New Orleans, Louisiana, September 26-30, 1973, The George Banta Co., Menasha, WI, 931 p.
Bredehoeft, J.D., et. al., 1976, Hydraulic Fracturing to Determine the Regional In-Site Stress Field, Piceance Basin, Colorado. Geol. Soc. of Amer. Bulletin, Volume 87, p. 250-258.
Brower, R.D., Krapac, I.G., Hensel, B.R., Visocky, A.P., Peyton, G.R., Nealon, J.S., and Guthrie, Mark, 1986, Evaluation of current underground injection of industrial waste in Illinois: Hazardous Waste Research Information Center Report HWRIC RR 008, Savoy, IL, 179 p.
Brown, D.L., and Silvey, W.D., 1973, Underground storage and retrieval of fresh water from a brackish-water aquifer, in Braunstein, Jules, editor, Underground waste management and artificial recharge, Volume 1: The George Banta Co., Menasha, WI, p. 379-419.
Carson, R.L., 1962, Silent spring: Fawcett Crest, New York, NY, 157 p.
Case, L.C., 1970, Water problems in oil production - an operators' manual: Petroleum Publishing Co., Tulsa, OK, 133 p.
Caswell, C.A., 1970, Underground waste disposal: Concepts and misconceptions: Environmental Science and Technology, v. 4, no. 8, p. 642-647.
Charbeneau, R.J., 1983, Groundwater restoration with in situ uranium leach mining, in Studies in geophysics, groundwater contamination: National Research Council, National Academy Press, Washington, D.C., p. 147-150.
Chemical Manufacturers Association, 1984, Deep-well disposal: an option for responsible management of chemical wastes: Washington, D.C., 13 p.
CH_2M Hill, 1986, A class I injection well survey of selected sites: Underground Injection Practices Council, Oklahoma City, OK, 361 p.
Cleary, E.J., and Warner, D.L., 1970, Some considerations in underground wastewater disposal: Journal American Water Works Association, v. 62, no. 8, p. 489-498.
Coleman, J.B., Jr., 1986, Maintaining the option: an overview: Underground Injection, v. 1, no. 1, Chemical Manufacturers Association, Washington, D.C., p. 1-2.
Conner, J.R., 1984, The modern engineered approach to fixation and solidification technology: Proceedings of Conference on Hazardous Wastes and En-

vironmental Emergencies, Houston, March 12-14, 1984, Hazardous Materials Control Research Institute, Silver Springs, MD, p. 293-298.
Conrad, E.T., and Hopson, N.E., 1975, Outlooks for the future of deep-well disposal: Water Resources Bulletin, v. 11, no. 2, p. 370-378.
Davis, K.E. and Funk, R.J., 1974, Subsurface disposal of industrial wastes: Industrial Water Engineering, v. 2, p. 14-17.
Davis, S.N. and Bentley, H.W., 1982, Dating groundwater, in Nuclear and Chemical Dating Techniques, Interpreting the Environmental Record, L.A. Curie, editor: Amer. Chemical Society Symposium Series, no. 176, p. 187-222.
Davis, K.E. and T.L. Hineline, 1986, Two decades of successful hazardous waste-disposal well operation - a compilation of case histories: Proceedings of the International Symposium on Subsurface Injection of Liquid Wastes (New Orleans, LA), Water Well Journal Publishing Co., Dublin, OH., p. 295-308.
DiTommaso, Anthony, and Elkan, G.H., 1973, Role of bacteria in decomposition of injected liquid waste at Wilmington, North Carolina, in Braunstein, Jules, editor, Underground Waste Management and artificial recharge, Volume 1: The George Banta Co., Menasha, WI, p. 585-599.
Donaldson, E.C., 1972, Injection wells and operations today: American Association of Petroleum Geologists Memoir 18, Tulsa, OK, p. 24-47.
Donaldson, E.C. and Rezaei, A.A., 1986, Analysis of the migration pattern of injected waste: Proceedings of the International Symposium on Subsurface Injection of Liquid Wastes, New Orleans, National Water Well Assoc, Dublin, Ohio, p. 464-484.
Dunaway, J.O., 1972, Our newest dilemma: We versus us, Signature, p. 38-41.
Ellison, R., 1976, Oral communication. Department of Natural Resources, Lansing,Michigan.
Environmental Science and Technology, 1968, Deep well injection is effective for waste disposal: v. 2, no.6, p. 406-410.
Epstein, S.S., Brown, L.O., and Pope, Carl, 1982, Hazardous Waste in America: Sierra Club Books, San Francisco, CA, 593 p.
Evans, D.M., 1966, The Denver area earthquakes and the Rocky Mountain Arsenal disposal well: The Mountain Geologist, vol. 3, no. 1, p. 25-36.
Faust, S.D. and Vecchioli, J., 1974, Injecting Highly Treated Sewage into a Deep Sand Aquifer. Journal American Water Works Assoc'n., Volume 66, p. 371-377.
Ferris et al., 1962, Theory of Aquifer Tests: U.S. Geological Survey Water Supply Paper 1536-E, 174 p.
Fetter, C.W., Jr., 1980, Applied Hydrogeology: Charles E. Merrill Publishing Company, Columbus, OH, 488 p.
Filip, Z., Kaddu-Mulindwa, D., et. al., 1983, Überlebensdauer einiger pathogenerund potentiell pathogener Mikroorganismen im Grundwasser. DVGM - Schrift, R. Wasser, 35, Franfurkt/Main/ZfGW/, p. 81-87.
Freeze, R.A. and Cherry, J.A., 1979, Groundwater: Prentice-Hall, Inc. Englewood Cliffs, New Jersey, 604 p.
Fritz, P. and Fontes J.Ch., 1980, Handbook of Environmental Isotope Geochemistry: vol. 1, Elsevier Scientific Publishing Company, New York.
Galley, J.E., 1968, Economic and industrial potential of geologic basins and reservoir strata, in Galley, J. E., editor, Subsurface disposal in geologic basins - a study of reservoir strata: Association of Petroleum Geologists Memoir 10, Tulsa, OK, p. 1-10.

Gass, T.E., 1986, Ground-water monitoring study finds major problems in EPA implementation: Ground Water, v. 24, no. 3, p. 428.
Geraghty and Miller, Inc., and Booz, Allen and Hamilton, Inc., 1982, Injection well construction practices and technology: U.S. Environmental Protection Agency, Office of Drinking Water, Washington, D.C., 309 p.
Goldberg, V.M., 1972, Main characteristics and the status of the problem of underground disposal of industrial wastewater: in The Impact of Economic Activities on Ground-water Flow, p. 79-87, Moscow (in Russian).
Goldberg, V.M., and Skvortsov, N.P., 1986, Permeability and seepage in clays: Nedra Publ., 161 p. (in Russian).
Goldberg, V.M., Lukyanchikova, L.G., Grafskii, B.V., and Tarasova, N.V., 1986, Generalization of the exploration experience in the validation of underground industrial wastewater disposal: Inzhenernaya Geologiya, No. 1, p. 110-118 (in Russian).
Goolsby, D.A., 1972, Geochemical effects and movement of injected industrial waste in a limestone aquifer, in Cook, T.D., ed., Underground Waste Management and Environmental Implications, American Association Petroleum Geologists, Memoir 18, Tulsa, OK, p. 355-368.
Gordon, Wendy, and Bloom, Jane, 1986, Deeper problems: Limits to underground injection as a hazardous waste disposal method: Natural Resource Defense Council, Inc., New York, NY, 82 p.
Grubbs, D.M., Haynes, C.D., and Tucker, W.E., 1970, Conservation of freshwater resources by deep-well disposal of liquid wastes: The University of Alabama Natural Resource Center, Tuscaloosa, AL, 85 p.
Hall, E.S., 1974, Some Chemical Principles of Groundwater Pollution. In Groundwater Pollution in Europe, Proceedings of the Reading Conference, 1972, p. 96-115.
Hanby K.P., 1986, Sixteen successful years - a history of Stauffer Chemical Company's underground injection at Bucks, Alabama: Proceedings of the International Symposium on Subsurface Injection of Liquid Wastes (New Orleans, LA), Water Well Journal Publishing Co., Dublin, OH., p. 280-296.
Hartman, C.D., 1966, Deep-well disposal at Midwest Steel: Iron and Steel Engineer, no. 12, p. 118-121.
Healy, J., 1976, Oral Communication. U.S. Geological Survey, Menlo Park, California.
Healy, J.H., Rubey, W.W., Griggs, D.T., and Raleigh, C.B., 1968, The Denver Earthquakes: Science, vol. 161, p. 1301-1310.
Hickey, J.J., and Wilson, W.E., 1982, Results of deep-well injection testing at Mulberry, Florida: U.S. Geological Survey Water Resources Investigation 75-81.
Hower, W.F., Lasater, R.M., and Mihram, R.G., 1972, Compatibility of injection fluids with reservoir components: in Cook, T.D., editor, American Association of Petroleum Geologists Memoir 18, Tulsa, OK, p. 287-293.
Hubbert, M.K. and Willis, D.C., 1972, Mechanics of Hydraulic Fracturing, in Underground Waste Management and Environmental Implications. T.D. Cook, Ed., American Assoc. Petroleum Geologists Memoir 18, p. 239-257.
Huff, Pat, 1985, Survey shows reliability of injection wells used by American Chemical Industry: Underground Injection, v. 1, no. 1, Chemical Manufacturers Association, Washington, D.C., p. 2-4.
Hughes, T.H., Norris, B.W., Brooks, K.E., Wilson, B.M., and Roche, B.N., 1985, A survey of current waste management technologies - methods of recovery, treatment, disposal, and storage of hazardous waste: The University of

Alabama Environmental Institute for Waste Management Studies Open-File Report No. 2, Tuscaloosa, AL, 140 p.
Hutchinson, M., 1974, Microbiological Aspects of Groundwater Pollution in Europe, Proceedings of the Reading Conference, 1972, p. 167-202.
Ianitsky, I.N., 1979, Helium survey: VIEMS Publ., Moscow, 80 p. (in Russian).
Interstate Oil Compact Commission, 1983, The 1983 annual meeting, Orlando, Florida, December 4-7, 1983: The Oil and Gas Compact Bulletin, v. XLII, no. 2, 20 p.
Ives, R.E., and Eddy, G.E., 1968, Subsurface disposal of industrial wastes: Interstate Oil Compact Commission, Oklahoma City, OK, 109 p.
Jorling, T.C., 1986, Environmental concerns, in Symposium on the technologies, policies, and implications of hazardous waste management: The University of Alabama Environmental Institute for Waste Management Studies, Tuscaloosa, AL, p. 222-230.
Kaufmann, M.I., D.A. Goolsby, and G.L. Faulkner, 1973, Injection of acidic industrial waste into a saline carbonate aquifer: geochemical aspects: International Symposium on Underground Waste Management, p. 526-551.
Kell, D. and Perry, R., 1975, 1976, Subsurface Disposal of liquid Industrial Wastes. Environmental Pollution Management 11/12, 1975, p. 159-163 and 1/2, 1976 p. 21-27.
Kent, R.T. and Mullican, J., 1976, Oral Communication. Texas Water Quality Board, Austin, Texas.
Keys, W.S., and Brown, R.F., 1973, Role of borehole geophysics in underground waste storage and artificial recharge, in Braunstein, Jules, editor, Underground waste management and artificial recharge, Volume 2: The George Banta Co., Menasha, WI, p. 147-191.
Kiang, Y., and Metry, A., 1982, Hazardous waste processing technology: Ann Arbor Science Publishers, Inc., Ann Arbor, MI, 549 p.
Kovalevsky, V.S., 1986, Groundwater regime studies in connection with groundwater development: Nedra Publ., Moscow, 200 p. (in Russian).
Kreidler, W.L., 1975, Underground disposal of liquid waste in New York: The University of New York, State Education Department, New York State Museum and Science Service, Map and Chart Series, no. 26, 29 p.
Kruseman G.P. and De Ridder, N.A., 1970, Analysis and evaluation of pumping test data: International Institute for Land Reclamation and Improvement, Bull. 11, Wageningen, The Netherlands, 200 p.
Ku, H.F.H., Vecchioli, J. et. al., 1975, Changes in Concentration of Certain Constituents of Treated Waste Water During Movement Through the Magothy Aquifer, Bay Park, New York. Jour. Research, U.S. Geological Survey, v. 3, p. 89-92.
Kunin, V.N., Kovalevsky, V.S., Eremeev, A.N., and Ianitsky, I.N., 1974, Studies of artesian water movement using natural and technogenic helium: IAH Memoires, Vol. X, Communications, Congres de Montpellier, p. 212-217.
Kuznetsov, S.I. et. al., 1962, Introduction to Geologic Microbiology. Izd. Akad. Nauk. SSSR, Baku, 320 p.
Lehr, J.H., 1986, Underground injection: a positive advocate: Proceedings of the International Symposium on Subsurface Injection of Liquid Wastes (New Orleans, LA), Water Well Journal Publishing Co., Dublin, OH., p. 51-56.
Little, Arthur D., Inc., 1979, Cost of compliance: Proposed underground injection control program; oil and gas wells: U.S. Environmental Protection Agency, Office of Drinking Water, EPA Contract No. 68-01-4698 (Task 6).

Lohman, S.H.,1972, Ground-water Hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.
Matthess, G., 1973, Die Beschaffenheit des Grundwassers -Lehrbuch der Hydrogeologie 2. Gebrüder Borntrager Berlin, Stuttgart, 324 p.
Matthess, G., 1985, Theoretical Background, Hydrogeology and Practice of Groundwater Protection Zones. Vol.6.
Matthews, C.S. and Russell, D.G. 1967, Pressure buildup and flow tests in wells: American Institute of Mining, Met. Monograph, v. 1.
Mayerhofer, H., 1977, Oral Communication. Kali + Salz, Kassel.
Meers, R.J., 1973, Design, drilling and completion, operation and cost of underground waste-disposal wells in Gulf Coast Region of Texas and Louisiana, in Braunstein, Jules, editor, Underground waste management and artificial recharge, Volume 1: The George Banta Co., Menasha, WI, p. 337-343.
Miller, L.M., 1957, Underground waste disposal and control: Journal American Water Works Association, v. 49, no. 10, p. 1334-1342.
Miller, R.A., Fox, R.D., and Pitts, D.M., 1981, Evaluation of catalyzed wet oxidation for treating hazardous waste, in Schultz, D.W. and Black, David, editors, Land Disposal: hazardous waste: Proceedings of the Seventh Annual Research Symposium, Philadelphia, PA, March 16-18, U.S. Environmental Protection Agency, Cincinnati, OH, NTIS-PB/81-173882, p. 272-276.
Miller, C., Fisher, T.A., II, Clark, J.E., Porter, W.M., Hales, C.H., and Tilton, J.R., 1986, Flow and containment of injected wastes: Proceedings of the International Symposium on Subsurface Injection of Liquid Wastes (New Orleans, LA), Water Well Journal Publishing Co., Dublin, OH., p. 520-559.
Modell, Nichael, Gaudet, G.G., Simson, Morris, Hong, G.T., and Biemann, Klaus, 1982, Supercritical water-testing reveals new process holds promise: Solid Wastes Management, v. 25, no. 8, August, p. 26-28, 30, 76.
Moffett, T.B., LaMoreaux, P.E., Smith, J.Y., and Dismukes, M.B., 1987, Management of hazardous wastes by deep-well disposal: Environmental Institute for Waste Management Studies, The University of Alabama, Tuscaloosa, Alabama, Open-File Report No. 11, 275 p.
Moore, P.L., 1986, Drilling practices manual, 2nd edition: Tulsa, Oklahoma, Penn Well Publishing Co., 586 p.
National Water Well Association, 1986, Proceedings of the international symposium on the subsurface injection of liquid wastes: National Water Well Association, Dublin, OH, 739 p.
Ostroot, G.W., and Ramos, Joe, 1972, Deep-well acid disposal - planning and completion, in Cook, T.D., editor, Underground waste management and environmental implications: American Association of Petroleum Geologists Memoir 18, Tulsa, OK, p. 77-85.
Paque, M.J.,1986, Class I injection well performance survey: Groundwater Monitoring Review, vol. 6, no. 3, p. 68-69.
Piper, A.M., 1969, Disposal of liquid wastes by injection underground - neither myth nor millenium: U.S. Geological Survey Circular 631, 15 p.
Plotnikov, N.I., 1963, On the problem of hazardous industrial wastewater disposal to deep horizons of the earth's crust, in Problems of Formation of Groundwater Chemical Composition: Nedra Publ., Moscow, p. 164-191 (in Russian).

Pojasek, R.B., 1979, Solidification as an ultimate disposal option for hazardous wastes, in Pojasek, R.B., ed., Toxic and hazardous waste disposal, volume one - processes for stabilization/solidification: Ann Arbor Science Publishers, Inc., Ann Arbor, MI, p. 1-8.

Proctor, C.L., III, 1984a, Overview of alternative technologies for hazardous waste management: Proceedings of the symposium on alternative technologies for hazardous waste management in Florida, The Hazardous Waste Management Program, Center for Biomedical and Toxicological Research, Institute of Science and Public Affairs, Florida State University, Tallahassee, FL, April, p. 13-21.

Proctor, C.L., III, 1984b, Technical assessment of alternative technologies for waste management in Florida: The Hazardous Waste Management Program, Center for Biomedical and Toxicological Research, Institute of Sciences and Public Affairs, Florida State University, Tallahassee, June, 59 p.

Pye, V.I., Patrick, R., and Quarles, J., 1983, Groundwater contamination in the United States: University of Pennsylvania Press, Philadelphia, PA, 315 p.

Randall, T.L., 1981, Wet oxidation of toxic and hazardous compounds, in Huang, C.P., editor, Industrial Waste: Proceedings of the Thirteenth Mid-Atlantic Conference, Ann Arbor Science Publishers, Inc., Ann Arbor, MI, p. 501-508.

Reeder, L.R., and Associates, 1977, Review and assessment of deep-well injection of hazardous waste: U.S. Environmental Protection Agency Report EPA-600/2-77-029, Solid and Hazardous Waste Research Division, Municipal Environmental Research Laboratory, Cincinnati, OH, NTIS PB-269-001, 186 p.

Reeder, L.T. et. al., 1977, Review and Assessment of Deep-Well Injection of Hazardous Waste. U.S. Environmental Protection Agency, Office of Research and Development, Municipal Environmental Research Laboratory, v. 1-4, EPO 600/2-77-029 a, Cincinnati, Ohio, 1446 p.

Rockwell International, 1980, Molten salt destruction (MSD) of hazardous wastes: Publication no. 523-K-18-1, Canoga Park, CA.

Rottgart, D., 1976, Versenkung Industrieller Abfallflüssigkeiten in den Untergrund Über Bohrungen. Deutsche Gesellschaft fÜr Mineralölwissenschaft und Kohlechemie e.v. Forschungsbericht 45125, Hamburg, 57 p.

Senkan, S.M., and Stauffer, N.W., 1981, What to do with hazardous wastes: Technology Review, November/December, p. 72-77.

Sharply, J.M., 1961, Applied Petroleum Microbiology. Memphis, Tennessee, Buckman, 196 p.

Smith, D.K., 1976, Cementing: Society of Petroleum Engineers of AIME, Monograph v. 4.

Stow, S.H., and Haase, C.S., 1986, Subsurface disposal of liquid low-level radioactive wastes at Oak Ridge, Tennessee: Proceedings of the International Symposium on Subsurface Injection of Liquid Wastes, National Water Well Association, Dublin, OH, p. 656-675.

Strnad, M., and Novotny, D., 1973, Determination of the mechanical compatibility of porous rocks with waste water in its subsurface disposal: Water Research, v. 7, no. 11, p. 1599-1607.

Sun, R.J., 1973, Hydraulic Fracturing as a Tool for Disposal of Wastes in Shales. 2nd Int. Symp. on Underground Waste Management and Artificial Recharge, New Orleans, Sept. 26-30, 1973, v.1, New Orleans, p. 219-272.

Sun, R.J.. et. al., 1974, Hydraulic Fracturing in Shale at Waste Valley, New York - Study of Bedding-Plane Fractures Induced in Shale for Waste Disposal. U.S. Deparment of the Interior, Geological Survey Open File Report 71-365, Reston, Virginia, 152 p.

Sun, R.J., 1976, Oral Communication. U.S. Geological Survey, Reston, Virginia.

Syde, T., Mechem, F.R., and Anzzolin, A.R., 1986, Technical requirements for permitting a Class I hazardous waste injection well - an overview: Journal of the Underground Injection Practices Council, Oklahoma City, OK, Number 1, p. 153-172.

Talbot, J.S., 1972, Requirements for monitoring of industrial deep-well waste-disposal systems: American Association of Petroleum Geologists Memoir 18, Tulsa, OK, p. 85-93.

Talbot, J.S., and Beardon, P., 1964, The deep-well method of industrial waste disposal: Chemical Engineering Progress, v. 60, no. 1, p. 49-52.

Texas Water Quality Board, 1972, Subsurface waste disposal in Texas: Publication no. 72-QS.

Thornhill, J.T., and Benefield, B.G., 1986, Mechanical integrity research: Proceedings of the International Symposium on Subsurface Injection of Liquid Wastes, National Water Well Association, Dublin, OH, p. 241-278.

Thornhill, J.T., Short, T.E., and Silka, L., 1982, Application of area of review concept: Ground Water, v. 20, no. 1, p. 32-38.

Tucker, W.E., and Kidd, R.E., 1973, Deep-well disposal in Alabama: Alabama Geological Survey, Bulletin 104, Tuscaloosa, AL, 230 p.

Underground Injection Practices Council, 1985, Groundwater: Oklahoma City, OK, 3 p.

UIPC, 1987, A class I injection well survey - phase II report: survey of operations: Oklahoma City, Oklahoma, Underground Injection Practices Council, 49 p.

U.S. Environmental Protection Agency, 1973, Groundwater pollution from subsurface excavations: Office of Air and Water Programs Report, EPA-430/9-73-123, Washington, D.C., 236 p.

U.S. Environmental Protection Agency, 1980, Treatability manual Volume IV - cost estimating: Office of Research and Development, EPA-600/8-80-042d, Washington, D.C., 402 p.

U.S. Environmental Protection Agency, 1983, Highlights of preliminary finds, national survey of hazardous waste generators and treatment, storage, and disposal facilities regulated under RCRA in 1981: Office of Solid Waste, Washington, D.C.

U.S. Environmental Protection Agency, 1984, p. 101, Environmental News: Office of Public Affairs, Washington, D.C., May 10, 3 p.

U.S. Environmental Protection Agency, 1985, Report to Congress on injection of hazardous waste: U.S. Environmental Protection Agency, Office of Drinking Water, Washington, D.C., 265 p.

U.S. Environmental Protection Agency, 1986, Federal underground injection control reporting system, summary report: Office of Drinking Water, Washington, D.C., 8-16-85, 54 p.

U.S. Environmental Protection Agency, 1988, 40 CFR Parts 124, 144, 146, and 148, Underground Injection Control Program, Hazardous Waste Disposal Injection Restrictions and Requirements for Class I Wells, Final Rule: Federal Register, July 26, 1988, p. 28118-28157.

Van der Velde, George, 1985, The coming capacity crunch in hazardous waste management: Chemical Waste Management, Oak Brook, IL, 11 p.

Van Everdingen, R.O., and Freeze, R.A., 1971, Subsurface disposal of waste in Canada: Inland Water Branch, Department of the Environment Technical Bulletin no. 49, Ottawa, Ontario, 64 p.

Vecchioli, J., 1981, Subsurface injection of liquid waste in Florida, United States of America: The Science of the Total Environment, v. 21, p.127-136.

Velde, G.V., 1986, A case study of Chemical Waste Management facility at Vickery, Ohio: Proceedings of the International Symposium on Subsurface Injection of Liquid Wastes (New Orleans, LA), Water Well Journal Publishing Co., Dublin, OH., p. 355-356.

Virginia Water Resources Research Center, 1974, Deep-well disposal: institutional, physical, and economic considerations, preliminary draft: Virginia Polytechnic Institute and State University, Blacksburg, VA, 304 p.

Walker, W.R., and Cox, W.E., 1973, Legal and institutional considerations of deep-well disposal, in Braunstein, Jules, editor, Underground Waste Management and Artificial Recharge, Volume 1: The George Banta Co., Menasha, WI, p. 3-190.

Walker, W.R., and Cox, W.E., 1976, Deep-well injection of industrial wastes: government controls and legal constraints: Virginia Water Resources Research Center, Blacksburg, VA, 163 p.

Walters, J.V., Norris, W.B., Brewer, J.S., and Roche, B.N., 1986, Hazardous waste incineration: The University of Alabama Environmental Institute for Waste Management Studies Open-File Report No. 9, Tuscaloosa, AL, 77 p.

Ward, D.S., Wadsworth, T.D., Buss, D.R., and Mercer, J.W., 1986, Analysis of potential failure mechanisms pertaining to hazardous-waste injection in the Texas Gulf Coast region: Journal of the Underground Injection Practices Council, no. 1, p.120.

Warner, D.L., 1968, Subsurface disposal of liquid wastes by deep-well injection, in Galley, J.E., ed., Subsurface disposal in geologic basins - a study of reservoir strata, American Association of Petroleum Geologists, Memoir 10, Tulsa, OK, p. 11-20.

Warner, D.L., 1975, Monitoring Disposal-Well Systems. Environmental Monitoring and Support Laboratory, Office of Research and Development, U.S. Evironmental Protection Agency, EPA-680/4-74-008, Las Vegas, Nevada, 100 p.

Warner, D.L., Davis, S.N., and Syed, T., 1986, Evaluation of confining layers for containment of injected wastewater: Proceedings of the International Symposium on Subsurface Injection of Liquid Wastes, New Orleans, LA, National Water Well Assoc., Dublin, Ohio, p. 417-446.

Warner, D.L., Koederitz, L.F., Simon, A.D., and Yow, M.G., 1979, Radius of pressure influence of injection wells: U.S. Environmental Protection Agency Report 600/2-79-170, Washington, D.C., 204 p.

Warner, D.L., and Lehr, J.H., 1977, An introduction to the technology of subsurface wastewater injection: U.S. Environmental Protection Agency, Office of Research and Development, Report EPA-600/2-77-240, Ada, OK, 345 p.

Warner, D.L., and Lehr, J.H., 1981, Subsurface wastewater injection; the technology of injecting wastewater into deep wells for disposal: Berkeley, California, Premier Press, 344 p. (Also released in 1977 as "An introduction to the technology of subsurface wastewater injection, "EPA-600/2-77-240, 345 p.)

Wedephol, K.H., 1967, Geochemie. Sammlung Göschen 1224/1224a/1224b, Walter de Gruyter Co., Berlin, 220 p.

Westat, Inc., 1984, National survey of hazardous waste generators and treatment, storage, and disposal facilities regulated under RCRA in 1981: U.S.

Environmental Protection Agency, Office of Solid Waste, Washington, D.C., Westat Inc., Rockville, MD, 306 p.
Wiles, C.C., 1978, Assessment of deep-well injection of hazardous waste: in Shultz, David, compiler, Land Disposal of hazardous waste: Proceedings Fourth Annual Research Symposium, EPA-600/9-78-016, Cincinnati, OH.
Wilson, Lee, and Holland, M.T., 1984, Aquifer classification for the UIC program: prototype studies in New Mexico: Ground Water, v. 22, no. 6, p. 706-716.
Winar, R.M., 1967, The disposal of wastewater underground: Industrial Water Engineering, 5 p.
Wolff, R.G., et. al., 1975, Stress determination by hydraulic fracturing in subsurface waste injection. Journal American Water Works Assn., v. 67, No. 9, 4 p.
Wood, L., 1976, Oral Communication. U.S. Survey, Reston, Virginia.
Worthy, W., 1982, Hazardous waste: treatment technology grows: Chemical and Engineering News, March, p. 10-16.

APPENDIX A: CASE HISTORIES

SUBSURFACE INJECTION OF LIQUID WASTE WITH EMPHASIS ON INJECTION PRACTICES IN FLORIDA

John J. Hickey
and
John Vecchioli

1. Abstract

Subsurface injection of liquid waste is used as a disposal method in many parts of the country. It is used particularly when other methods for managing liquid waste are either not possible or too costly. Interest in subsurface injection as a waste-disposal method stems partly from recognition that surface disposal of liquid waste may establish a potential for degrading freshwater resources. Where hydrogeologic conditions are suitable and where surface disposal may cause contamination, subsurface injection is considered an attractive alternative for waste disposal. Decisions to use subsurface injection need to be made with care because, where hydrogeologic conditions are not suitable for injection, the risk to water resources, particularly groundwater, could be great. Selection of subsurface injection as a waste-disposal method requires thoughtful deliberation and, in some instances, extensive data collection and analyses.

Subsurface injection is a geological method of waste disposal. Therefore, many State and local governmental officials and environmentally concerned citizens who make decisions about waste-disposal alternatives may know little about it. This report serves as an elementary guide to subsurface injection and presents subsurface injection practices in Florida as an example of how one State is managing injection.

2. Introduction

Subsurface injection of liquid waste is used as a disposal method in many parts of the country. It is used particularly when other methods for managing liquid are either not possible or too costly. The petroleum industy, since the 1930s, has used subsurface injection to dispose of brine wastewater that is produced with oil and gas. More recently, chemical and manufacturing industries have begun to dispose of liquid wastes into the subsurface in a number of States. In Florida several municipalities have adopted subsurface injection for disposal of effluent from sewage-treatment plants because stringent water-quality regulations make surface disposal costly. Interest in subsurface injection as a waste-disposal method stems partly from recognition that surface disposal of liquid waste may establish a potential for degrading freshwater resources. Where hydrogeologic conditions are suitable and where surface disposal may cause contamination, subsurface injection is considered a viable alternative for waste disposal.

Decisions to use subsurface injection are made carefully because, where hydrogeologic conditions are not suitable for injection, the risk to water recources, particularly groundwater, could be great. Selection of subsurface injection as a waste-disposal method requires thoughtful deliberation and, in some instances, extensive data collection and analyses.

Subsurface injection is a geological method of waste disposal. Therefore, many State and local governmental officials and environmentally concerned citizens who make decisions about waste-disposal alternatives may know little about the method. This report serves as an elementary guide to subsurface injection and presents subsurface injection practices in Florida as an example of how one State is managing injection. The first half of the report describes hydrogeologic factors, classification and distribution of injection wells, and regulation of injection. The second half of the report describes experience with subsurface injection in Florida, where it has been widely practiced for many years. Support for this report was provided by the Information Transfer Program of the U.S. Geological Survey, Water Resources Division.

3. Subsurface Injection Fundamentals

Subsurface injection is the forcing of liquid through a well into underground rock openings that generally are filled with water. Sometimes the weight of the liquid column in a well provides sufficient force for injection. In this application, the well is called a gravity injection well /Fig. A1/. Commonly, another force is added to the weight of the liquid to cause injection. Pumps add this force by increasing the pressure on the liquid until its pressure, at the point of injection, exceeds the pressure of the water in the underground rock openings. Where a pump is employed, the well is called a pressure injection well /Fig. A1/.

An injection well is a cylindrical conduit extending from land surface into underground rock openings. Most of an injection well generally is lined with a casing to prevent the collapse of the conduit and to restrict outflow of the liquid to the desired injection depths. Wells that are constructed in unconsolidated sand and gravel strata commonly are equipped with a perforated casing or a screen attached to the end of the casing to emplace the injected liquid at the chosen depths. Wells constructed in consolidated rock, such as limestone, typically have an interval of unlined borehole below the casing for the same purpose. Two or more concentric casings, each having a surrounding cement grout sheath, commonly are installed through the shallow strata to facilitate drilling and to provide maximum protection of fresh groundwater resources.

Underground rock openings are called pores, the volume of pore space in a unit volume of rock is called porosity and is expressed as a percentage. Generally, a rock contains both isolated and connected pores /Fig. A2/. Only the connected pores can accept, store, and transmit injected liquid away from a well. Pressure buildup that results from injection increases porosity by expanding the receiving rocks. Additional storage space is also created by compression of the native water by the increased pressure.

In some hydrogeologic terrains, most available space for storage of waste would be related solely to expansion of rock and compression of native water.

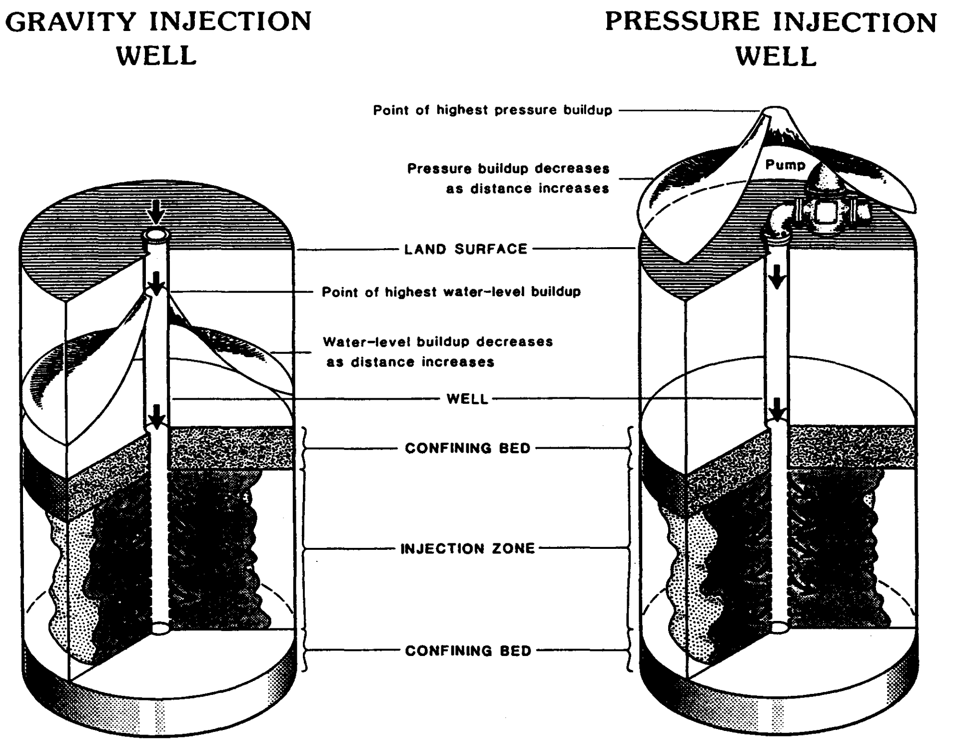


Fig. A1. Gravity and pressure injection wells.

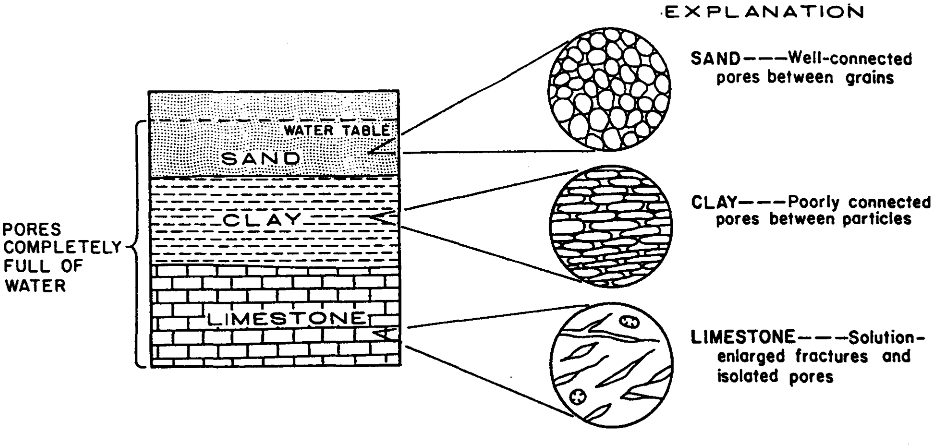


Fig. A2. Common types of underground rock openings.

This is likely when the aquifer chosen for injection is well confined vertically and laterally. In other hydrogeologic terrains, particularly those that place little restriction on lateral flow, the greatest amount of storage space for injected liquid waste would be provided in the long term by displacement of the native water. This displacement could be an important constraint on use of subsurface injection because, in aquifers chosen for waste disposal, native water generally is saline. When saline water is displaced it could discharge into or mix with freshwater. The possibility of movement of native water at distances from the injection point is an important consideration when making decisions about whether or not to use subsurface injection.

3.1. Injection Well Construction

A typical injection well is constructed of several components. The number and type of these components depend on the chemical nature of the liquid waste and the degree of consolidation of the host rock. A well used for injection of treated sewage into a consolidated formation has at least three components: /1/ wellhead, /2/ casing/s/, and /3/ cement sheath/s/.

In contrast, a well used for injection of industrial waste into an unconsolidated formation has at least eight components: /1/ wellhead, /2/ casing/s/, /3/ cement sheath/s/, /4/ noncorrodible injection tubing, /5/ annular fluid between casing and tubing, /6/ packer at end of tubing, /7/ well screen and /8/ gravel pack /Fig. A3/. Items 7 and 8 may be replaced by an open hole in consolidated rock.

To minimize corrosion and to ensure long-term structural integrity, the material used for each component must be matched to all other components, to the liquid waste, and to the native formation water. Most injection wells have multiple casings, cement sheaths, and injection tubing /Fig. A3/. The multiple casings are a pipe within a pipe within a pipe, each separated from the others by cement sheaths. The injection tubing, the smallest diameter pipe, commonly is separated from the innermost casing by an annulus that is filled with a corrosion inhibiting liquid. All components of an injection well are chosen as needed for structural integrity of the well and for protection of underground sources of drinking water.

3.2. Hydrogeologic Requirements for Injection

For subsurface injection to succeed as a disposal method within the constraints of Federal and State requirements, the injection site and the surrounding region should possess a number of hydrogeologic characteristics, as follows:

- The injection zone's geometry and hydraulic characteristics allow liquid waste to be injected at a pressure lower than that which would cause fracturing of the rocks;
- The injection zone is regionally extensive so that liquid waste can be stored with minimal, if any, impact on underground sources of drinking water;
- The injection zone is underlain and overlain by confining beds that retard upward and downward movement of native water and liquid waste;
- The injection zone and confining beds have mappable and geologically simple

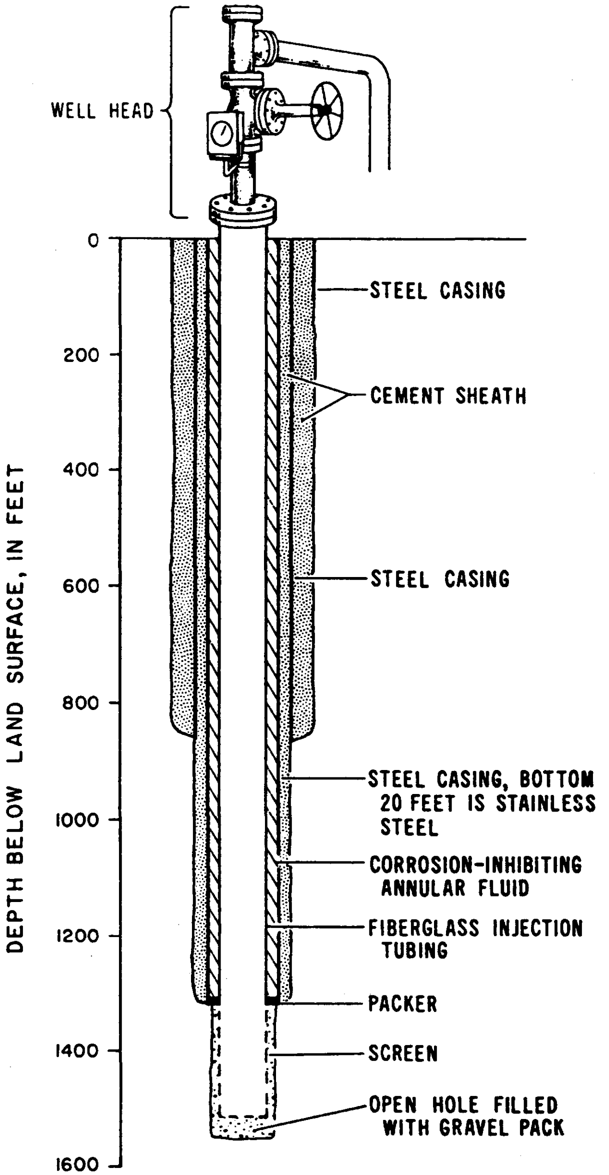


Fig. A3. Typical well designed for injection of corrosive waste into an unconsolidated formation.

shapes that are not complicated by folds or crossed by hydraulically open faults;

The injection zone contains native water that has a dissolved solids concentration equal to or greater than 10.000 mg/L/milligrams per liter/. Injection of waste into an aquifer containing water having a dissolved-solids concentration of less than 10.000 mg/L is sometimes allowable, providing that the waste is highly treated or the aquifer is exempted following procedures spelled out in Federal or State regulations;

- Liquid waste chemistry is sufficiently compatible with the chemical composition of the rocks and native water to prevent or limit reactions that damage well components by corrosion, plug the injection zone, weaken the structural integrity of the rocks, or create toxic substances;
- Mineral and petroleum resources are absent from the injection zone so as not to constrain their development; and
- The injection zone and confining beds are not penetrated by improperly abandoned wells or test holes that could provide pathways to underground sources of drinking water or to mineral and petroleum resources.

The possible consequences of subsurface injection at a site that lacks some of these hydrogeologic characteristics are shown in Fig. A4.

Assessment of the regional and local hydrogeology of a proposed injection site is needed to evaluate the site's suitability for subsurface injection. A regional assessment by the prospective injector is a preliminary step. If the regional assessment reveals that injection may be feasible, a local assessment in the immediate vicinity of the proposed injection site is performed.

3.3. Regional Hydrogeologic Assessment

A regional assessment provides an overview of the hydrogeologic characteristics of the proposed site and the surrounding region. It typically makes use of available information, including information from other geographic areas that have rock types similar to those found at the proposed site.

A regional assessment commonly consists of the following:

- Preliminary identification of potential injection zones and confining beds and their probable lateral extent;
- Probable presence or absence of complicating folds or faults at the proposed injection site and in the region;
- Probable areal and vertical distribution of dissolved-solids concentrations of native water in the rocks;
- Location of known underground sources of drinking water;
- Location of known mineral and petroleum resources;
- Location of abandoned wells and test holes in the region surrounding the proposed injection site; and
- Qualitative evaluation of the probable regional impact of subsurface injection.

3.4. Local Hydrogeologic Assessment

A local assessment is an evaluation of the impact of injection in the vicinity

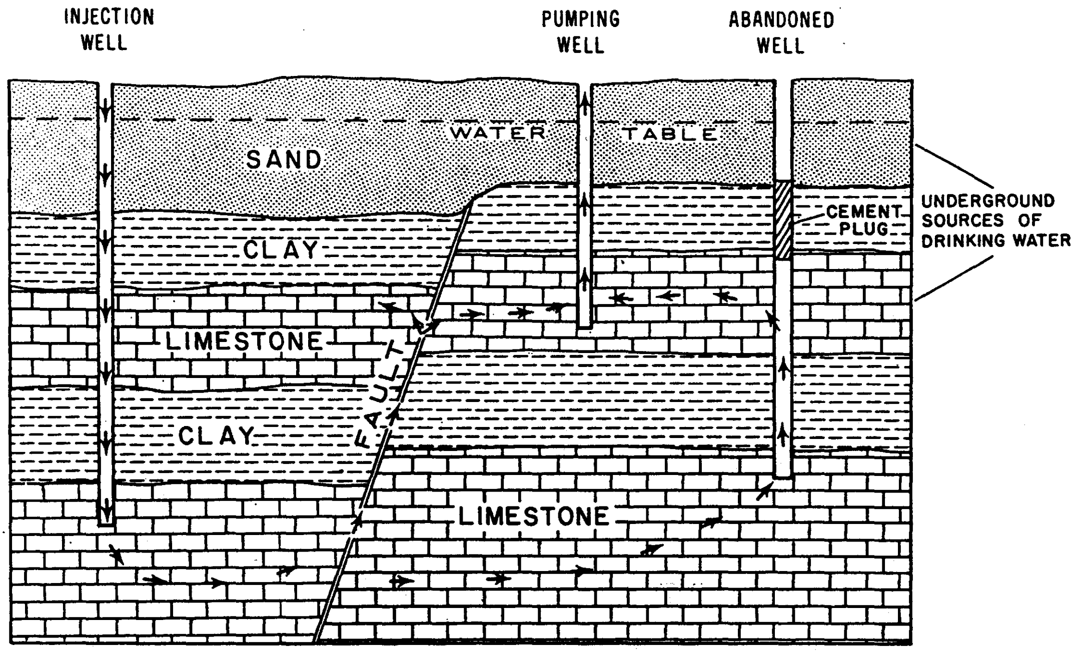


Fig. A4. Possible consequences of subsurface injection at a site not having the necessary hydrogeologic characteristics.

of a proposed injection site. Data from drilling and hydrologic testing at the site are used to evaluate the specific hydrogeologic characteristics of the site.

Examples of some of the lithologic, geophysical, and hydraulic data that are commonly collected in a drilled borehole are shown in Fig. A5.

A local hydrogeological assessment commonly consists of the following:

- Delineation and description of the injection zone, confining beds, and underground sources of drinking water;
- Determination of chemical compatibility of the liquid waste with rocks and native water in the injection zone;
- Determination of the hydraulic characteristics of the injection zone and confining beds;
- Demonstration of the injection zone's capability to accept liquid waste at the desired rate;

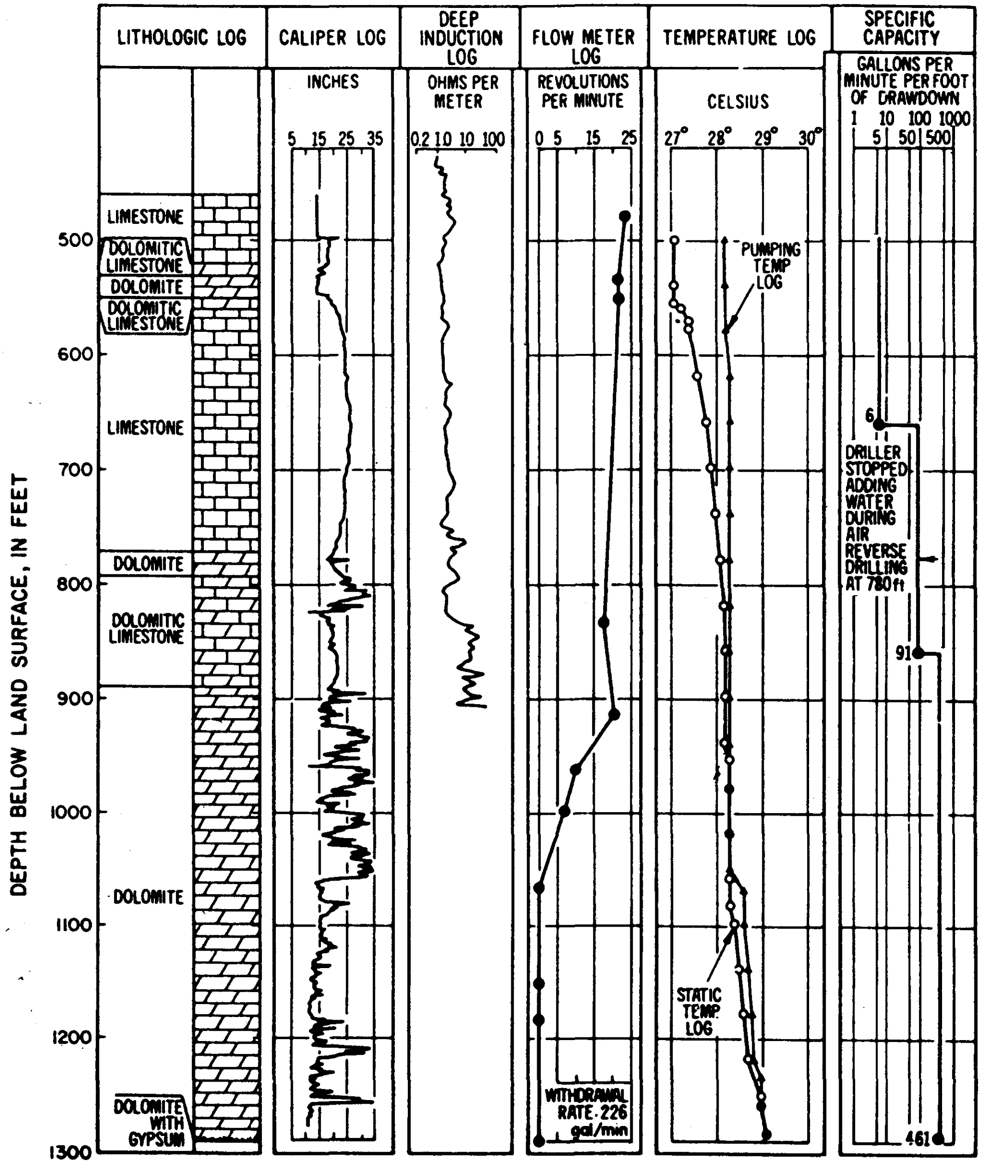


Fig. A5. Examples of lithologic, geophysical, and hydraulic data that are collected in a drilled hole. /From Hickey and Barr, 1979, p.16/.

- Estimation of pressure and water quality changes likely to occur because of long-term injection; and
- Specification of a monitoring program for long-term observation of the impact of injection on the subsurface.

3.5. Monitoring

Monitoring of subsurface injection of liquid waste generally consists of measuring and recording the effects of injection at the injection well and the surrounding observation wells. Injection rate, wellhead pressure, annulus pressure /if pertinent/, and waste properties are monitored at an injection well. Pressure and water properties are monitored at observation wells at various distances from the injection well. These data can be used to assess the injection well's performance and the environmental impact of subsurface injection.

On the basis of their distance from an injection well, observation wells can be classified as onsite, satellite, or regional /Vecchioli, 1979/. Onsite wells are generally within tens of feet from an injection well and are used to monitor vertical migration of waste or displaced saline formation water. Satellite wells monitor the injection zone at distances of hundreds to several thousands of feet from an injection well and are used to monitor:

1. Hydraulic response of the aquifer to individual injection systems,
2. Position and direction of movement of waste, and
3. Alterations in the chemical and physical quality of the waste.

Regional wells monitor the injection zone at distances of miles from an injection well and are used to record the effects of injection wells on the groundwater flow system, such as on the position of distant saltwater-freshwater interfaces. Fig. A6 is a schematic diagram of observation wells installed at several distances from an injection well to measure hydraulic and chemical changes.

Migration of injected waste from the point of injection involves flow of native water that commonly has a density different from the waste. Under these variable density circumstances, pressure is the appropriate physical quantity to measure to determine flow directions. In addition to the pressure data, chemical concentration of water from observation wells is used to assess the impact of injection on underground sources of drinking water.

Monitoring requirements vary depending on the class of injection well; in some instances, they also can vary from State to State for the same class of well. /Classification of injection wells is discussed in the following section./ For example, Florida regulations allow for requiring observation wells in the vicinity of a class I injection well, whereas Texas regulations have no such allowance. Both States require that operation of a class I injection well be monitored.

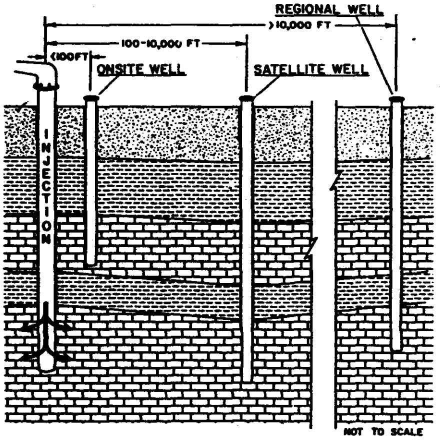


Fig. A6. Observation wells around an injection well. /Modified from Vecchioli, 1981/.

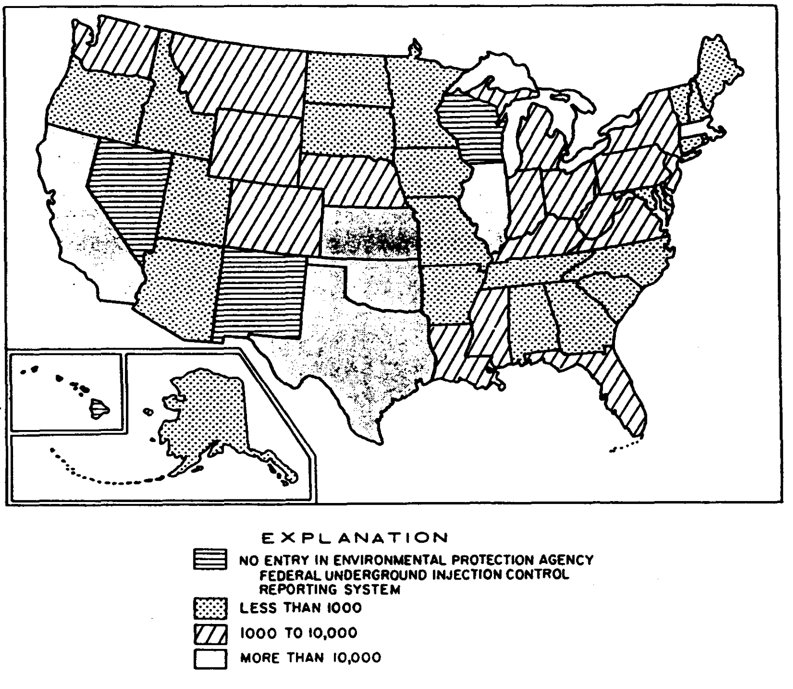


Fig. A7. Distribution of injection wells in the United States. /Source: U.S. Environmental Protection Agency Federal Underground Injection Control Reporting System, June 21, 1983/.

4. Subsurface Injection in the United States

The first large-scale use of subsurface injection for the disposal of liquid wastes in the United States was by the petroleum industry in the 1930s. Brine produced with oil was injected back into the subsurface instead of discharged onto the land surface. Since the 1930s, the petroleum industry has added injection wells for secondary and enhanced recovery of oil to an increasing number of brine-disposal wells.

In contrast to the half-century-old practice in the petroleum industry, injection wells for disposal of industrial and municipal wastes have been employed mainly within the last few decades. However, once begun, their use grew rapidly.

The five classes of injection wells defined by the U.S. Environmental Protection Agency /EPA/ are:

1. Class I wells are used for disposal of industrial or municipal waste beneath a formation that contains, within one-quarter mile, an underground source of drinking water.
2. Class II wells are used by the petroleum industry.
3. Class III wells are used during the process of extracting minerals or energy from the subsurface.
4. Class IV wells are used for disposal of hazardous or radioactive wastes into or above a formation that contains, within one-quarter mile, an underground source of drinking water.
5. Class V wells are those wells not included in the other classes.

The EPA maintains a record of the number of injection wells by class in each State based on information reported to EPA by the States. A "Condensed Summary Report" from the EPA's Federal Underground Injection Control Reporting System, June 21, 1983, is given in Table A1. At that time, Texas had the most class I, class II, and class III injection wells; New York, the most class IV injection wells; and Massachusetts, the most class V injection wells.

There were more than 222,000 injection wells in the United States in 1983. Class II wells, used by the petroleum industry, made up more than 60 percent of these wells. The distribution of recorded injection wells throughout the country is shown by State in Fig. A7 and by class in Fig. A8.

Federal regulation of subsurface injection has evolved over the last two decades. Increased disposal of industrial and municipal wastewaters by subsurface injection during the 1960s prompted the Federal Water Quality Administration /FWQA/ to issue a Federal policy statement on wastewater injection. The policy stated that subsurface injection should be used as a waste-disposal method only as a last alternative - and then only with great caution and for a limited period of time. In 1973, after creation of the EPA /in 1970/ and absorption of the FWQA, EPA issued a policy statement on subsurface emplacement of fluids by well injection that was similar tq the FWQA policy. In the EPA policy, subsurface injection was also viewed as a temporary practice until new technology to treat the waste became available.

In response to the general concern with ensuring the safety of drinking water in the United States, Congress in 1974 enacted the Safe Drinking Water Act, Public Law 93-523. Protection of underground sources of drinking water from damage by subsurface injection of liquids was dealt with in detail in part C of the Act. In 1977, part C was amended by Public law 95-190. Through the Safe Drinking Water Act, Congress assigned responsibility for developing regulations for underground injection control to the EPA. These regulations were published in the Federal Register May 19 and June 24, 1980, and were amended and republished in the Federal Register on April 1, 1983. The regulations allow a State to accept primary enforcement responsibility for an underground injection control program providing that the State's program contains regulations at least as stringent as the Federal regulations. By mid-1983, 13 States had accepted primary enforcement responsibility for some or all of the five classes of injection wells. Identification of States with enforcement responsibility will be made during 1984. EPA is required by the Safe Drinking Water Act to propose, promulgate, and enforce an underground injection control program for all injection wells within those States that do not accept primary enforcement responsibility.

5. Waste Management Through Subsurface Injection

Waste management has been a major concern in the United States for the past 40 years. This is reflected in the number of Federal laws enacted during that period. Management of waste may become more difficult if the quantities of waste increase because of continuing urban, agricultural, and industrial growth and if more hazardous types of wastes are generated. The search for reliable and economic means to ensure that man's environment is minimally influenced by the residue of society has been, is, and will be an ongoing process.

Subsurface injection can offer a direct and effective means for managing liquid waste where hydrogeologic conditions are favorable. However, before injection can be used, at least two questions have to be addressed. The first is, can an injection well be soundly constructed at the proposed site? The second is, can the hydrogeology of the proposed injection site and the surrounding area be described in sufficient detail so that flow paths of displaced native water and injected liquid waste can be determined and monitored with confidence?

Injection wells are constructed using well-established technology. Consequently, the principal engineering problem to be solved is selection of methods and materials suited to a site's hydrogeology and a waste's composition. Although simple in concept, the task is not always easy in practice; it may not be possible to collect suffficent hydrogeologic data on which to base an appropriate selection of methods and materials. Most hydrogeologic terrains exhibit small-scale spatial variations in hydraulic characteristics. Important small-scale changes in hydraulic characteristics could be below the resolution limits of the available data. Incomplete data about permeable zones could lead to selection of an inappropriate cement type and emplacement method. This could cause incomplete cement coverage around casing strings, which in turn could lead to vertical migration of injected waste. Incomplete cement coverage is a potential shortcoming for all injection wells, particularly wells drilled in

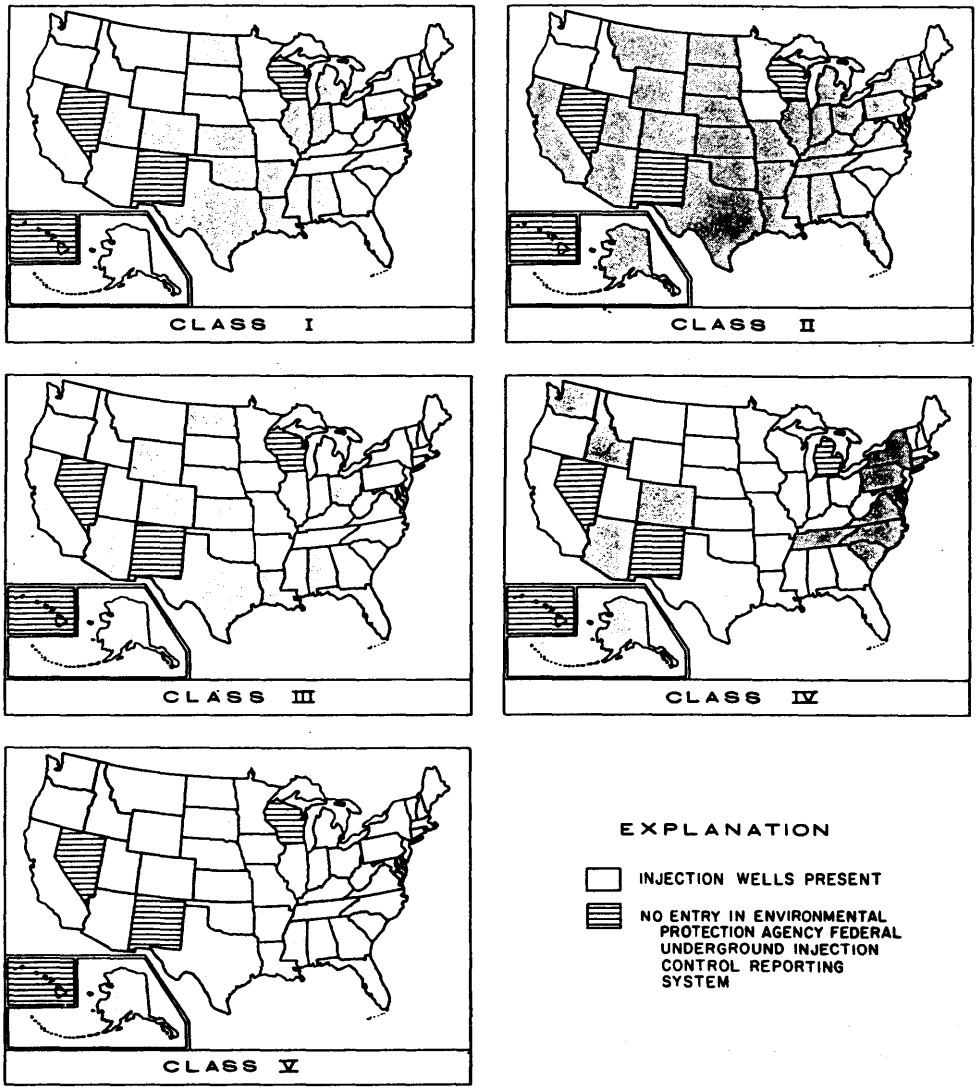


Fig. A8. Distribution of injection wells in the United States, by class. /Source: U.S. Environmental Protection Agency Federal Underground Injection Control Reporting System, June 21, 1983/.

Table A1. National distribution of injection wells /Source: U.S. Environmental Protection Agency Federal Underground Injection Control Reporting System, June 21, 1983/ (Number of wells in Florida adjusted to reflect a more recent Florida Department of Environmental Regulation inventory of injection wells.).

Region	State	All wells	Well class: I	II	III	IV	V
01----	Connecticut	173	9	--	--	7	157
	Massachusetts	18,252	--	--	--	--	18,252
	Maine	18	--	--	--	--	18
	New Hampshire	27	--	--	--	--	27
	Rhode Island	42	--	--	--	--	42
	Vermont	1	--	--	--	--	1
02----	New Jersey	1,327	--	--	--	--	1,327
	New York	6,348	11	3,853	149	184	2,151
03----	Delaware	3	--	--	--	--	3
	Maryland	968	--	--	--	3	965
	Pennsylvania	8,760	5	4,607	--	31	4,117
	Virginia	1,676	--	1	--	3	1,672
	West Virginia	2,034	7	319	17	--	1,691
04----	Alabama	169	8	152	9	--	--
	Florida	7,075	52	80	3	3	6,937
	Georgia	4	--	--	--	--	4
	Kentucky	4,642	--	4,357	--	--	285
	Mississippi	1,348	7	1,223	--	--	118
	North Carolina	33	3	--	--	3	27
	South Carolina	63	--	--	--	30	33
	Tennessee	57	--	13	--	11	33
05----	Illinois	18,503	10	18,492	--	--	--
	Indiana	3,669	76	3,565	--	--	28
	Michigan	4,207	97	1,275	110	--	2,725
	Minnesota	19	--	--	--	--	19
	Ohio	6,417	--	3,601	2	--	2,814
06----	Arkansas	871	23	808	--	--	40
	Louisiana	4,544	80	4,249	215	--	--
	Oklahoma	11,291	13	11,278	--	--	--
	Texas	65,470	129	41,859	23,124	--	358
	Indian lands within the region	3,300	--	3,300	--	--	--

(continued)

Table A1. (continued)

07----	Iowa	14	--	--	--	--	14
	Kansas	16,298	57	15,175	394	--	672
	Missouri	223	--	223	--	--	--
	Nebraska	1,983	--	1,983	--	--	--
08----	Colorado	1,069	1	1,001	59	2	6
	Montana	1,448	--	1,447	--	--	1
	North Dakota	434	1	429	4	--	--
	South Dakota	8	--	8	--	--	--
	Utah	541	--	504	30	--	7
	Wyoming	4,924	--	4,016	898	--	10
09----	Arizona	509	--	3	484	5	17
	California	13,844	--	13,844	--	--	--
	Guam	136	--	--	--	--	136
	Indian lands within the region	519	--	518	--	--	1
10----	Alaska	164	--	160	--	1	3
	Idaho	581	--	--	--	1	580
	Oregon	712	--	--	--	--	712
	Washington	5,640	1	--	--	10	5,629
	Total	220,358	590	142,344	25,498	294	51,632

carbonate rocks. Whether or not incomplete cement coverage actually contributes to vertical migration depends on where the cement is missing. For example, cement could be missing from a small interval of a very thick confining bed and not contribute to vertical migration of waste, whereas cement missing from the same size interval in a thin confining bed could contribute to vertical migration of waste.

Hydrogeologic descriptions are based on borehole data collection and interpretative methods that generally are also well established. The principal hydrogeologic problem to be solved is the formulation of a three-dimensional description of hydraulic characteristics using data collected from widely separated boreholes. Areas that have significant variability in hydraulic characteristics cannot be described using widely spaced data. Areas that have relatively homogeneous, or at least mappable, hydraulic properties can be described. However, even in this case, the small-scale spatial variations of most hydrogeologic terrains cannot be readily assessed, and this introduces an element of risk. Because this risk is generally not measurable and could be very important, cautious hydrogeologic and engineering judgments are needed for making decisions about whether or not to use subsurface injection for waste disposal.

Under proper conditions, subsurface injection can be an appropriate and workable waste management alternative. However, because proper conditions are difficult to demonstrate conclusively in many geologic terrains, a cautious approach to the use of subsurface injection for waste management is a reasonable course of action.

6. Selected References

The following references are provided so that interested readers can obtain additional information on the topics discussed in this report. This list includes both publications mentioned in the preceding text and other publications that could be useful for further understanding of subsurface injection.

Aplin, P.L., et. al, 1944, Regional subsurface stratigraphy and structure of Florida and southern Georgia: American Association of petroleum Geologists Bulletin, v. 28, No. 12, p. 1673-1753.

Braunstein, J., et. al, 1973, Underground waste management and artificial recharge: American Association of Petroleum Geologists, Preprints of papers presented at the Second International Symposium on Underground Waste Management and Artificial Recharge, v. 1, p. 3-633, v. 2, p. 667-931.

Cook, T.D., et. al, 1972, Underground waste management and environmental implications; American Association of Petroleum Geologists, Memoir 18, 412 p.

Ehrlich G.G., et. al, Chemical changes in an industrial waste liquid during post-injection movement in a limestone aquifer, Pensacola, Florida: Ground Water, v. 17, No. 6, p. 562-573.

Florida Department of Environmental Regulation, 1982, Florida underground injection control program: Report in the files of the Florida Department of Environmental Regulation.

Florida Department of Natural Resources, 1966, Special order No. 3: State of Florida Department of Natural Resources Oil and Gas Statute, Rules, Forms, and Orders.

Goolsby, D.A., 1972, Geochemical effects and movement of injected industrial waste in a limestone aquifer: American Association of Petroleum Geologists, Memoir 18, p. 355-368.

Hickey, J.J., 1982, Hydrogeology and results of injection tests at waste-injection test sites in Pinellas County Florida: U.S. Geological Survey Water-Supply Paper 2183, 42 p.

Ibid, 1984, Subsurface injection of treated sewage into a saline-water aquifer at St. Petersburg, Florida-aquifer pressure buildup: Ground Water, v. 22, No. 1, p. 48-55.

Hickey, J.J. et. al, 1979, Hydrogeologic data for the Bear Creek subsurface-injection test site, St. Petersburg, Florida: U.S. Geological Survey Open-File Report 78-853, 53 p.

Hickey, J.J., et. al, 1982, Results of deep-well injection testing at Mulberry, Florida: U.S. Geological Survey Water Resources Investigations 75-81, 15 p.

Hull, R.W., et. al, 1982, Data on subsurface storage of liquid waste near Pensacola, Florida, 1963-1980: U.S. Geological Survey Open File Report 82-689, 179 p.

Kaufman, M.I., et. al, 1973, Injection of acidic industrial waste into a saline carbonate aquifer: geochemical aspects, in Braunstein, J., ed., Underground waste management and artificial recharge: American Association of Petroleum Geologists, Preprints, v.1, p. 526-551.

Kimrey, J.O., et. al, 1982, Geohydrologic reconnaissance of drainage wells in Florida - an interim report: U.S. Geological Survey Open File Report 82-860, 59 p.

Piper, A.M., 1969, Disposal of liquid wastes by injection underground - neither myth nor millennium: U.S. Geological Survey Circular 631, 15 p.

Puri, H.S., et. al., 1964, Summary of the geology of Florida and a guidebook to the classic exposures: Florida Geological Survey Special Publication 5 /revised/, 312 p.

Shannon and Wilson, 1976, Evaluation of cavity development and stability, Disposal well No. 1, Mulberry, Florida: Consultants' report in files of the Florida Department of Environmental Regulation.

Ibid, 1980, Review and evaluation of monitoring data through December 1979, Disposal well No. 1, Mulberry, Florida: Consultants report in files of the Florida Department of Environmental Regulation.

Ibid, 1983, Review and evaluation of monitoring data through December 1982. Disposal well No. 1, Mulberry, Florida: Consultants report in files of the Florida Department of Environmental Regulation.

Stringfield, V.T., 1966, Artesian water in Tertiary limestone in the south-eastern states: U.S. Geological Survey Professional Paper 517, 226 p.

U.S. Environmental Protection Agency, 1980a, consolidated Permit Regulations: Federal Register, v.25, no. 98, Monday, may 19, p. 33290-33588.

Ibid, 1980b, Water Programs, Consolidated Permit Regulations and Technical Criteria and Standards, State Underground Injection Control Program: Federal Register, v. 45, No. 123, Tuesday, June 24, p. 42472-42512.

Ibid, 1983, Environmental Permit Regulations; Federal Register, v. 48, No. 64, Friday, April 1, p. 14146-14209.

Vecchioli, J., 1979, Monitoring of subsurface injection of wastes, Florida: Ground Water, v. 17, no. 3, p. 244-249.

Ibid, 1981, Subsurface injection of liquid waste in Florida, United States of America, in the science of the total environment: Amsterdam, Netherlands, Elsevier Scientific Publishing Co., v. 21, p. 127-136.

Warner, D.L. et. al., 1977, An introduction to the technology of subsurface wastewater injection: U.S. Environmental Protection Agency, Environmental Protection Technology Series EPA-600/2-77-240, 345 p.

GEOLOGY OF THE HOST FORMATION FOR THE NEW HYDRAULIC FRACTURING FACILITY AT OAK RIDGE NATIONAL LABORATORY

C.S. Haase and S.H. Stow
Environmental Sciences Division,
Oak Ridge National Laboratory, P.O. Box X,
Oak Ridge, Tennessee 37831

C.L. Zucker
Department of Geological Sciences,
The University of Tennessee
Knoxville, Tennessee 37996

1. Abstract

Liquid low-level radioactive wastes are disposed of at Oak Ridge National Laboratory /ORNL/ by the hydrofracture process. Wastes are mixed with cement and other additives to form a slurry that is injected into a low permeability shale at 300 m depth. Important properties for a host shale formation at a hydrofracture facility include:

1. Predictable fracture behavior,
2. Hydrologic isolation, and
3. Favorable mineralogy and geochemistry to retard radionuclide migration and enhance grout stability.

The stratigraphy, petrology, diagenesis, structural geology, and hydrology of the Pumpkin Valley Shale host formation at the ORNL site are summarized and discussed in the light of these three properties. Empirical data from hydrofracture operations at ORNL over the past 25 years suggest that many aspects of the Pumpkin Valley Shale make it favorable for use as a host. This observation agrees with analysis of several aspects of the Pumpkin Valley Shale geology at the ORNL site. Although presently available data suggest that the permeability of the Pumpkin Valley Shale is low and that it should provide sufficient hydrologic isolation, more data are needed to properly evaluate this aspect of host formation performance.

2. Introduction

Oak Ridge National Laboratory /ORNL/ has disposed of low-level liquid radioactive wastes by a unique technology based on hydraulic fracturing and grout injection for over 20 years /Delaguna et. al, 1968; International Atomic Energy Agency, 1983/.

In this paper we present a brief overview of the site geology of the hydraulic-fracturing facility at Oak Ridge. Our purpose is to document and to discuss critical aspects of site geology as they relate to the performance and long-term success of the hydraulic-fracturing radioactive waste disposal technology.

2.1. Hydraulic Fracturing at ORNL

A detailed description of the ORNL hydraulic-fracturing process appears elsewhere in this volume /Weeren, et. al, 1985/. A brief description of the process is included here for background purposes. The process is based on the subsurface injection of radioactive waste-bearing grouts into hydraulically fractured intervals of a geological formation selected as a host for the emplaced wastes. At the ORNL site, this host formation, the Pumpkin Valley Shale, occurs at depths between 225 and 340 m in the subsurface. During waste injection, a steel-cased injection well is pressurized with water to initiate a hydraulic fracture within the host formation. After initial fracturing, waste-bearing cementitious grouts are pumped downhole to further propagate the hydraulic fracture. During subsequent pumping, the grout spreads out to form irregularly shaped sheets that typically are 2 to 25 mm thick and extend outward from the injection well for distances of 150 to 200 m. Grout injection occurs from a slot cut near the bottom of the well and several injections may be made from the slot. Subsequent slots are cut at shallower depths so that over the lifetime of the facility, grout sheets will be injected from the bottom to the top of the host formation. Grout injection produces surface uplifts and seismic signals that can be used to determine the orientation of the grout sheet. An analysis of these aspects is found elsewhere in this volume /Stow, et. al, 1985/.

2.2. Host Formation Considerations

After subsurface injection and solidification, the cementitious grout acts, more or less, as a waste package for the radioactive waste. The grout is the primary containment feature of the technology and is responsible for retention and isolation of the radioactive wastes. The role of the host formation is that of an isolation medium for the emplaced wastes. It should isolate the waste-bearing grouts from groundwater, provide a favourable geochemical environment to ensure long-term grout stability, and provide protection against waste migration should the grouts ultimately break down and release their contained radionuclides.

General site selection criteria for a hydrofracture facility are discussed elsewhere /International Atomic Energy Agency, 1983/. However, because of the site's important role in enhancing and augmenting the isolation and containment functions of the grout, several specific criteria for the evaluation of potential host formations are contained in the general site selection consideration. Such criteria include the evaluation of several properties of the host formation that are regarded as essential. These host formation properties are the ability to (1) hydraulically fracture in a predictable manner, (2) to hydrologically isolate the grout sheets, and (3) retard radionuclide migration and promote long-term grout stability. The importance of each of these properties to the successful operation of a hydrofracture facility is briefly discussed below.

To ensure that all injected grout sheets stay within the host formation, it must have properties that result in hydraulic fractures oriented parallel to its top and bottom contacts. Ideally, such fractures should maintain a constant orientation throughout their extent and remain in the particular stratigraphic interval in which they were initiated.

The host formation should have low porosity, contain insignificant quantities of groundwater, and have low permeability. such properties minimize the quantities of groundwater that could come into contact with the grouts and prevent the outward flow of any fluids introduced during hydraulic fracturing operations.

The mineralogy and geochemistry of the host formation should promote the retention of radionuclides contained in the grout sheets. Clay minerals, such as illite and smectite, that have large capacities to sorb radionuclides should be abundant so that the mineralogy of the host formation will provide adequate retention characteristics for the radionuclides of concern. The geochemical environment within the host formation also must be compatible with the chemical and physical stability of the radionuclide-bearing grouts.

With these considerations as a background, the relevant aspects of the site geology of the ORNL hydraulic-fracturing facility will be summarized in the following sections. Most of the data resulted from an ongoing research project, begun in 1980, to reexamine the interaction between the ORNL facility and the surrounding geological environment. Initial site characterization and preliminary geological investigation occurred 20 to 25 years ago, when the hydraulic-fracturing technology for radioactive waste disposal was initially developed at ORNL /Delaguna et. al, 1968/. The objective of the current research is to develop a more comprehensive picture of the geohydrological aspects of this unique waste disposal technology.

3. Location and Geological Setting

3.1. Location and Regional Geological Setting

The ORNL hydraulic-fracturing facility is located in the U.S. Department of Energy's Oak Ridge Reservation in east Tennessee /Fig. A9/. The facility is within the city limits of Oak Ridge Tennessee, and is approximately 30 km northwest of Knoxville, Tennessee.

The ORNL site is located in the Valley and Ridge province of the Appalachian orogenic belt /Fig. A9/. The Valley and Ridge province in east Tennessee is characterized by a series of regional thrust faults that strike parallel to the borders of the province.and extend from Alabama to Virginia. Motion along these thrust faults during the Alleghanian orogeny /230 to 250 My ago/ resulted in southeast to northwest crustal shortening of 100 to 150 km /Harris et. al, 1977/. This shortening resulted in the formation of a series of imbricate thrust sheets that repeat a stratigraphic succession consisting of sandstones, shales and limestones as many as 7 times from the southeastern to the northwestern border of the province. Within the sediments on each of the imbricate thrust sheets, a significant amount of small-scale folding and faulting results in a complex structural fabric within all rocks of the Valley and Ridge province.

3.2 Site Geological Setting

Major geological features of the ORNL hydraulic-fracturing site are summarized in Figs. A10 and A11. The site occurs on the leading edge of the Copper Creek thrust sheet within 1 km of where the fault comes to the surface /Fig. A10/. The strike of strata at the site is N 45° to 55° E and the dip of the strata is variable. Within 500 m of the Copper Creek fault trace, dip values range from 45° to 90° to the SE. Further from the fault trace, at the hydrofracture facility, dip values range from 10° to 20° to the SE.

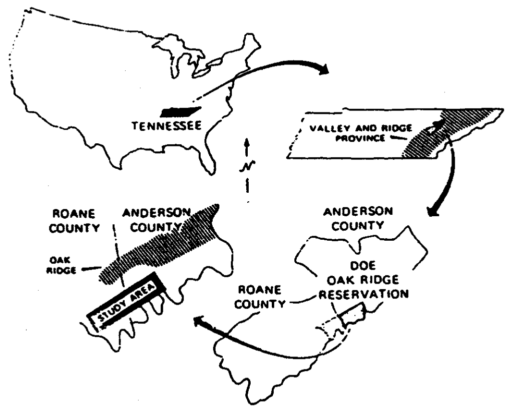
The stratigraphic sequence in the basal portion of the Copper Creek fault block consists of, from top to bottom, the Rome Formation, the Conasauga Group, that includes the host formation and the Knox Group. The Rome Formation ranges from 100 to 150 m in thickness and consists of massive sandstones, thinly bedded siltstones and laminated shales and mudstones /Hasse et. al, in press/. The Conasauga Group ranges from 550 to 600 m in thickness and consists of six formations, that are, in ascending order, the Pumpkin Valley Shale /the host formation/, the Rutledge Limestone, the Rogersville Shale, the Maryville Limestone, the Nolichucky Shale, and the Maynardville Limestone. The clastic-rich formations, including the Pumpkin Valley Shale, consist of thinly bedded siltstones and laminated shales and mudstones. The carbonate-rich formations consist of coarse- to fine-grained limestone conglomerates, and calcareous siltstones and shales /Haase, et. al, in press/. The Knox Group consists of carbonates, principally dolostone with subordinate amounts of limestone, and locally abundant sandstones. The group has been divided into five formations in the vicinty of the ORNL site and ranges from 600 to 650 m in thickness /Milici, et. al, 1973/.

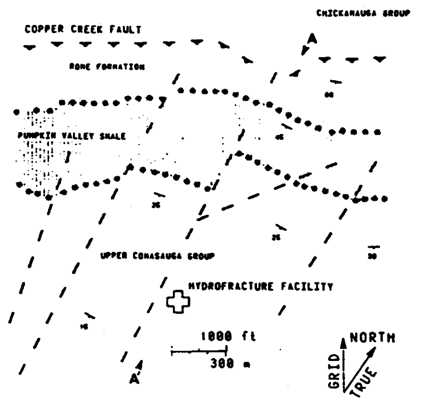
Strata in the basal portion of the Copper Creek thrust sheet are characterized by a pervasive structural fabric consisting of multiple joint sets and several generations of smale-scale folds and faults /Ossi, 1979; Slecz et. al, 1981/. Such features are associated with the major episode of thrust faulting that deformed the entire Valley and Ridge province. In addition to these features, several major structural features of the ORNL site are illustrated in Fig. A10. Of importance are several tear faults that cut across the leading edge of the Copper Creek thrust sheet in the immediate vicinty of the ORNL site. The net effect of these faults is to divide the leading edge of the fault block into a series of discrete units that have been translated or rotated with respect to each other. Note the prominent tear fault /Fig. A10/ that passes close to the ORNL hydraulic-fracturing facility. Fault strike is generally normal to that of the Copper Creek fault, and fault dip is steep. Motion along the tear faults is complex and is typically a combination of strike- and dip-slip movement. Total displacement along the faults appears to be in the order of several tens of meters. Most tear faults are 1 to 3 km and die out within strata of the Knox Group that crop out to the SE of the ORNL site.

4. Geology of the Pumpkin Valley Shale

4.1 Stratigraphy

Knowledge of the lateral and vertical distribution of rock types within the Pumpkin Valley Shale is essential to understand local variations in physical,





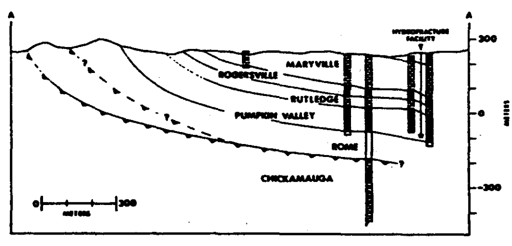


Fig. A9. Location map for the Oak Ridge locality. The ORNL hydrofracture facility is within the study area indicated.

Fig. A10. Site geological map illustrating the major geological structures and outcrop areas for the stratigraphic units on the Copper Creek thrust sheet in the vicinity of the ORNL hydrofracture facility. Lines with teeth mark the trace of the Copper Creek fault. Dashed lines mark the trace of tear faults in the Copper Creek thrust sheet. Dotted lines mark formational contacts.

Fig. A11. Cross section along a line between points A and A' in Fig. A10. The subsurface distribution of the Conasauga Group, the Rome Formation, and the Copper Creek fault in the vicinity of the ORNL hydrofracture facility are illustrated.

mineralogical, and geochemical properties within the formation. At the ORNL site, the Pumpkin Valley Shale is 105 m thick and can be divided into a siltstone-rich, 45 m thick lower member and a shale-rich, 60 m thick upper /Haase, et. al, in press; Haase, 1982/. The lower contact of the formation is gradational over a 2 m thick interval into massive to thickly bedded sandstones of the upper Rome Formation. The upper contact of the formation is also gradational over a 3 m thick interval into limestones and calcareous shales of the Rutledge Limestone. The Pumpkin Valley Shale is composed of several distinct types of mudstones, shales, and siltstones that are common to both members. The two members differ principally in the relative proportions of the different lithologies, in the character of the interstratification sequences of the different lithologies throughout the member, and in the nature of the primary bedding structures within the constituent lithologies /Haase, et. al, in press; Haase, 1982; Haase, 1983/.

Based on compositional differences, the lower member of the Pumpkin Valley Shale can be divided into individual stratigraphic intervals that are 0,25 to 3 m thick. Such intervals are complexly interstratified and may be composed of massive mudstones, laminated shales with wavy, discontinuous siltstone stringers, thinly bedded siltstones, or massive, irregularly bedded bioturbated shaly siltstones. An individual horizon almost always contains several other lithologies in subordinate amounts to the principal one. The stratigraphic intervals appear to be lenticular and do not have great lateral continuity /Haase, 1982; Haase, 1983/. Bedding patterns within the shales vary from planar and continuous to wavy and discontinuous. Some siltstones have thinly bedded, planar, continuous laminations, although most have wavy and discontinuous bedding; cross bedding and current-rippled laminations are locally abundant. Within bioturbated shaly siltstones, churning by bottom-feeding organisms has largely destroyed primary depositional features and produced a homogenized lithology that lacks significant sedimentary structure. Complex interstratification of different lithologies within the lower member of the Pumpkin Valley Shale has produced a highly anisotropic distribution of physical properties within the member /Haase et. al, 1983/.

The upper member of the Pumpkin Valley Shale also consists of complexly interstratified, 0,5 to 5 m thick horizons of massive mudstones, laminated shales, and thinly bedded siltstones and shales with discontinuous siltstone stringers /Haase et. al, in press; Haase 1982; Haase, 1983/. The upper member is similar to the lower member except that it lacks the bioturbated shaly siltstones of the lower member and has a greater abundance of thinly laminated shales. As with the lower member, there is significant compositional variability with statigraphic position. Lateral continuity of beds within the shale-rich horizons appears to be greater than within similar intervals in the lower member. Siltstone-rich horizons, however, are lenticular and lack long-range continuity on the scale of several tens of meters. As in the lower member, the complex interstratification of differing lithologies in the upper member of the Pumpkin Valley Shale has produced a rock unit with an anisotropic distribution of mineralogical, chemical, and physical properties.

4.2. Petrology

Compositionally, shales and mudstones from throughout the Pumpkin Valley Shale are similar to each other. Both contain 75 to 95% clay-sized material composed of illite/vermiculite + illite + kaolinite + chlorite + quartz. The shales typically contain 5 to 25% silt-sized material composed of detrital quartz, plagioclase and potassium feldspars, muscovite, and biotite. The mudstones contain 0 to 5% silt-sized material and have the same clay mineral assemblage as the shales /Haase, 1982; Haase 1983/.

Siltstones of the Pumpkin Valley Shale contain 50 to 99% silt-sized detrital grains of quartz, plagioclase and potassium feldspar, muscovite, biotite, and glauconite pellets. The amount of matrix, or clay-sized material, in siltstones ranges from less than 1 to 50%. This matrix material consists of mixtures of primary clay-sized detrital material, partially recrystallized detrital clays and altered feldspar grains, and clay cements. Siltstones can be differentiated into two types by the amount of matrix material. The most abundant siltstones are subarkosic graywackes that have greater than 10% matrix material. These siltstones are moderately well to poorly sorted with subrounded detrital grains of quartz, plagioclase and potassium feldspar, and trace amounts of muscovite and biotite. They are wavy bedded and current-ripple laminations are locally common. A subordinate amount of Pumkin Valley Shale siltstones are subarkosic in composition with less than 10% matrix material. These siltstones have aquigranular and well sorted detrital grains of quartz and plagioclase and potassium feldspars, and are characterized by planar stratification patterns that locally are cross-bedded.

Knowledge of the mineral assemblages, their distribution, and their variability within the lithologies of the Pumpkin Valley Shale is necessary to characterize the radionuclide sorption and retention capability of the formation. Furthermore, data on the mineralogy and the distribution of mineral components throughout the host formation are needed to evaluate the compatibility of the Pumpkin Valley Shale with the injected grouts and to determine if groundwaters within the formation are compatible with the mineral assemblages present. Lack of such compatibilies could have serious negative consequences for grout stability and the radionuclide retention capability of the formation.

4.3. Diagenesis

The nature and character of diagenesis within sedimentary rocks is important because the mineralogy, the porosity and permeability, and the physical properties of sediments can be significantly modified by this recrystallization event. The Pumpkin Valley Shale is no exception: during diagenesis, it experienced various recrystallization reactions that significantly changed its ultimate mineralogical and porosity/permeability characteristics. The nature and the extent of reactions during diagenesis differed within the major rock types of the Pumpkin Valley Shale. In general, the diagenetic episode had three stages: (1) a period of early cementation and occlusion of primary porosity, (2) a subsequent period of grain dissolution and secondary porosity development, and (3) a final period of cementation and occlusion of remaining primary and all secondary porosity /Haase, 1982; Haase, 1983/.

All three stages of diagenesis are best developed in the low matrix content siltstones. Early cementation consisted of the development of quartz overgrowths and grain-rimming kaolinite and chlorite cements within intergranular pore spaces. Dissolution of detrital feldspars and, locally, early quartz cement and detrital quartz grains marked the episode of secondary porosity formation. The final diagenetic stage is marked by the occlusion of all remaining intergranular porosity by calcite. Within other lithologies of the Pumpkin Valley Shale, the amount of matrix material determined the extent of diagenetic reaction /Haase, 1982; Haase 1983/. In siltstones with greater than 10% matrix, diagenesis consisted simply of cementation and porosity occlusion. Secondary porosity formation occurred only locally. Diagenesis within shales and mudstones is characterized by recrystallization of the clay-sized material into patches of coarser-grained illite, kaolinite, or chlorite. Variability in the amounts of primary illite/vermiculite-rich matrix and of secondary illite, kaolinite, and chlorite within shales and mudstones represents different degrees of diagenetic recrystallization /Haase,1982/.

Analysis of diagenetic trends is necessary to determine the ultimate distribution of mineral assemblages and porosity and permeability patterns within the Pumpkin Valley Shale. This analysis of diagenesis also illustrates the importance of understanding the character of the compositional heterogeneity within a formation. The nature of the diagenetic recrystallization within a particular interval of the Pumkin Valley Shale. This analysis of diagenesis also illustrates the importance of understanding the character of the compositional heterogeneity within a formation. The nature of the diagenetic recrystallization within a particular interval of the Pumpkin Valley Shale was controlled by the original composition of that interval. Therefore, knowledge of the original distribution of rock types within the formation would allow predictions to be made about the post-diagenetic distribution of mineral assemblages, porosity and permeability patterns, and physical properties.

4.4. Structural Fabric

Deformation features associated with major tectonic events of the Alleghanian orogeny are ubiquitous in the Pumpkin Valley Shale. Joint sets, fractures, folds, and faults occur throughout the Pumpkin Valley Shale /Haase, et. al, in press; Ossi, 1979; Sledz et. al, 1981/. Because such features can produce significant amounts of secondary fracture porosity and permeability within a formation, detailed knowledge of such features is essential to understanding their potentially large impact on subsurface hydrology and flow patterns. Furthermore folds and faults may have an influence on the orientation of induced hydraulic fractures and injected grout sheets. Evaluation of these factors requires a detailed knowledge of the structural fabric of the Pumpkin Valley Shale at the ORNL site.

At least two and, locally, as many as four joint sets have been identified within the Pumpkin Valley Shale /Sledz, et. al, 1981/. All of these can be related to major structures, such as the Copper Creek thrust fault or specific folding events. Within a particular interval, joint spacing, length, and density is a complex function of lithology and bed thickness. Furthermore, although joint sets show fairly constant orientations with respect to major structures, specific joint sets exhibit significant variability within lateral distances of several hundreds of meters. Joints within siltstone-rich lithologies are commonly filled with secondary carbonates, although locally such joints may be unfilled. Joints within mudstones and shales are frequently unfilled. The vertical and lateral continuity of joints is limited by the complex interstratification patterns with the Pumpkin Valley Shale. Single joints rarely cut more than several adjacent beds and typically die out at siltstone/mudstone contacts. Because of the generally lenticular nature of many bedforms within the Pumpkin Valley Shale, the lateral continuity of a particular joint does not exceed several tens of meters /Sledz, et. al, 1981/.

Small-scale fractures within the siltstone-rich intervals of the Pumpkin Valley Shale are abundant. At least two generations of cross-cutting fractures can be identified in drill cores /Haase, in press/. As with the joints, fractures are most numerous within siltstones, although locally, mudstones and shales contain significant concentrations of fractures. Most fractures are filled with secondary carbonate minerals; at relatively shallow depths, however, many fractures are unfilled or only partially filled and sealed /Haase et. al, in press; Sledz, et. al, 1981/.

Small-scale folds and faults are common throughout much of the Pumpkin Valley Shale. Folds have amplitudes of 0,5 to 3 m and are tight, occasionally being isoclinal. Many folds are associated with small-scale faults that occur throughout the Pumpkin Valley Shale. Such fault zones are 0.1 to 3 m thick and typically have nearly vertical dips, although lower angle faults have been observed /Haase, in press; Sledz, et. al, 1981/.

4.5. Hydrology

The hydrologic properties of the Pumpkin Valley Shale at the ORNL site are important because the formation must isolate the injected grout sheets from contact with groundwater. Hydrologic isolation requires that small quantities of groundwater are present in the host formation and that groundwater moves through the formation slowly and is of small volume: that is, the formation must have low porosity and permeability, and hydrologic heads within the formation must be low.

The hydrology of the ORNL hydraulic-fracturing facility site is complex and not understood in detail. Available data suggest that the subsurface groundwater regime consists of a shallow, freshwater system and a deep, saline system /Haase, et. al, 1985/. In general, the permeability of the Conasauga Group is low and flow directions for much of the shallow groundwater system are influenced by structural fabric elements, such as joints and fractures /Sledz, 1981; Vaughan et. al, 1982; Rothschild et. al, 1985/. The shallow groundwater system at the site extends to depths of 60 to 150 m. Groundwater within this system is fresh, with TDS values less than 5000 ppm. Within the upper portions of the zone of shallow fresh groundwater, at depths less than 50 m, the weathered portions of Conasauga Group strata contain moderate amounts of groundwater. Below this depth, borehole geophysical logs suggest that fresh groundwater is increasingly confined to fracture and fault zones. At present, little is known about the behavior of groundwater at the bottom of the shallow zone.

The nature of the deep, saline groundwater system within the lower portions of the strata of the Conasauga Group is not known. Waters within this deeper system appear to be high-TDS fluids /see Table A2/ with chloride concentrations ranging from 100,000 to 120,000 ppm /Switek et. al, in press/. Because of the dramatic compositional differences between shallow and deep groundwaters, the deep system is thought to be largely separate from the shallow system. Details of possible coupling between the two systems are not known. By analogy with the shallow groundwater system, it is hypothesized that flow directions of the deep system are largely controlled by the fracture permeability related to structural fabric elements. No data are available at present on the formation pressures or hydrologic heads associated with the Pumpkin Valley Shale or adjacent formations in the deep subsurface. Currently, research is in progress to make such determinations within the Pumpkin Valley Shale.

The chemistry of groundwater within the Pumpkin Valley Shale is complex. Analysis of water from wells finished within the interval of the Pumpkin Valley Shale and the two overlying formations /the Rutledge Limestone and the Rogersville Shale - total combined thickness of 70 m/ indicated that the groundwaters are high-chloride brines /see Table A2/ /Haase, et. al, 1985; Switek et. al, in press/. Research in progress is intended to better characterize such waters and to determine the stratigraphic variability of groundwater within the Pumpkin Valley Shale.

At depths greater than 200 m, the Pumpkin Valley Shale appears to have low permeabilities. Laboratory measurements from drill core samples indicate exceedingly low permeability values in the range of 0.0003 to 0.00003 md /Delaguna et. al, 1968/. Research in progress will determine permeability values by in situ methods for specific stratigraphic intervals of the Pumpkin Valley Shale. Porosity values determined by laboratory measurements on core samples range from 1,0 to 3,0% /Delaguna et. al, 1968/. Such values are consistent with the range of values determined by petrographic study of thin sections from siltstones.

5. Performance of the Pumpkin Valley Shale as a Host Formation

5.1. Hydraulic-Fracture Orientation

The orientation of hydraulic fractures and injection grout sheets has been determined by core drilling, gamma-ray logging in observation wells, and measurement of surface deformation patterns associated with grout injection /Delaguna et. àl, 1968; Stow et. al, 1985 /this volume/. The results indicate that the Pumpkin Valley Shale hydraulically fractures in a consistent manner and that such fractures typically occur along, or parallel to, bedding planes. Because of the relatively shallow dip of the Pumpkin Valley Shale at the ORNL site, such fracturing behavior results in a near-horizontal orientation for injected grout sheets. Results from an extensive core drilling of experimental injections indicate that structures such as folds and faults have only localized influence on grout sheet orientation /Delaguna et. al, 1968/. Typically, grout sheets remained within 4 m of the stratigraphic interval in which they were injected. Such observations suggest that the complex structural fabric of the Pumpkin Valley Shale, which could produce erratic fracture orientation, does not play a significant role in determining fracture behavior of the formation at the ORNL site.

Grout sheet orientations have been determined for operational hydrofracture

Table A2. Chemical data for deep groundwater.

Component	Samples from borehole S400/µg/ml except where noted/ 960*	120**
pH/pH units/	5.1	7.0
Na	36,400	900
K	137	8.2
Ca	10,000	85.5
Mg	2,070	13.8
Sr	952	1.6
Ba	94	0.5
Fe	65	0.4
Mn	44	0.3
Cl	100,000	1,200
Br	550	7
SO_4	<40	100
NO_3	<40	<4
Alkalinity	0	603
Conductivity /µmhos/cm/	156,400	5,020

* Saline, deep groundwater sample from 293 m.
** Fresh, shallow groundwater sample from 37.6 m.

injections making use of gamma-ray logging in a network of cased observation wells in the immediate vicinity of the new hydrofracture facility /Weeren et. al, 1985/ this volume/. Data from 13 injections obtained by this technique at the new ORNL hydrofracture facility suggest that grout sheets have an essentially horizontal orientation near the facility /Weeren, 1984/. Similar results were obtained for 25 injections at a previous facility located within 250 m of the new facility /Delaguna, et. al, 1968; Weeren, 1974; Weeren, 1976; Weeren, 1980/.

Research reported elsewhere in this volume /Stow/ has addressed the problem of determining the orientation of the entire grout sheet through analysis of surface deformation associated with the injection. Preliminary results from this research also suggest that grout sheet orientation is nearly horizontal and that grout sheet orientation remains constant throughout the course of an injection.

The data gathered over the past 25 years indicate that grout sheets injected into hydraulic fractures within the Pumpkin Valley Shale have a consistent and predictable orientation and that they remain in the intended host formation. The Pumpkin Valley Shale rates highly, with respect to the "predictable fracture behavior" consideration discussed in the introduction.

5.2. Hydrologic Isolation

The hydrologic properties of the Pumpkin Valley Shale appear to be favorable to the "hydrologic isolation" considerations discussed in the introduction. Laboratory-determined porosity and permeabilities fall within a range that would indicate water movement through the rock matrix of the Pumpkin Valley Shale should be very slow, in the order of a few meters in 100 y.

Evaluation of the total permeability of the Pumpkin Valley Shale must include not only the primary permeability associated with the rock matrix - discussed above - but also any secondary permeability associated with fractures and joints. This important aspect of permeability within the Pumpkin Valley Shale has not been adequately evaluated. The pervasive structural fabric of the formation can produce a significant fracture permeability that cannot be fully characterized by laboratory measurements on core samples. For example, joint and fracture set spacings could be larger than core sample dimensions, making the contribution of joints and fractures to total rock permeability difficult to determine. Furthermore, folds and faults could produce local zones of greatly increased permeability that would not be adequately sampled by drill core material. Total permeability values for 30 m long intervals of Conasauga Group strata overlying the Pumpkin Valley Shale have been determined from pressure decay measurements in boreholes. The values are similar to those determined by laboratory measurements /Weeren et. al, 1984/. However, such measurements were not carefully controlled and the potential influence of fracture permeability on the total permeability of the formation has not been rigorously evaluated. Research in progress includes in situ hydrologic measurements that will allow such an evaluation to be made.

The high-chloride groundwater indicates that fluids within the Pumpkin Valley Shale are not linked directly to the shallow, fresh water-bearing groundwater system overlying the host formation at the ORNL site. This is a positive aspect because it suggests the lack of effective communication between shallow and deep groundwater systems, and, hence, good isolation for the deep groundwater immediately surrounding the injected grouts.

The overall assessment of the "hydrologic isolation" property for the Pumpkin Valley Shale hydrology at the ORNL site shows that several aspects need further clarification. The formation has the low permeability, but the possible localized effects of structural features needs to be clarified.

5.3. Radionuclide Retention and Favorable Geochemical Environment

The clay mineralogy of the Pumpkin Valley Shale is relatively simple and the assemblage of clay minerals present throughout the formation is constant. Such a feature has both positive and negative consequences for the suitability of the formation as a host for injected grout sheets. The illite and illite/-vermiculite content of the Pumpkin Valley Shale can be as high as 80% and because these clay minerals have high sorption properties for ^{137}Cs, the Pumpkin Valley Shale is extremely efficient in sorbing and retaining this radionuclide /Delaguna et. al, 1968/. This fact is essential to the ORNL facility because ^{137}Cs is a major component of ORNL wastes. Available data indicate, however, that the mineralogical composition of the Pumpkin Valley Shale is much less favorable for sorption and retention of ^{90}Sr, which is also a major component of ORNL waste /Rothschild, 1984/. Under ambient geochemical conditions, the illite and illite/vermiculite in the Pumpkin Valley Shale are inefficient in retaining ^{90}Sr, and no other mineralogical constituent of the formation is an effective sorption agent for this radionuclide.

The Pumpkin Valley Shale gets mixed ratings with respect to the "efficient sorption and retention" consideration discussed in the introduction. Because of its high illite and illite/vermiculite content, the formation is very effective in retaining one major waste component. However, because of the lack of other clays, such as smectites, the Pumpkin Valley Shale is much less effective at retaining other important waste components. Increased mineralogical diversity would be desirable.

Another aspect is that the host formation provides an unfavorable geochemical environment for the injected grout. The high-chloride waters within the Pumpkin Valley Shale may have potentially negative effects on the long-term stability of the waste-bearing grouts. Evaluation of such factors is in progress at ORNL.

6. Summary

Empirical data gathered largely from operational experience over the past 25 years at the ORNL site suggest that the Pumpkin Valley Shale has many of the necessary attributes required of a successful host formation. The formation fractures in a regular fashion so that injected grout sheets have predictable orientations and remain within the stratigraphic extent of the formation. Available data suggest that the formation has low intrinsic permeability. The ambient groundwater in the formation is saline and therefore not in rapid communication with overlying freshwater groundwater systems. The mineralogy of the formation is an effecient sorption agent for some radionuclides, especially ^{137}Cs, that comprise the ORNL waste.

Several aspects of Pumpkin Valley Shale hydrology at the ORNL site need additional research. Principal among these is determination of the potential effect of structural features on permeability within the formation. Rocks with generally low permeability are difficult to characterize, and research is underway to address this issue more completely. The geochemistry of the high-chloride formation water of the Pumpkin Valley Shale is under study to determine the age and origin of these waters and to determine the nature of their interaction with the overlying fresh groundwater system.

Research on the characterization of groundwater chemistry and on the in situ determination of the hydrologic characteristics will continue for the next several years to further determine the behavior of the Pumpkin Valley Shale as a host formation. The long term goals of this research are to provide a rigorous scientific understanding for the large amount of empirical data derived from hydrofracture operations at the ORNL site over the past 25 years and to further clarify the role of the host formation to the long-term success of the hydrofracture process.

7. References

Delaguna, W., et al, 1968, Engineering Development of Hydraulic Fracturing as a Method for Permanent Disposal of Radioactive Wastes. ORNL-4259, Oak Ridge National Laboratory.

Haase, C.S., et. al, in press, Stratigraphic and Structural Data for the Conasauga Group and the Rome Formation on the Copper Creek Fault Block near Oak Ridge, Tennessee: Preliminary Results for Test Borehole ORNL-JOY No. 2. ORNL/TM-9159, Oak Ridge National Laboratory.

Haase, C.S., 1982, Petrology and Diagenesis of the Pumpkin Valley Shale in the Vicinity of Oak Ridge, Tennessee. Geological Society of America Abstracts with Program, 14, p. 22.

Haase, C.S., 1983, Petrologic Considerations Relevant to the Disposal of Radioactive Wastes by Hydraulic Fracturing: An Example at the U.S. Department of Energy's Oak Ridge National Laboratory. Proceedings of the Sixth Materials Research Society Symposium on the Scientific Basis for Radioactive Waste Management, Boston, Massachusetts, November 1-4, 1982, Vol. 15, p. 307, Elsevier, New York.

Haase, C.S., et. al, 1985, Formation Water Chemistry of the Conasauga Group and the Rome Formation near Oak Ridge, Tennessee: Preliminary data for Major Elements. Geological Society of America Abstracts with Program, 17, p. 94.

Harris, L.D., et. al., 1977, Characteristics of Thin-Skinned Style of Deformation in the Southern Appalachians and Potential Hydrocarbon Traps. Professional Paper 1018, U.S. Geological Survey Washington, D.C.

International Atomic Energy Agency, 1983, Disposal of Radioactive Grouts into Hydraulic Fractured Shale. IAEA Technical Reports Series No. 232, International Atomic Energy Agency Vienna, Austria.

Milici, R.C., 1973, The Stratigraphy of Knox County. Bulletin No. 70, p. 9. Tennessee Division of Geology, Nashville, Tennessee.

Ossi, E.J., 1979, Mesoscopic Structures and Fabric within the Thrust Sheets Between the Cumberland Escarpment and the Saltville Fault. M.S. Thesis, The University of Tennessee, Knoxville, Tennessee.

Rothschild, E.R., et. al, 1984, Geohydrologic Characterization of Proposed Solid Waste Storage Area /SWSA/ 7. ORNL/TM-9314, Oak Ridge National Laboratory.

Rothschild, E.R., et. al, 1985, Geological Influence on Shallow Groundwater Flow in the Conasauga Group near Oak Ridge, Tennessee. Geological Society of America Abstracts with Program, 17, p. 132.

Sledz, J.J., et al., 1981, Computer Model for Determining Fracture Porosity and Permeability in the Conasauga Group, Oak Ridge National Laboratory. ORNL/TM-7695, Oak Ridge National Laboratory.

Stow, S.H., et. al, 1985, Monitoring of Surface Deformation and Microseismicity Applied to Radioactive Waste Disposal by Hydraulic Fracturing at Oak Ridge National Laboratory. Proceedings of Waste Management '85, Tucson Arizona, March 24-28, /this volume/.

Switek, J., et. al, in press, Geochemical Investigation of Formation Waters in the Lower Conasauga Group at the ORNL Hydraulic Fracturing Facility: Data from the Rock Cover Wells. ORNL/TM-9422, Oak Ridge National Laboratory.

Vaughan, N.D., et. al., 1982, Field Demonstration of Improved Shallow Land Burial Practices for Low-Level Radioactive Solid Wastes: Preliminary Site Characterization Report. ORNL/TM-8477, Oak Ridge National Laboratory.

Weeren, H.O., 1974, Shale Fracturing Injections at Oak Ridge National Laboratory - 1925 Series. ORNL/TM-4467, Oak Ridge National Laboratory.

Weeren, H.O., 1976, Shale Fracturing Injections at Oak Ridge National Laboratory - 1975 Series. ORNL/TM-5545, Oak Ridge National Laboratory.

Weeren, H.O., 1980, Shale Fracturing Injections at Oak Ridge National Laboratory - 1977-1979 Series. ORNL/TM-7421, Oak Ridge National Laboratory.

Weeren, H.O., 1984, Hydrofracture Injections at Oak Ridge National Laboratory - 1982-1984 Series. ORNL/NFW-84/43, Oak Ridge National Laboratory.

Weeren, H.O., et. al, 1985, Status of Hydrofracture Operations at Oak Ridge National Laboratory. Proceedings of Waste Management, Tucson, Arizona, March 24-28 / this volume/.

INFORMATION REPORT ON UNDERGROUND INJECTION IN POLAND

Stanislav Witczak

Institute of Hydrogeology and Engineering Geology
University of Mining and Metallurgy
Krakow

1. Abstract

Safe disposal of hazardous and general wastes is one of the most critical environmental problems in Poland. Deep injection as a disposal method, not only for hazardous wastes, has been considered many times. Despite that, there are no permanently working injection wells for hazardous waste in Poland. This is partly due to certain economic reasons and partly to many technical and environmental problems concerning deep well injection. Improvement of the knowledge of hydrogeologic processes is necessary if injection is to be used at an accelerated rate in the future.

2. History of the Use of Deep Injection Wells in Poland

First of all the problem of what the "hazardous wastes" mean should be taken under consideration. Hazardous wastes in Poland have not been strictly classified. There are several criteria applicable to properly manage hazardous, toxic and radioactive waste, and several classifications of hazardous waste exist in Poland. In the author's opinion the last proposition of Polkowski /1985/ from the Environmental Protection Institute /Warsaw/ should become the state regulation. This classification is applicable for every kind of waste /solid, fluid and gaseous/.

All wastes are classified according to the following criteria:

- so called "harmfulness coefficient" - K
- concentration of toxic and hazardous substances

$$K = A * X_A + B * X_B + C * X_C + D * X_D$$

Where: K = harmfulness coefficient

X_A, X_B, X_C, X_D = coefficients depending on toxicity class of substances. All substances are divided into 4 groups mentioned above from the hazardous /A/ to the least hazardous /D/. The value of the coefficients are: A = 100, B = 10, C = 1, D = 0.01.

Table A3. Waste classes.

Class number	harmfulness coefficient	Environmental impact	Hydrogeological site criteria
1	>5	The most hazardous. Disposal/landfill or underground/ is forbidden without pretreatment. Wastes must be treated to be less toxic before storing.	Very careful selection of disposal site. Individual criteria.
2	0.5 - 5	Hazardous waste easily migrating, contact dangerous to man and biota. Wastes may be stored only in strictly controlled disposal sites.	Disposal site with natural insulating layer and or polymer foil. Special attention is necessary.
3	0.05 - 0.5	Hazardous waste not easily migrating. Disposal is possible in controlled disposal sites.	Disposal site with natural insulating layer, with permeability $K < 10^{-6}$ m/s
4	0.005 - 0.05	Nondangerous, burdensome waste. Disposal is possible in a normal landfill.	-
5	<0.005	Nondangerous waste. Wastes can be freely let out.	-

Toxicity classes were established on the basis of the maximum permissible level of individual species in drinking water and in surface water /Water Act/, U.S. EPA list of toxic and hazardous substances and other regulations.

All wastes are divided into 5 classes as shown in Table A3.

As was mentioned above, there are no permenently working deep injection wells for hazardous waste in Poland. There are some plans for deep injection of hazardous waste from the chemical industry, but they have not been realized. The method of deep injection has been used, tested or considered for some kinds of nontoxic wastes and in other kinds of activities.

All types of deep injection may be classified into five classes:

1. Frasch process	Hot water injection for underground sulphur melting
2. Oil and gas industry	Reinjection of brines
3. Underground injection of mineral salt waters in Spas	Reinjection of waste mineral salt water
4. Geothermal wells	Reinjection of reused water
5. Discharge of the salt waters and brines from deep coal mine dewatering	

Ad 1. There are several hundred /200-300/ active injection wells used for the Frasch process in SE Poland. Injection wells are about 100-200 m deep and were made in Miocene limestones covered by Miocene clays and claystones. Wide experience concerning the problem of injected water migration through low permeable clay and claystone and shallow groundwater contamination has been acquired.

Ad 2. In the exploitation of oil fields large volumes of brines are often obtained. In several oil fields this water is repumped into the deposit through the injection wells. More than 15 examples of such injection have been known. The optimal technique for treating brines before injection and injection well operation have been studied. Injection wells were 300 - 900 m deep. Lithology of confining zones was mainly sandstones and limestones. The average injection rate was several tens of cubic meters per day, with a maximum of 500 cubic meters per day in a test disposal program. Maximum total volume of injected water was about 300,000 m^3.

Ad 3. Underground injection of mineral salt water was tested at two sites (Ustron Spa and Iwonicz Spa in south Poland) as a tool for surface water protection. The exhausted gas and oil structure in the neighbourhood of the Spas was used for injection. The wells which formerly had been used for oil and gas exploitation were tested. Injection wells were several hundred meters deep. Volume of salt water injected underground could be measured as several hundred cubic meters per day. Lithology of injection zones consists of sandstones and carbonate rocks.

Ad 4. The possibility of underground reinjection of reused hot water from geothermal wells in the south of Poland is being studied. The first injection well will probably be tested next year.

Ad 5. A big environmental problem has arisen in Poland with the management of salt waters from coal mining activity. Dewatering of deep coal mines gives as much as 7,000 tons per day of salt (in salt waters and brines). This discharge goes to the Odra and Vistula rivers. Chloride content in the river water has risen three or more times above the maximum permissible level.

Discharging the salt waters and brines to the subsurface is an alternative to the process of desalination as a method for river water protection. This possibility is being studied now. It is necessary to inject more than 10,000 cubic meters of salt water per day. Injection will probably be into wells several hundred meters deep. The lithology of injection zones is likely to consist of sandstones.

3. Regulations Governing the Siting, Construction and Operation of Deep Injection Wells

The Ministry of Environmental Protection and Natural Resources is the authority responsible for water protection and management. The basic law is the Water Act, last update 1974. The law covers the protection of surface and groundwater catchment areas and provides general rules as far as protection of aquifer recharge areas is concerned.

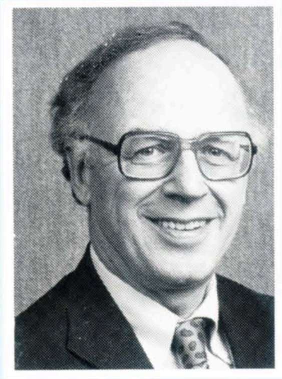
Waste water must be treated before discharging into a surface water body or underground. Special permission is necessary for this purpose. Theoretically, wastes cannot be freely let out into surface water or underground. Practically, irresponsibility of many factories and the low level of taxes and penalties causes in many sites surface and groundwater contamination.

The Mining Act and Geologic Act regulate such activities as siting, construction and operation of deep injection wells. There are no special regulations for underground injection. Deep injection wells are treated similarly to other wells and boreholes for water, gas and oil exploitation etc. Individual project siting, construction and operation proposals are necessary before special permission is obtained.

4. Conclusions

Deep waste injection as a disposal method will be considered in Poland, as in many other countries, at some stage. For that reason we are interested in the continuation of IAH Commission activities.

Interdisciplinary research and exchange of information about waste disposal is necessary. This should include hydrogeologic processes, hydrogeology of semi-permeable and impermeable layers, waste treatment technologies, site location and long range projections of environmental impact.



Dr. Philip E. LaMoreaux

J. Vrba

The technology for managing hazardous waste has been slower to develop than the technology for generating it. The importance of properly managing hazardous waste commonly has been unrecognized until after the manufactured product has become an accepted „necessity" and the harmful effects of the by-products on the environment become evident.

Initially, hazardous wastes were sent along with the non-hazardous materials to streams, dumps, or municipal landfills. Treatment, incineration, storage and disposal are methods of managing hazardous wastes; each of these include different techniques for handling hazardous wastes. Injection of hazardous waste into deep wells is one of several alternatives.

This monograph deals with deep-well disposal of hazardous liquid wastes; radioactive waste is not included in this report. No international standards provide guidelines for handling and management of hazardous liquid wastes; however, several countries regulate the injection of liquid waste by legislation. Some examples of deep-well disposal are presented in case histories in the second part of the monograph. This monograph was prepared as a reference source for decision makers, political representatives and citizens.

ISSN 0936-3912
ISBN 3-922705-93-6

Verlag Heinz Heise GmbH & Co KG, P.O.B. 610407, D-3000 Hannover 61, Germany