TEXAS DEPARTMENT OF WATER RESOURCES

REPORT 291

UNDERGROUND INJECTION OPERATIONS IN TEXAS

A Classification and Assessment of Underground Injection Activities

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TEXAS DEPARTMENT OF WATER RESOURCES

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ABSTRACT

Underground injection operations in Texas are regulated by the Texas Department of Water Resources and the Railroad Commission of Texas. Injection wells under the jurisdiction of the Texas Department of Water Resources include industrial and municipal waste disposal wells, injection wells used for *in situ* mining of uranium and sodium sulfate, injection wells producing sulfur by the Frasch process, injection wells used to produce brine from underground salt deposits, and wells used for aquifer artificial recharge, air conditioning and heating, agricultural drainage, sewage disposal, and backfilling mine shafts and pits. The Railroad Commission's authority over injection wells extends principally to wells related to the production of oil and gas, including wells used for enhanced recovery of oil and gas, wells used for disposal of produced brine, and disposal wells for refinery and gas processing plant wastes. Presented herein is the history of regulatory program development for underground injection operations in Texas, with information describing the construction features, operating practices, nature and volume of injected fluids, relative pollution potentials, legal and jurisdictional considerations, and regulatory recommendations for the various types of injection wells in the State.

TABLE OF CONTENTS

TABLE OF CONTENTS—Continued

APPENDICES

PART I—GENERAL INFORMATION

CHAPTER 1

INTRODUCTION

Underground injection began in Texas over 70 years ago with sulfur mining by the Frasch process. It is not known when disposal of wastewater by underground injection began in Texas; however, the first major project to utilize injection wells for disposal of liquid wastes into the subsurface occurred in 1938 in an East Texas oil field where salt water produced with oil from the Woodbine Formation was returned to the lower part of the formation. This injection well project was permitted and regulated by the Railroad Commission of Texas. Today, regulatory responsibility for subsurface injection of fluids is divided between the Railroad Commission of Texas and the Texas Department of Water Resources.

Texas has more than 48,000 injection wells associated with the production of oil and gas, over 500 underground hydrocarbon storage wells, approximately 20,000 solution mining wells, over 100 industrial waste disposal wells, and an unknown number of miscellaneous injection wells. The uses of underground injection wells include: industrial waste disposal; secondary recovery of oil, and disposal of salt water produced with oil; storage of natural gas and petroleum products in salt domes and other underground reservoirs; recovery of minerals such as uranium, salt, sulfur, and sodium sulfate; injection of excess agricultural or urban runoff and excess ponded surface waters; and disposal of water used in heat pump air conditioning systems. Possible future uses of underground injection include control of surface subsidence, and control of intrusion of salt water into fresh ground water resources.

Purpose and Scope

The primary purpose of this report is to describe injection well activities within the regulatory jurisdiction of the Texas Department of Water Resources. Included are types of injection wells for which regulatory programs involving issuance of permits have previously been established. Also included are assessments of injection wells which have recently been brought under the Department's underground injection control program.

This report is made partly in response to the federal Safe Drinking Water Act of 1974, which provides for protection of underground sources of drinking water through regulation of subsurface injections of fluid. On January 6, 1982, the Department received primary enforcement authority (primacy) from the U.S. Environmental Protection Agency to administer a state underground injection control program in lieu of a separate federal underground injection control program. One of the provisions enabling Texas to receive primacy was an agreement by the Texas Department of Water Resources to conduct an inventory and assessment of certain miscellaneous injection wells (e.g. Class V) in the State. By federal and state agreement, within three years of receiving primacy, the Department was to complete and submit to the Environmental Protection Agency a report containing:

(1) information on the construction features of Class V wells and on the nature and volume of the injected fluids;

(2) an assessment of the contamination potential of Class V wells based upon hydrogeological data available to the State;

(3) an assessment of the available corrective alternatives where appropriate and their environmental and economic consequences; and

(4) recommendations for the most appropriate regulatory approaches and for remedial actions where appropriate.

After receiving primacy, the Department decided to conduct an inventory and assessment of other injection wells within the Department's jurisdiction concurrently with the miscellaneous injection well assessments. The Department's investigation of these wells involved collection and analysis of information relating to underground injection of fluid by these wells. This information was used to describe injection processes and to determine the potentials for contamination of usable quality ground water. The project also involved the formulation of recommendations concerning the regulation of certain injection wells.

Classification of Wells and Regulatory Responsibilities

The Injection Well Act (Chapter 27 of the Texas Water Code) as amended in 1981 and Title 3 of the Texas Natural Resources Code provides statutory authority for regulation of all underground injections in Texas. The Injection Well Act divides regulatory responsibilities between the Railroad Commission of Texas and the Texas Department of Water Resources. Both state agencies have full authority to regulate those underground injections within their own jurisdiction as defined by the Act. Accordingly, the Texas Department of Water Resources has full authority to regulate the following activities:

Class I

(A) Wells, other than Class IV wells, used by generators of hazardous wastes or owners or operators of hazardous waste management facilities to inject hazardous waste.

(B) Other industrial and municipal waste disposal wells which inject fluids beneath the lowermost formation containing an underground source of drinking water within one-quarter mile of the wellbore. This category includes disposal wells operated in conjunction with uranium mining activities.

Note: All Class II wells are under the jurisdiction of the Railroad Commission of Texas.

Class III

Wells which inject fluids for extraction of minerals, exclusive of oil and gas. Presently, injection well technology is used to solution mine uranium, sodium sulfate, and brine, and to mine sulfur by the Frasch process.

Class IV

Wells used by generators of hazardous wastes or of radioactive wastes, by owners or operators of hazardous waste management facilities, or by owners or operators of radioactive waste disposal sites to dispose of hazardous wastes or radioactive wastes into or above a formation which contains an underground source of drinking water within one-quarter mile of the wellbore. Class IV injection activities were generally prohibited under the pre-1981 State program and are specifically prohibited under the current Texas Department of Water Resources Underground Injection Control program.

Class V

Miscellaneous injection wells that are not Class I, II, III, or IV wells, or single family residential cesspools or septic system disposal wells. Class V wells include:

(A) Recharge wells used to replenish the water in an aquifer.

(B) Subsidence control wells used to inject fluids into a nonoil or gas producing zone to reduce or eliminate subsidence associated with the overdraft of fresh water.

(C) Salt water intrusion barrier wells used to inject water into a fresh water aquifer to prevent intrusion of salt water into fresh water.

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

(E) Cooling water return flow wells used to inject water previously used for cooling.

(F) Drainage wells used to drain surface fluids, primarily storm runoff, into a subsurface formation.

(G) Septic system wells used:

  (i) to inject waste or effluent from a multiple family dwelling, business establishment, or community or regional business establishment septic tank; or

  (ii) for a multiple family dwelling, community, or regional cesspool.

(H) Cesspools or other devices that receive wastes and which have an open bottom or perforated sides.

(I) Dry wells used to inject nonhazardous wastes other than domestic sewage into the unsaturated zone of a subsurface formation.

(J) Sand backfill wells used to inject a mixture of water and sand, mill tailings, or other solids into mined-out portions of subsurface mines.

The Railroad Commission of Texas has full authority to regulate the following activities:

Class II

(A) Wells used to inject fluid (usually salt water) which is brought to the surface in connection with oil or natural gas production and may be commingled with wastewaters from gas plants, unless those waters are classified as hazardous waste at the time of injection.

(B) Wells used for enhanced recovery (secondary recovery) of oil or natural gas.

(C) Wells used for storage of hydrocarbons which are liquid at standard temperature and pressure.

Class V

(A) Wells used for in situ combustion of fossil fuels (in situ coal and lignite gasification).

(B) Injection wells associated with geothermal resources.

(C) Geothermal wells used in heating and aquaculture.

Underground injection activities under the jurisdiction of the Department are discussed in Chapters 3 through 12 of this report. However, Class IV wells and Class V dry wells are not discussed because the Department's investigation found no evidence of the existence or operation of any such wells, nor of any anticipated future use of such wells.

Class II wells are also absent from the list of chapter topics in this report. To explain further what Class II wells are and how they are regulated, the following section of this chapter presents basic information on the Railroad Commission's regulatory program for these wells, with additional statements describing the Railroad Commission's regulatory involvement with certain Class V wells.

The Railroad Commission of Texas UIC Program

The Railroad Commission of Texas was created in 1890 for the primary purpose of regulating the railroad industry. As such, it was the first regulatory agency authorized for the State of Texas. Today, the Railroad Commission's regulatory responsibilities extend to regulation of oil and gas production to promote conservation of hydrocarbons, and protection of water resources and surface and mineral rights. The Railroad Commission's broad authority over oil and gas production derives from the Texas Natural Resources Code, and from Chapters 26, 27, and 29 of the Texas Water Code.

The Railroad Commission has been active in the control of underground injection activities for more than 40 years. The first permit to inject gas into a reservoir producing oil or gas was issued by the Railroad Commission in 1928; the first permit to inject water into a producing reservoir was issued in 1938. These original permits specified that injected fluids must enter only those formations authorized for injection. This policy has continued to be an important provision of all Railroad Commission injection well permits. On April 23, 1982, the Railroad Commission received primacy from the U.S. Environmental Protection Agency to administer a state underground injection control (UIC) program for injection wells within its jurisdiction.

Class II Injection Wells Under Railroad Commission Jurisdiction

The Railroad Commission has jurisdiction over Class II wells injecting "oil and gas waste," a term that is defined in Chapter 27 of the Texas Water Code to include waste arising out of or incidental to drilling for or production of oil, gas, or geothermal resources, waste arising out of or incidental to the underground storage of hydrocarbons other than storage in artificial tanks or containers, or waste arising out of or incidental to the operation of gasoline plants, natural gas processing plants, or pressure maintenance or repressurizing plants. The Railroad Commission also has authority over Class II wells used for enhanced recovery (secondary recovery) of oil and gas, and for underground storage of hydrocarbons (Chapter 91 of the Texas Natural Resources Code).

The Railroad Commission has authorized by permit over 15,000 salt-water disposal wells, over 33,000 secondary-recovery wells, and over 500 hydrocarbon-storage wells. Salt water disposal and secondary-recovery wells are found throughout the State, specifically in areas of oil and gas production. Hydrocarbon-storage wells, however, are limited to the salt domes of the Gulf Coast and bedded salt formations in west Texas and the High Plains.

Salt-water disposal wells are allowed to inject fluids only into formations which do not produce oil or gas. In contrast, secondary-recovery wells, by design, inject into oil or gas zones to improve recovery of these valuable resources. Both types of wells in Texas range in depth from a few hundred feet to more than 10,000 feet with a basic requirement that the injection zone lie below the base of moderately saline ground water (less than 10,000 mg/l in total dissolved solids).

Hydrocarbon-storage wells inject into cavities in a salt dome or bedded salt which have been established by solution mining. Gulf Coast salt domes are intrusions of salt from deep source beds into the shallow subsurface. These salt domes generally rise to within a few hundred to a thousand feet of the surface. Accordingly, hydrocarbon-storage wells in Texas are generally shallow relative to salt-water disposal and secondary recovery wells.

New Class II wells are required by the Railroad Commission to have surface casing set to the depth recommendations of the Department of Water Resources, and be completely cemented in place to protect fresh to slightly-saline ground-water resources (less than 3,000 mg/l in total dissolved solids). In cases where existing oil or gas wells are converted to Class II wells, the Department advises the Railroad Commission on the occurrence and necessary protection of ground-water resources.

Class II wells are required to have long-string casing inside and extending below the surface casing to the depth of the injection zone. Evidence of sufficient cement between the long-string casing and borehole is required to assure isolation of injected fluids within the injection zone. Class II wells are required to inject through tubing which is set with a packer not more than 100 feet above the injection zone. Pressure monitoring is required for all uncemented annuli in Class II wells to detect casing, tubing, or packer leaks. Also, injection pressures and injection rates of these wells must be monitored and reported to the Railroad Commission.

A Class II injection or disposal well permit may authorize disposal of other oil and gas wastes in the well, including wastes from natural gas processing plants, provided that these wastes are nonhazardous at the point of injection. However, disposal of industrial wastes in a Class II well can only be authorized by a Class I permit issued by the Department.

Class V Injection Wells Under Railroad Commission Jurisdiction

The Railroad Commission's involvement with Class V injection wells has been limited to permitting three in situ coal and lignite gasification operations in East Texas. All three operations have terminated because of unfavorable economic conditions.

The typical in situ coal and lignite gasification operation consists of a two-well system completed in a coal or lignite bed ideally more than 6 feet thick. Wells of this type in Texas have ranged in depth from approximately 200 to 600 feet. The wells are cased with steel pipe and cemented to keep ground-water zones from extinguishing combustion downhole. Combustion is initiated and maintained in a cavity established between and connecting the two wells. Combustion is sustained by forcing air down one well while gases resulting from combustion are produced up the second well. In situ coal and lignite combustion produces a low BTU natural gas which can be used for fuel, and carbon dioxide gas as a by-product.

The Railroad Commission also has jurisdiction over Class V injection wells associated with the recovery of geothermal energy to produce electric power. A single pilot study is being conducted by the Texas Bureau of Economic Geology along the Gulf Coast to investigate the feasibility of geothermal wells, but no operation of geothermal wells for production of electric power has yet occurred. The two wells in the pilot study, a geothermal production well and an injection well for water disposal, use standard oil field casing and cementing designs to protect ground-water resources and maintain the natural isolation of the subsurface formations. The geothermal production well is completed in salt water bearing beds of the Frio Formation in the subsurface interval from 14,644 to 14,704 feet. The injection well for water disposal is completed in the Catahoula Formation in the subsurface interval from 6,480 to 6,518 feet.

The Railroad Commission's Underground Injection Control Program includes Class V geothermal wells used for heating or aquaculture. The *Geothermal Resources of Texas* map, published by the Bureau of Economic Geology in 1982, shows areas of the State where there may be a potential for use of such Class V injection wells in conjunction with geothermal wells. The map contains tabulated data on the producing aquifer, well depth, water temperature, water total dissolved solids concentration, and flow rate of wells and springs producing water which is at least 10°F (5.6°C) warmer than normal ground-water temperature for various areas of the State.

One of the major concentrations of known geothermal waters in Texas occurs along the trend of the parallel Balcones and Luling-Mexia-Talco fault systems and underlying Ouachita fold belt which course from the northeast corner of the State through the Dallas-Fort Worth area, Waco, Austin, San Antonio, and west to Del Rio (Figure 2-5). This group of geothermal wells and hot springs produces water primarily from the Trinity sands at the base of the lower Cretaceous rock section.

Another major concentration of known geothermal waters in Texas lies along a trend parallel to and southeast of the Trinity group of geothermal waters. This second group of geothermal waters lies within the Gulf Coast structural basin and produces mostly from Tertiary formations.

The Texas Department of Water Resources UIC Program

Statutory Background

Disposal of chemical and petrochemical process wastes by deep well injection was investigated during the fifties based on the successful injection of salt water into underground strata by the petroleum industry. By 1961, approximately six industrial waste disposal wells had been drilled and placed in operation. The Injection Well Act was originally adopted in 1961. It established that the underground injection of such wastes would be regulated by permits issued by the Board of Water Engineers in order to protect ground-water resources from contamination. Over 200 waste disposal well permits have since been issued. The use of waste disposal wells (Class I wells) in Texas has, therefore, been closely regulated by State permit from a very early date.

The waste disposal well permit program passed from the Board of Water Engineers to a successor agency, the Texas Water Development Board, and then to the Texas Water Quality Board by amendment of the Injection Well Act in 1969 in view of its role as the primary state water quality agency. The Texas Department of Water Resources was created in 1977 and assumed all water quality functions formerly carried out by the Texas Water Quality Board. The Injection Well Act was amended in 1977 and retitled the Disposal Well Act. The title reverted to the Injection Well Act when the Act was amended in 1981. The Injection Well Act is now codified as Chapter 27 (originally as Chapter 22) of the Texas Water Code.

In the 1970's, the mining of uranium ore by solution mining techniques developed in South Texas. The ore generally occurs in formations which contain usable quality ground water. The importance of these water resources led the Texas Water Quality Board to regulate these mineral mining activities through Chapter 26 of the Texas Water Code. All uranium solution mining activities have been regulated by State permit. Mineral mining activities are now subject to regulation through Chapter 27 of the Texas Water Code as a result of the 1981 amendments.

A federal initiative in the area of underground injection regulation was established through passage of the Safe Drinking Water Act of 1974. The process of promulgating federal program rules and regulations for underground injection control was substantially completed on June 24, 1980. The Injection Well Act was amended in 1981 to assure that the state program was equivalent to the new federal program and would qualify for primacy under the federal program. These amendments led to adoption of new rules by the Texas Department of Water Resources. On January 6, 1982, the Department of Water Resources received primacy from the U.S. Environmental Protection Agency to administer a State underground injection control program for injection wells within its jurisdiction.

The 1981 amendments to the Injection Well Act enlarged the meaning of the term "injection well" to include wells used for injection of any fluid where "fluid" was defined as "a material or substance that flows or moves in a liquid, gaseous, solid, semi-solid, sludge, or other form or state." The term "injection well" had previously been limited to a well used for injection of industrial and municipal waste, or oil and gas waste. This redefinition laid the groundwork for a comprehensive State underground injection control program. The amendments also established that an injection well operator may be required to maintain a performance bond or other form of financial security to ensure that a well is properly plugged when abandoned.

As previously noted, the Injection Well Act was originally passed in 1961. The legislature also acted in 1961 to establish a Texas Water Pollution Control Board under the Department of Health. A waste discharge permit program, designed primarily to regulate industrial and municipal wastewater treatment plants, came into being. The permit program was given new emphasis by passage of the Texas Water Quality Act in 1967 which established a new agency, the Texas Water Quality Board, a predecessor agency of the Texas Department of Water Resources. The Texas Water Quality Act is now codified as Chapter 26 (originally as Chapter 21) of the Texas Water Code.

Chapter 26 of the Texas Water Code provides for state regulation of waste discharges into or adjacent to water in the State. The terms "waste," "to discharge," and "water in the state" have broad application. The latter includes ground water, percolating or otherwise. It is therefore possible to regulate some underground injection activities through this statute. While the UIC permit program relies primarily on the Injection Well Act, underground injection control permits are generally issued pursuant to both statutes.

Rules and Method of Regulation

The relevant Department rules are found in Chapter 353 (relating to Underground Injection Control) and Chapter 341 (relating to Consolidated Permits) of Title 31 of the Texas Administrative Code.

These rules require that all Class I and Class III injection wells be regulated by permit. These facilities must be permitted or repermitted by January 6, 1987. Interim status standards concerning such items as financial responsibility, mechanical integrity testing, and operating and reporting requirements are contained in these rules to regulate subject facilities until new permits can be considered.

Class IV wells are specifically prohibited by Department rule. This investigation found no evidence of the existence or operation of any such wells.

Existing Class V wells are authorized by rule. In order to maintain authorization by rule, existing Class V operators were required to register with the Department by January 6, 1983. Proposed new Class V wells must be registered with the Department prior to construction of the wells to assure authorization by rule. The Department has the discretion to regulate Class V wells through the existing registration program as provided by rule, or to develop more appropriate regulatory approaches for specific categories of Class V wells. Such approaches might involve regulation by site specific permit, by special rules, or by a local agency.

Class V wells will be regulated primarily through a registration process. The owner, operator, and driller of such an injection well is required to submit to the Executive Director of the Department the following information with regard to each proposed injection well:

(1) The name of the facility;

(2) The name and address of the legal contact;

(3) The ownership of the facility;

(4) The nature, type, and operating status of each injection well; and

(5) The location, depth, and construction of each well.

This information allows the Executive Director to register each injection well facility and to conduct a review of the proposed operation on a site specific basis with regard to potential environmental hazards. Based on this review, the Executive Director may require the owner or operator of an injection well authorized by rule to apply for and obtain an injection well permit pursuant to Department rules. It is anticipated that the majority of Class V wells registered with the Department will not be required to secure an underground injection control permit. Assessments of each category of Class V wells are contained in this report.

A summary of the method of regulation for the classes of wells under the jurisdiction of the Texas Department of Water Resources follows:

Class	Category	Method of Regulation
I	Industrial and Municipal Waste Disposal	Permit
III	Uranium	Permit and Production Area Authorization
III	Brine, Sulfur and Sodium Sulfate	Permit
IV	Hazardous Injection Into or Above Drinking Water Supplies	Prohibited
V	Sewage Disposal	Permit
V	Artificial Recharge, Air Conditioning Return-Flow, Agricultural Drainage, and Mine Backfill	Registration and Review

Organization of the Department

The Texas Department of Water Resources came into existence on September 1, 1977, succeeding the Texas Water Quality Board, the Texas Water Development Board, and the Texas Water Rights Commission. The Texas Department of Water Resources is the administrative agency of the State given primary responsibility for implementing the State's constitutional and statutory provisions relating to water. The legislative functions of the Department are vested in the Texas Water Development Board; the executive functions, in the Executive Director; and the judicial functions, in the Texas Water Commission.

The Texas Water Development Board establishes any rules necessary to carry out the Department's powers and duties under the Texas Water Code and other laws, such as the Texas Solid Waste Disposal Act. The Executive Director and the Texas Water Commission may recommend to the Board for its consideration any rules that they consider necessary. Any person may petition the Board to consider a rule. The Texas Water Commission establishes separate rules of procedure to be followed in Commission hearings.

The Executive Director manages the administrative affairs of the Department and exercises the executive functions of the Department including the execution of the rules, orders, and decisions of the Department. The Executive Director organizes the divisions of the Department in a manner that will achieve the greatest efficiency. The Class I and Class III permit applications and Class V registrations are received by the Permits Division for administrative and technical review and preparation of the preliminary recommendations of the Executive Director. These recommendations are reviewed with other appropriate divisions of the Department. These recommendations, together with the permit application, are subsequently filed with the Texas Water Commission.

The Texas Water Commission is responsible for taking final action on permit applications. The applications are subject to requirements of public notice and opportunity for the public to request a public hearing. The Commission decides whether to grant a request for a public hearing. If granted, the public hearing is conducted by a Commission hearing examiner. The findings of fact and conclusions of law prepared by the examiner based on the record of the hearing serve as the basis of the Commission's decision in these contested cases. The Executive Director is a statutory party in all Commission hearings and makes a recommendation in each case. Commission hearings are conducted in accordance with the procedural rules established by the Commission and in accordance with the requirements of the Texas Administrative Procedure and Texas Register Act.

Definition of Terms

Abandoned well—A well for which the original purpose and use has been permanently discontinued or which is in such a state of disrepair that its original purpose cannot reasonably be achieved.

Acidizing—The process of introducing acid into an acid-soluble formation for the purpose of enlarging the pore space by dissolving the surrounding matrix. Acidizing also refers to the removal of encrustants from well screen and gravel pack, and dissolving cemented materials.

Aerobic—In the presence of oxygen.

Alluvium—Sediments deposited by streams, including floodplain deposits and stream-terrace deposits. Also called alluvial deposits.

Anaerobic—In the absence of oxygen.

Annulus—The space between two concentric cylindrical pipes or between the wellbore and pipe placed in the wellbore.

Aquiclude—A porous formation capable of absorbing water but not capable of transmitting it fast enough to supply a well.

Aquifer—A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Argillaceous—Having a notable proportion of clay minerals as constituents.

Artesian aquifer, confined aquifer—Artesian (confined) water occurs where an aquifer is overlain by rock of lower permeability (such as clay) that confines the water under pressure greater than atmospheric pressure. The water level in an artesian well will rise above the top of the aquifer even without pumping.

Artificial penetrations—In injection well reservoir technology, wells or test holes extending from the surface into a specific subsurface zone of interest. Artificial penetrations may be avenues for movement of fluids between different formations.

Attenuation—The process of reducing a contaminant level through dilution, sorption, or chemical or biological action.

Backflow, and *backwater*—To reverse the flow of water in a well by pumping or jetting.

Bail—To recover bottom-hole fluids or sediment by repeatedly lowering, filling, and retrieving a cylindrical vessel called a bailer.

Calcareous—Containing calcium carbonate ($CaCO_3$).

Casing—A tubular retaining structure, generally metal, which is installed in the excavated hole to maintain the well opening.

Cavern—A large scale underground cavity formed from a smaller solution channel by the dissolution of rock by ground water.

Cesspool—A pit for the disposal of raw sewage constructed in permeable soil with unmortared brick or stone casing the sides. Solids settle to the bottom of the pit, while partially treated wastewater is adsorbed into the soil through the pit walls.

Clay—A fine-grained inorganic material (grains less than 0.0005 mm in diameter) which has very low permeability and is plastic.

Cone of depression—The conical surface (apex down) of the water level created in an unconfined aquifer due to pumping.

Confining bed—A bed that, because of its position and its impermeability or low permeability relative to that of the aquifer, keeps the water in the aquifer under artesian pressure.

Confined ground water—Ground water under pressure significantly greater than atmospheric pressure, because it is bounded above by the bottom of a bed with distinctly lower hydraulic conductivity than that of the material in which it occurs.

Contamination—An impairment of the quality of water by sewage, industrial waste, oil and gas waste, or intraformational migration of fluids to a degree which creates an actual hazard to public health.

Core (side hole)—A formation sample obtained by a device that scrapes the side of an existing hole with a pneumatically operated coring blade as the device is raised up the sampling interval. The sample passes the bladed coring bit and falls into a bag within the core barrel.

Dike—A tabular intrusion of igneous rock cutting across or discordant with the beds of the enveloping rock.

Dip of rocks—The angle at which a bed is inclined from the horizontal in a direction perpendicular to the strike of the bed (expressed as 1 degree, southeast; or 90 feet per mile, southeast).

Domestic water supply—One-family water supply.

Drawdown—The lowering of the water table or piezometric surface caused by pumping (or artesian flow). In most instances it is the difference in feet between the static level and the pumping level.

Drilling mud—A fluid composed primarily of water and bentonite clay used in the drilling (primarily rotary) operation to remove cuttings from the hole, to clean and cool the bit, to reduce friction between the drill stem and the sides of the hole, to cake the sides of the hole, and to control downhole pressures. Such fluids range from relatively clear water to carefully prepared mixtures of special purpose compounds.

Effluent—Liquid waste material discharged to the environment after treatment.

Electric log—A graph log of a well showing the relation of the electrical properties of the subsurface rocks and their fluid contents. The electrical properties are natural potentials and resistivities to induced electrical currents, some of which are modified by the presence of the drilling mud.

Elution—Process of washing or removing adsorbed material from an adsorbent by means of a solvent ("eluant"). In uranium solution mining, elution is a processing operation at the mine surface, in which uranium minerals are washed from the surface of resin beads by an eluant. In solution in the eluant, uranium is ready for final precipitation and drying to form the yellowcake product (U_3O_8).

Evapotranspiration—Water withdrawn by evaporation from a land area, or a water surface, and water consumed by transpiration of plants.

Fault—A fracture or fracture zone along which there has been displacement of the two sides relative to one another.

Fault zone—A trend or system of numerous interconnecting small faults.

Flaggy—Thinly bedded. Flaggy limestones may be parted along bedding planes to produce tabular flagstones suitable for markers or paving.

Formation—A body of rock that is sufficiently homogeneous or distinctive to be regarded as a mappable unit, usually named from a locality where the formation is typical (such as Glen Rose, Paluxy, and Georgetown Formations.)

Fracture—Cracks in rocks caused by intense folding, pressure, or changes in temperature. Also, the process of breaking oil, gas, or water-bearing strata by injecting a fluid under sufficient pressure to cause planes of parting in the rock.

Geophysical (mechanical) well logging—Geophysical well logging is comprised of a number of techniques to measure electrical, chemical, or radioactive properties of subsurface rocks and their fluid contents. Typical techniques include: resistivity and self-potential logging (called "electric logging"), and gamma and neutron logging (called "radiation logging").

Geothermal gradient—The change in temperature of the earth with depth below ground surface, usually expressed in degrees per unit depth.

Gravel packed well—A well in which filter material is placed in the annular space to increase the effective diameter of the well and to prevent fine-grained sediments from entering the well.

Ground water—Water in the zone of saturation.

Hazardous waste—An official designation by the U.S. Environmental Protection Agency for any solid or liquid waste which will contribute significantly to an increase in mortality or serious illness, or will pose a substantial present or potential hazard to human health or the environment when it is improperly treated, stored, transported, disposed of, or otherwise managed.

Head—(See "Hydrostatic pressure").

Homogeneous—Material of essentially uniform characteristics of composition, texture, appearance, etc.

Hydraulic gradient—The change in static head per unit of distance in a given direction, usually expressed in feet per mile. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head.

Hydrologic communication—Condition of exchange of fluids between different surface or subsurface systems, zones, strata, or formations. Hydrologic communication generally exists between the component formations of a large aquifer. Usually synonymous with hydrologic continuity and hydraulic communication.

Hydrologic properties—The properties of rocks which control their capacity to absorb, hold, and transmit water.

Hydrostatic pressure, or *head*—The pressure exerted by the water at any given point in a body of water at rest, reported in pounds per square inch or in feet of water. The hydrostatic pressure of ground water is generally due to the weight of water at higher levels in the same zone of saturation.

Igneous rocks—Rocks formed by solidification from a molten or partially molten state.

Impermeable—Impervious or having a texture that does not permit water to move through it perceptibly under the head differences ordinarily found in subsurface water.

Infiltration—Flow or movement of water through the soil surface into the subsurface.

Irrigation—The controlled application of water to arable lands to supply water requirements not provided by rainfall.

Laccolith—An intrusion of rock which is concordant with the enveloping bedded rock, which has domed up the overlying rocks and also has a floor which is generally horizontal but may be convex downward.

Leaching—The process of removal of soluble material by passage of water through soil.

Lithology—The description of rocks, usually from observation of hand specimen or outcrop.

Lixiviant—A leaching solution used in solution-mining operations to dissolve ore minerals in the ore zone and to carry them in solution to the surface for reclamation and processing.

Logging—(See "Geophysical (mechanical) well logging.")

Marl—A calcareous clay, or a mixture of clay and calcite or dolomite, usually in the form of shell fragments or other marine fossils, and clay.

Metamorphic rocks—Rocks transformed in the solid state by the effects of temperature, pressure, and chemical environment, which generally occur below the zones of weathering and cementation.

Milligrams per liter (mg/l)—One milligram per liter represents one milligram of solute in one liter of solution. As commonly measured and used, one milligram per liter is numerically equivalent to one part per million.

Mineral—Any naturally occurring chemical element or compound.

Ore—Mineral deposit within a host rock that can be mined for economic profit.

Outcrop—That part of a rock layer that appears at the land surface.

Packer—In well technology, a downhole mechanical device that expands to seal off an annular space between two concentric pipes. Packers are routinely placed in injection wells at the top of the injection zone to isolate injected wastewater from the well casing and formations uphole.

Perched ground water—Ground water separated from an underlying body of ground water by unsaturated rock. Its water table is a perched water table.

Percolation—The movement under hydrostatic pressure of water through the interstices of a rock or soil, except the movement through large openings such as caves.

Perforations—A series of openings in a well casing, made either before or after installation of the casing, to permit the movement of fluids between the well and surrounding rock.

Permeable—Pervious or having a texture that permits water to move through it perceptibly under the head differences ordinarily found in subsurface water. A permeable rock has communicating interstices of capillary and supercapillary size.

Permeability—A measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient. It is a property of the medium alone and is independent of the nature of the liquid and of the force field causing the movement. It is dependent upon the shape and size of the pores of the medium.

Porosity—The ratio of the aggregate volume of pores (openings) in a rock or soil to the total volume of the rock or soil, usually stated as a percentage.

Recharge of ground water—The process by which water is absorbed and added to the zone of saturation. Also used to designate the quantity of water that is added to the zone of saturation, usually given in acre-feet or in million gallons per day.

Sedimentary rocks—Rocks formed by the accumulation of sediment in water or on land. The sediment may consist of rock fragments or particles, the remains or products of animals or plants, the products of chemical action or evaporation, or a mixture of these materials.

Seepage pit—A rock lined pit located at the end of a septic tank absorption field system, and used for disposal of wastewater not absorbed through the field lines.

Sill—A tabular intrusion of igneous rock oriented parallel to or concordant with the beds of the enveloping rock.

Soil absorption system—A method of subsurface disposal usually associated with septic tanks in which liquid effluent is distributed through perforated or open-jointed pipe for disposal in near-surface sediments, usually the soil zone. Generally synonymous with drainfield, leach field, tile field, trench bed, lateral lines, and mounded drain lines.

Solution mining—Practice of recovering valuable mineral resources from natural deposits in the earth without excavation or tunneling by using an array of injection and production wells to sweep leaching solutions (lixiviants) down through the ore body and up to the surface.

Solution porosity—Ratio of the aggregate volume of void space in a rock created by the dissolution of minerals by ground water to the given total volume of the rock. The void spaces include small channels, vugs, and caverns.

Sorption—The binding of chemical compounds, ions, and particulate matter onto surfaces or across membranes. The general term "sorption" encompasses processes such as absorption, adsorption, desorption, ion exchange, ion exclusion, ion retardation, chemisorption, and dialysis.

Spoil—Debris or waste material from a mine. Dirt or rock which has been removed from its original location.

Stratigraphic isolation—Geologic condition of separation of two or more strata by intervening strata.

Strike—The direction or bearing of a horizontal line in the plane of an inclined stratum. It is perpendicular to the direction of dip.

Structural feature, geologic—The result of the deformation or dislocation (such as faulting) of the rocks in the earth's crust. In a structural basin, the rock layers dip toward the center or axis of the basin. The structural basin may or may not coincide with a topographic basin.

Tailings—Those portions of washed or otherwise processed ore rock which are considered too poor in ore mineral content to be economically processed further.

Test hole—Hole designed to obtain information on ground-water or geological and hydrological conditions.

Transpiration—The process by which water vapor escapes from a living plant, principally the leaves, and enters the atmosphere.

Vug—A solution cavity in rock often with a mineral lining different in composition than the surrounding rock.

Water level—Depth to water in feet below the land surface (or depth to the top of the zone of saturation), where the water occurs under water-table conditions. Under artesian conditions, the water level is a measure of the pressure on the aquifer, and the water level may be at, below, or above the land surface.

Water table—The upper surface of a zone of saturation, except where the surface is formed by an impermeable body of rock.

Water-table aquifer (unconfined aquifer)—An aquifer in which the water is unconfined. The upper surface of the zone of saturation is under atmospheric pressure only and the water is free to rise or fall in response to changes in the volume of water in storage. A well penetrating an aquifer under water table conditions becomes filled with water to the level of the water table.

Well log—(See "Geophysical (mechanical) well logging.")

Well screen—Tubular screen installed in the completion zone at the bottom of a well that allows water to flow freely into a production well or from an injection well. Well screens prevent sand from entering the wellbore, and serve as structural retainers to support the borehole in unconsolidated sediments. Numerous types are available and their applications depend on the specific hydrogeologic conditions present at each well site.

Yield of a well—The rate of discharge, commonly expressed in gallons per minute or gallons per day.

Zone—Section of the subsurface characterized by mineralogy or lithology (e.g., *sulfur zone*), hydrology (e.g., *fresh-water zone*), structure (e.g., *fault zone*), or activity (e.g., *mining zone*).

Zone of aeration—The subsurface zone above the water table in which the interstices are partly filled with air. The term is synonymous with unsaturated zone.

Zone of saturation—The zone below the water table in which all interstices are filled with ground water.

Categories of Well Yields, Injection Rates, and Water Quality

For the purpose of this report, water well yields and injection rates are categorized as follows:

Small—less than 100 gal/min (gallons per minute), or 6.3 l/s (liters per second);

Moderate—100 to 1,000 gal/min (6.3 to 63 l/s); and

Large—more than 1,000 gal/min (63 l/s)

Additionally, water quality is categorized as follows:

Fresh—less than 1,000 mg/l (milligrams per liter) dissolved solids;

Slightly saline—1,000 to 3,000 mg/l dissolved solids;

Moderately saline—3,000 to 10,000 mg/l dissolved solids;

Very saline—10,000 to 35,000 mg/l dissolved solids; and

Brine—more than 35,000 mg/l dissolved solids.

Conversion From English to Metric Units

The table below gives factors for converting from English units of measurement used in this report to their metric equivalents in the International System of Units. This table may be referred to when using any of the tables or appendices.

From English units	Multiply by	To obtain metric units
inches (in)	2.54	centimeters (cm)
feet (ft)	0.3048	meters (m)
miles (mi)	1.609	kilometers (km)
square miles (mi^2)	2.590	square kilometers (km^2)
cubic feet per second (ft^3/s)	0.02832	cubic meters per second (m^3/s)
gallons per minute (gal/min)	0.06309	liters per second (l/s)

From English units	Multiply by	To obtain metric units
gallons per day (gal/d)	3.785	liters per day (l/d)
million gallons per day (million gal/d)	3.785	million liters per day (million l/d)
million gallons per day (million gal/d)	0.04381	cubic meters per second (m^3/s)
gallons per day foot [(gal/d)/ft]	12.418	liters per day per meter [(l/d)/m]
acre-feet (ac-ft)	0.001233	cubic hectometers (hm^3)
acres (ac)	0.4047	square hectometers (hm^2)
pounds (lb)	0.4536	kilograms (kg)
pounds per square inch ($lb/in.^2$)	0.07031	kilograms per square centimeter (kg/cm^2)

To convert degrees Fahrenheit (°F) to degrees Celsius (°C) use the following formula:

$$°C = (°F-32)\ (0.556)$$

Acknowledgements

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CHAPTER 2

GENERAL GEOLOGY

GENERAL GEOLOGY

The present-day geology of Texas reflects a variety of natural processes such as erosion, deposition, volcanism, igneous intrusion, salt dome intrusion, metamorphism, faulting, and folding. These processes have created the rocks that contain valuable water resources, valuable mineral deposits, and isolated strata suitable for injection of industrial waste. Fresh water aquifers, mineral deposits, and subsurface waste disposal zones may be found throughout the stratigraphic section in the various physiographic regions of the State (Figure 2-1), in rocks ranging in age from Precambrian to Recent (Table 2-1).

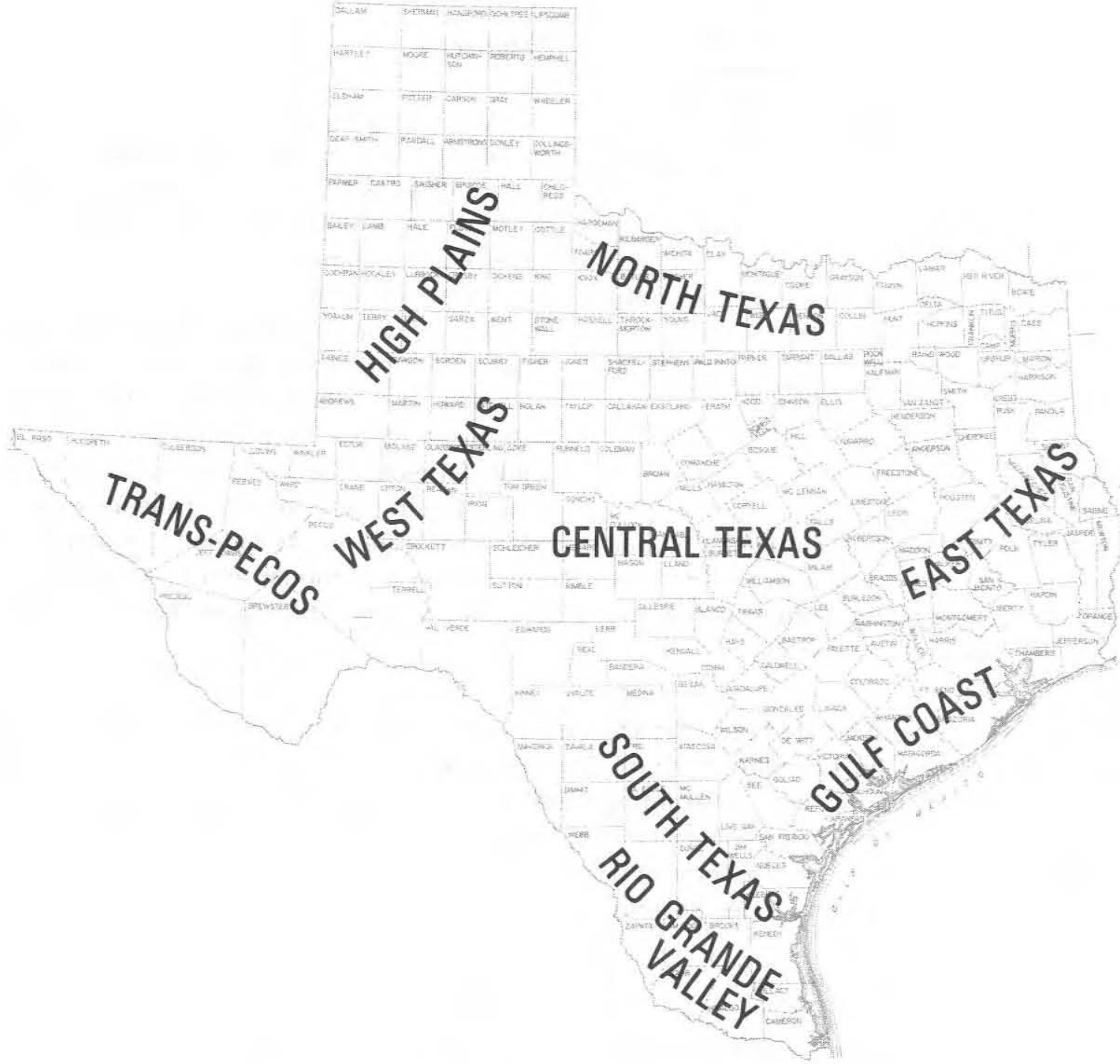

Figure 2-1.—Physiographic Regions of Texas

Table 2-1.—Geologic Time and Rock Units

Era	System
Cenozoic	Quaternary
	Tertiary
Mesozoic	Cretaceous
	Jurassic
	Triassic
Paleozoic	Permian
	Pennsylvanian
	Mississippian
	Devonian
	Silurian
	Ordovician
	Cambrian
Precambrian	

Stratigraphy

Precambrian

Precambrian rocks in Texas were, in part, derived from great deposits of sediments consisting of limestone, sandstone, and carbonaceous shales. After these sediments were deposited, they were intruded by igneous magmas, metamorphosed, and folded. The igneous and metamorphic rocks were then extensively eroded before the beginning of the Paleozoic Era.

Paleozoic

During most of the Paleozoic Era, sandstone, limestone, and carbonaceous shale were deposited in sedimentary basins throughout much of Texas. These basins received sediments until the latter part of the era (late Pennsylvanian), when the Llano Uplift and the Ouachita Fold Belt caused regional tilting of the land surface to the west and east off the flanks of the uplifted zones. At the close of the Paleozoic, during Permian time, deposition centered primarily in the Permian Basin area of the present-day High Plains, while the areas surrounding this basin underwent erosion. As lagoonal systems were developed around the fringes of the Permian Basin during the middle and late Permian, the restricted flow of sea water in these lagoons resulted in deposition of hundreds of feet of red beds, salt and other evaporite minerals.

The native sulfur and bedded salt that are mined in the Trans-Pecos and High Plains regions occur in the rocks of the Permian System. The upper Permian rock section in particular is characterized by formations with alternating beds of limestone, salt, dolomite, gypsum, and calcite. Sulfur occurs in association with calcite, in fractures and vugs, and with dolomite in the pore spaces of the rock. Salt, in the form of brine, is obtained chiefly from the massive rock salt beds of the Salado Formation (upper Permian).

Along the Gulf Coast, sulfur and brine are produced from salt domes. The deep source of the salt (Louann Salt) could range in age from Permian to upper Jurassic, and is probably on the order of 20,000 to 25,000 feet deep. Many geologists believe the salt is Permian in age and is related to the West Texas Permian evaporite deposits.

Mesozoic

Extensive land exposure and erosion continued through Triassic time in Texas, depositing continental sediments on the eroded surface of Permian rocks. Exposure and erosion continued in the Trans-Pecos part of the State until late Jurassic time, when the sea progressively inundated the region. The Jurassic sea was largely confined to the east Texas region until this transgression occurred.

At the beginning of the Cretaceous Period, the seas continued the advance begun in the late Jurassic, and eventually covered all of Texas. This major transgression, together with several minor regressions, created a continuously oscillating shoreline that is evidenced in the present sequence of Cretaceous age sediments. The sea reached its maximum extent during the middle Cretaceous. During the late Cretaceous, a general uplift occurred to the west and the Cretaceous sea withdrew to a position covering only the eastern portion of the State. The uplift continued and the sea finally regressed to the south, marking the end of the Cretaceous Period in Texas.

Stratigraphers generally divide the Cretaceous rock system into lower and upper series. The lower Cretaceous is represented throughout much of Texas by the Trinity, Fredericksburg, and Washita Groups, from bottom to top. The upper Cretaceous in southwest and east Texas is divided into the following rock groups, from bottom to top: Woodbine, Eagle Ford, Austin, Taylor, and Navarro. The Terlingua, Tornillo, and Gulfian represent the upper Cretaceous rocks in west Texas, from bottom to top.

There are three Cretaceous rock units of particular regional importance: (a) the Trinity Group (lower Cretaceous) furnishes good quality water in central and north-central Texas and has the potential for producing large quantities of oil and gas in east and south Texas; (b) the Edwards Formation (lower Cretaceous, Fredericksburg Group), located in south central Texas, is an important source of fresh water for many municipalities, including San Antonio; and (c) the Woodbine Group (upper Cretaceous) is one of the chief aquifers in northeast Texas and is a major source of oil in the East Texas Embayment (Figure 2-2).

Cenozoic

Following the close of the Cretaceous Period, noted by uplifting of the western part of the State and subsidence of the coastal area, sediments of the Tertiary and Quaternary Periods were deposited. A fluctuating gulf coastline characterized the Tertiary Period in Texas. Repeated transgression and regression of the sea resulted in an alternating sequence of marine and continental deposits. The Balcones faulting through the center of the State also occurred during the Tertiary Period, probably as a result of continued subsidence near the Gulf Coast and uplift in the west. Since the beginning of the Tertiary Period, broad areas from central Texas to the north and west have been subjected to erosion and weathering, producing the present topographic and geomorphic features.

For the purposes of this publication, Tertiary sediments are important because of their potential to produce water, mineral salts, and uranium, and because of their excellent disposal reservoir characteristics. The Tertiary rock system has been divided into five rock series which are, from bottom to top, the Paleocene, Eocene, Oligocene, Miocene, and Pliocene.

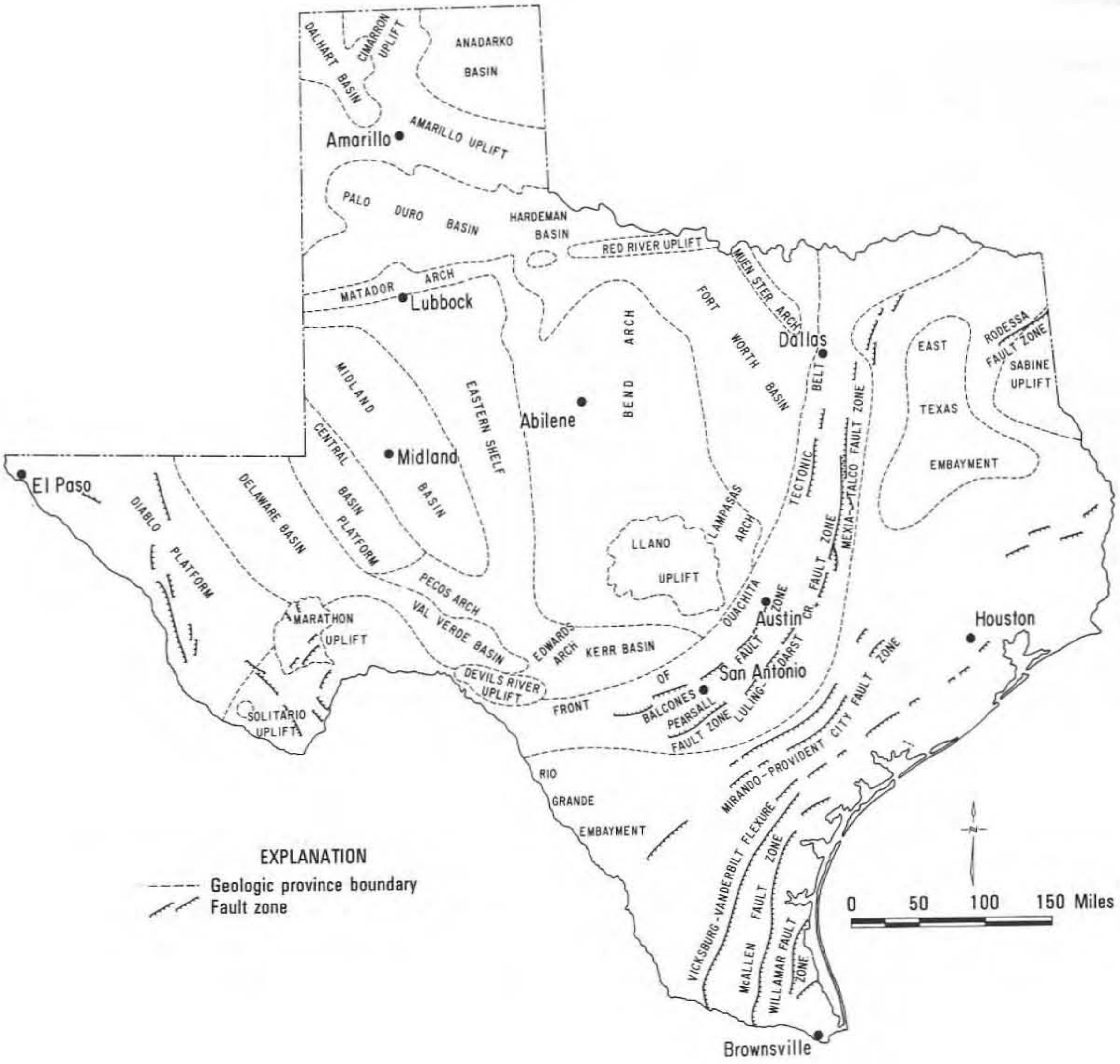

Figure 2-2.—Major Geologic Structural Features of Texas

The uranium solution mines of south Texas produce from the Jackson Sand (Eocene), Catahoula Tuff (Oligocene), Oakville Sand (Miocene), and Goliad Sand (Pliocene). These formations stretch along the entire length of the Texas coast, but production occurs only in the southern half of this stretch, generally south of San Antonio. These formations outcrop approximately 100 miles inland from the coast.

Most of the State's disposal reservoirs occur in the Tertiary sediments of the Gulf Coast region. The density of industrial development in the region, combined with the suitability of the subsurface environment, has led to the development of certain strata near the Gulf Coast as disposal reservoirs. Notable Tertiary disposal reservoirs occur in the Yegua Formation (Eocene Series), the Frio Formation (Oligocene Series), the Catahoula Tuff (Oligocene Series), and in the undifferentiated Miocene sands.

Sodium sulfate is produced by the mining of brines from sulfate deposits contained in playa lake or lacustrine silts, sands, and clays. These sediments are of Pleistocene age and occur in depressions of Cretaceous limestone and clay. Surrounding these playa lake deposits, and overlying the Cretaceous, is the Ogallala Formation of Pliocene age. Currently, the solution mining of sodium sulfate occurs only in Terry County.

Many of the State's major and minor aquifers are Tertiary and Quaternary in age. These aquifers yield large quantities of ground water for municipal, industrial, and irrigation use. They often are hydrologically connected to, and consequently include, underlying rocks as old as Precambrian. Because of the importance of the State's major and minor aquifers as valuable natural resources to be protected by the Department's Underground Injection Control Program, these aquifers are discussed in greater detail later in this chapter.

Structure

The importance of geologic structure to underground injection wells stems from the role that structure plays in creating the reservoirs for subsurface fluid injection, and in determining the natural direction of ground-water flow. The best reservoirs for accepting and containing injected fluids are porous and permeable sedimentary formations that are not highly folded, fractured, or intruded, and that are bounded above and below by impermeable confining formations. Extensive thick sedimentary basins and nearly flat-lying formations that satisfy these basic criteria for contained-injection reservoirs exist in most areas of the State.

Other major geologic structures of Texas include arches and uplifts that expose rocks as old as Precambrian, buried Paleozoic fold belts, and in west Texas, volcanic structures, uplifted mountains, and block-faulted basin and range structures. These major geologic structures are modified locally by folds, faults, and intrusives including dikes, sills, and salt domes. Of greatest significance for injection well operations are the large fault zones of central Texas, salt domes and growth faults of the Gulf Coast, salt dissolution structures of the High Plains, and the hard impermeable rocks of the Llano Uplift. Figure 2-2 shows the major structural features of Texas.

The Balcones Fault Zone, trending through the State from Dallas to Waco, Austin, and San Antonio, and the parallel Luling-Mexia-Talco Fault Zone to the east, should generally be avoided in siting wells that inject hazardous fluids, although stratigraphic evidence indicates that most of the movement along these faults occurred in Miocene time and no such movement has been noted within the period of recorded history. Particularly in the hard limestone portions of the central Texas Cretaceous section, these faults may present potential hazards to underground injection operations by providing avenues for fluid movement from injection zones into fresh water supplies. Where fault planes intersect the earth's surface, the percolation of rain water has slowly dissolved the limestone along the fault planes to form caverns and smaller solution channels for fluid flow.

Along the Gulf Coast, salt domes are the principal anomalies which disrupt the relative monotony of gently dipping strata. These large salt intrusions into the shallow subsurface are typically a mile or more in width and have been extruded from source beds of salt several miles below the surface. Salt domes have traditionally been sources of quarried and solution-mined salt. Some of their associated cap rocks have produced large quantities of sulfur. Because of salt's impermeable nature and its ability under stress to flow and deform significantly before breaking, some geologically stable Gulf Coast salt domes have been developed for storage of produced petroleum reserves. This type of storage is accomplished by dissolving out cavities in the salt and filling the cavities with petroleum. Studies by the Department and the Bureau of Economic Geology are currently underway to determine the potential of salt domes for storage of hazardous wastes by technology similar to that used for petroleum storage. Records from industry and from the regulatory programs of the Department and the Railroad Commission have already shown that with the proper precautions, mining of salt and sulfur and storage of petroleum in salt domes can be environmentally safe procedures.

Gulf Coast growth faults, representing adjustments in the subsurface section to differential compaction of sediments, should generally pose little problem for injection well operations. Growth faults principally involve the compaction of very low permeability clays; the fault planes typically are impermeable, creating horizontal boundaries for both waste migration and pressure transmission in an injection reservoir. These faults may be expressed on the surface in the form of damage to roads and building foundations or noticeable changes in fence lines, drainage, and vegetation. Many faults evident on well logs appear to have no surface expression. Growth faults generally dip at up to 60 degrees near the surface, with the dip angle decreasing with depth until the fault becomes parallel to the nearly horizontal bedding plane of the strata. From the ongoing and generally subtle changes noted at the land surface, it must be assumed that many growth faults are active. The movement of such faults is characteristically of a slow creeping type, rather than the abrupt slippage that is associated with perceptible earthquakes. Although the natural forces involved in the slow movement of growth faults are definitely sufficient to bend or disrupt well casings, the problems that may result are more of a nuisance to the well operator than a hazard to water resources.

On the High Plains, which are extensively underlain by salt beds of the Salado Formation (Permian), salt dissolution may form caverns and collapse structures such as sinkholes. These structures may disrupt the operation of injection wells and may establish communication between wastes and the fresh water zones. Ideally, areas should be evaluated for salt dissolution problems prior to extensive injection well development.

In the Llano Uplift region of central Texas, which is characterized by Precambrian igneous and metamorphic rocks, formations will generally be too impermeable to provide suitable disposal reservoirs and solution-mining zones for injection wells. Small Class III and Class V well operations may, however, be viable in the thin stream deposits and outwash deposits from the exposed Precambrian rocks of this region.

Major and Minor Aquifers

Major and minor aquifers underlie more than half of the land area of Texas and supply about 60 percent of the water used in the State.

A major aquifer is defined as one that yields large quantities of water in a comparatively large area of the State. The major aquifers referred to in this report are essentially the same as those described in the 1968 Texas Water Plan. The location and extent of the major aquifers are shown in Figure 2-3. Their water-bearing properties are described in Table 2-2.

The minor aquifers in Texas are important sources of water supply and are the only reliable sources of water in some areas. Minor aquifers are defined as those that yield large quantities of water in small areas of the State, or relatively small quantities of water in large areas of the State.

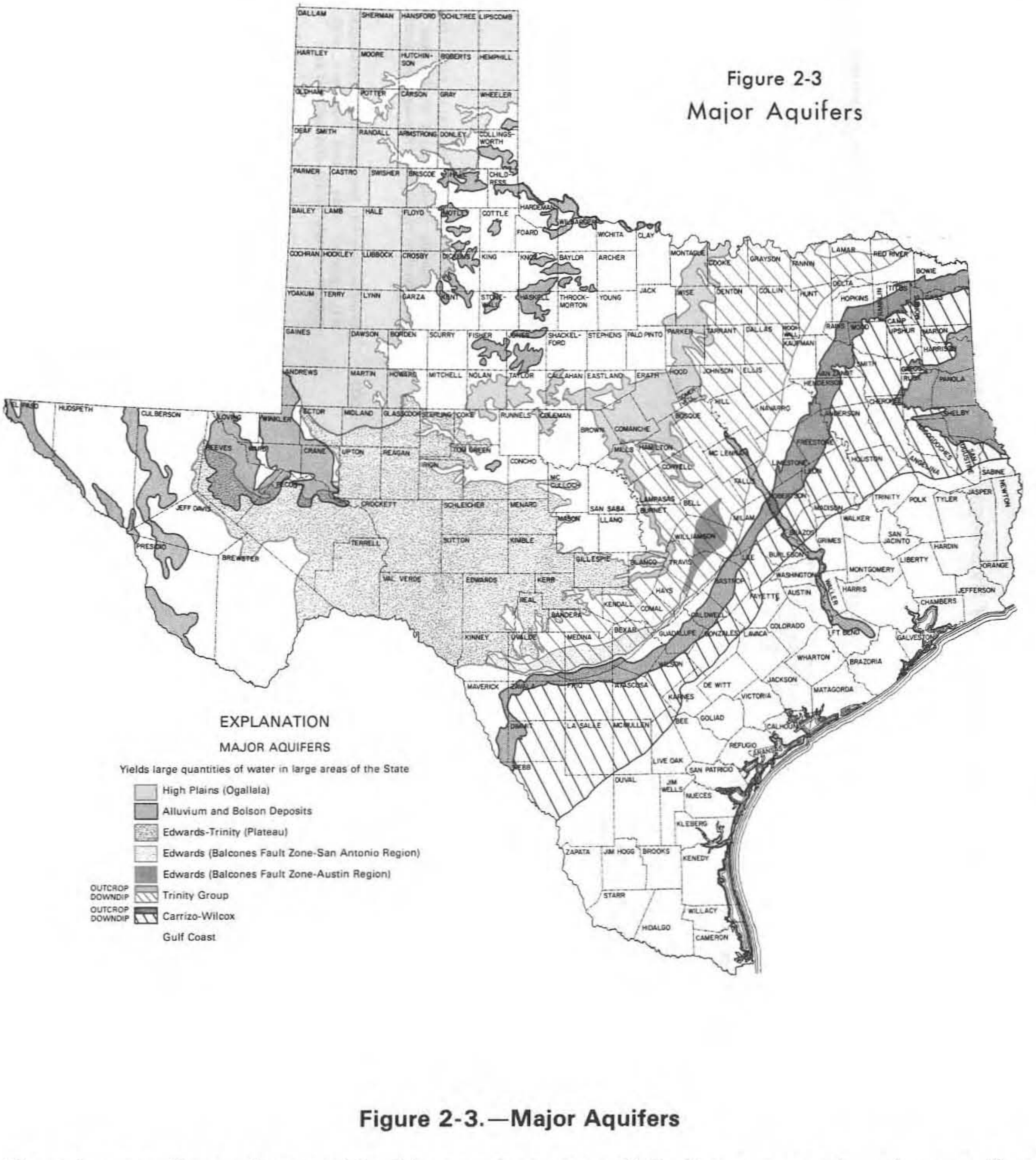

Figure 2-3.—Major Aquifers

The minor aquifers referenced in this report are essentially the same as the minor aquifers described in the 1968 Texas Water Plan, although a few more have been delineated and added here. The location and extent of the minor aquifers are shown in Figure 2-4. Their water-bearing properties are described in Table 2-3.

Table 2-2.—Major Aquifers and Their Hydrologic Properties

Major aquifer	Water-bearing properties	Geologic units	Aquifer thickness (feet)	Lithologic properties
High Plains	Yields moderate to large amounts of water in the High Plains. The water is generally fresh to slightly saline except where local contamination has occurred. The greatest saturated thickness occurs in the North Plains area and ranges up to 525 feet with thicknesses as much as 200 feet in the area south of Lubbock.	Ogallala Formation of Pliocene age, and underlying Cretaceous and Triassic formations in hydrologic continuity.	0-900	Unconsolidated, varicolored sand, silt, clay, and gravel with some caliche beds.
Carrizo-Wilcox	The Wilcox portion of the aquifer is poorly developed southwest of the Guadalupe River; to the northeast the Carrizo and Wilcox are about equal in importance. Usually yields moderate to large amounts of fresh to slightly saline water.	Carrizo Formation and Wilcox Group of Eocene age	150-3,000	Ferruginous, cross-bedded sand with clay, sand, silt, and gravel.
Edwards (Balcones Fault Zone)	Yields moderate to large amounts of fresh to slightly saline water. Acidizing usually improves yields of wells. Water quality deteriorates rapidly toward the southeast. The four largest springs in Texas (Comal, San Marcos, San Felipe, and Barton) issue from this aquifer.	Georgetown, Edwards, and Comanche Peak Formations of Cretaceous age	350-600	Massive to thin-bedded, nodular, cherty, gypsiferous, argillaceous limestone, dolomite, and shale. Some beds are highly cavernous.
Trinity Group	Yields small to large amounts of fresh to slightly saline water. Much of the aquifer has been overdeveloped, especially in the Fort Worth-Dallas area.	Trinity Group of Cretaceous age	100-1,200	Sand with silt, shale, and clay. Gravel and conglomerate usually found at the base. Limestone and dolomite replaces sand toward the southeast.
Alluvium and Bolson Deposits	Bolsons are the principal aquifers in the upper Rio Grande basin, supplying small to large quantities of fresh to moderately saline water. Elsewhere alluvium yields may be small to large, and water quality ranges from fresh to slightly saline.	Cenozoic and Recent formations of Tertiary and Holocene age	0-9,000	Unconsolidated and partially consolidated sand, silt, gravel, clay, and boulders with caliche, gypsum, conglomerate, and volcanic ash.
Gulf Coast	Yields moderate to large amounts of fresh to slightly saline water. Near the coast, salt-water intrusion may cause water-quality deterioration. The aquifer is thicker (1,000-3,200 feet thick) and more productive in the eastern area, while around Corpus Christi it is 500-2,500 feet thick.	Sediments of Miocene through Holocene age	500-3,200	Sand, silt, gravel, and clay, with sandstone, volcanic ash, and tuffaceous clay. Caliche beds are present in the central and southern portions.
Edwards-Trinity (Plateau)	Yields small to large amounts of fresh to slightly saline water. Over the eastern portion, the aquifer yields far more water than is used. West of the Pecos River the reverse is true, and water levels are rapidly declining.	Georgetown, Edwards, and Comanche Peak Formations, and the Trinity Group of Cretaceous age	0-800	Cherty, gypsiferous, argillaceous, cavernous limestone and dolomite, with sand, silt, and clay. Gravel and conglomerate are usually found at the base.

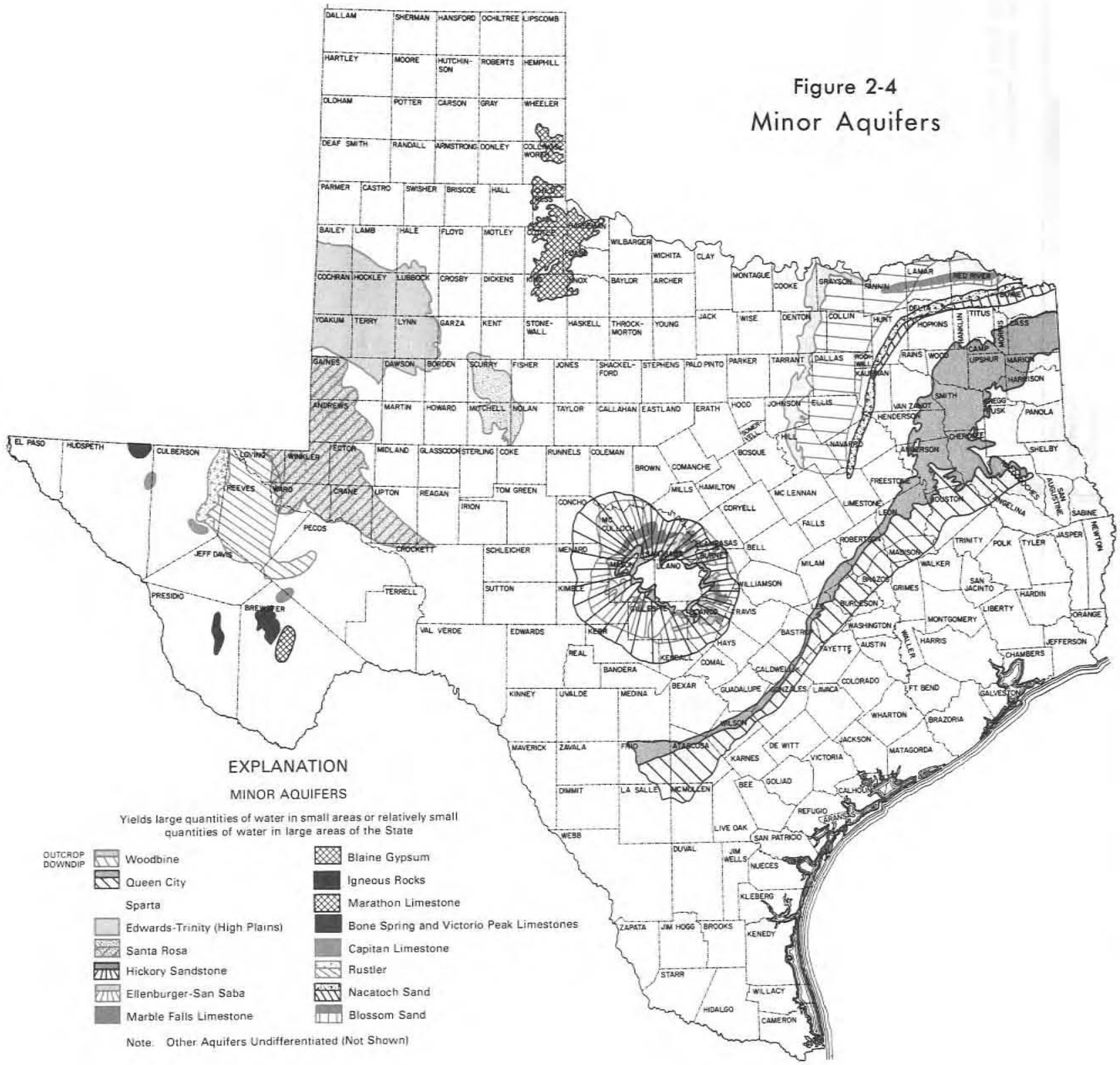

Figure 2-4.—Minor Aquifers

Table 2-3.—Minor Aquifers and Their Hydrologic Properties

Minor aquifer	Water-bearing properties	Geologic units	Aquifer thickness (feet)	Lithologic properties
Woodbine	Yields small to moderate quantities of fresh to slightly saline water. South of Dallas County the aquifer is thinner and the yields are lower.	Woodbine Group of Cretaceous age	100-600	Cross-bedded, ferruginous, tuffaceous sand, silt, clay, and lignite. More massive beds of sand and sandstone near the base.
Sparta	Yields moderate to large quantities of fresh to slightly saline water. Most production is from the northeast portion of the aquifer.	Sparta Formation of Eocene age	100-300	Sand interbedded with shale and clay. The more massive sand beds are near the base of the formation.
Queen City	Yields small to moderate supplies of fresh to slightly saline water. Yields are higher in the northeast portion.	Queen City Formation of Eocene age	100-500	Consolidated and unconsolidated cross-bedded sand, sandy shale, and clay with mica, glauconite, and limonite. The Sparta and Queen City are separated by a relatively thin glauconitic clay (50-100 feet) called the Weches Formation.
Edwards-Trinity (High Plains)	Yields small to moderate quantities of slightly to moderately saline water in the southern High Plains. Water occurs in the limestone only in the western portion of the aquifer.	Trinity and Fredericksburg Groups of Cretaceous age	0-300	Thin, locally discontinuous sand and sandstone overlain by clay, shale, caliche, and limestone.
Santa Rosa	In the eastern part, the aquifer yields moderate amounts of freshwater. In the western area, it yields moderate amounts of fresh to moderately saline water.	Santa Rosa Formation of Triassic age	100-700	Micaceous, cross-bedded sand with bituminous inclusions, interbedded with shale in the upper part. The eastern outcrop area has a basal conglomerate.
Hickory Sandstone	Generally yields moderate amounts of fresh to slightly saline water in the Llano Uplift area.	Hickory Sandstone of Cambrian age	100-500	Ferruginous sandstone with some shale near the top and conglomerate near the base.
Ellenburger-San Saba	Yields moderate amounts of fresh to slightly saline water in the Llano Uplift area.	Ellenburger Group and San Saba Formation of Cambrian and Ordovician age	400-2,000	Crystalline, cherty, sometimes sandy, limestone and dolomite, with some limestone conglomerate.
Marble Falls Limestone	Yields large amounts of fresh to slightly saline water in the Llano Uplift area.	Marble Falls Limestone of Pennsylvanian age	350-600	Dark cavernous limestone with some thin shale strata.
Blaine Gypsum	Yields small to large amounts of slightly to moderately saline water in Childress, Collingsworth, Cottle, Foard, Hardeman, King, and Wheeler Counties.	Blaine Formation of Permian age	200-300	Shale with lenticular, cavernous gypsum beds, dolomite, and some sandstone.
Igneous Rocks	Yields small to large amounts of freshwater in the Marfa-Alpine area. Elsewhere, in Jeff Davis, Presidio, Brewster, and Hudspeth Counties, yields are small.	Primarily extrusives of Tertiary age	0-4,000	Lava flows of rhyolite, trachyte, syenite, and basalt; tuffs, volcanic ash, breccia, unconsolidated sand, gravel, and silt.
Marathon Limestone	Yields small to moderate amounts of fresh to slightly saline water in the Marathon area of Brewster County.	Marathon Limestone of Ordovician age	350-900	Flaggy and dense, fractured, cavernous limestone, shale, conglomerate, and sandstone.
Bone Spring and Victorio Peak Limestones	Yields moderate to large quantities of slightly to moderately saline water, primarily in Hudspeth County.	Bone Spring and Victorio Peak Limestones of Permian age	1,300-2,000	Cavernous, cherty limestone, siliceous shale, clay, calcareous sand, and conglomerate.
Capitan Limestone	Yields moderate to large quantities of fresh to slightly saline water in West Texas.	Capitan and Goat Seep Limestones of Permian age	1,300-2,000	Reef limestone and back-reef beds of limestone and dolomite with minor amounts of siltstone, sandstone, and evaporites.
Rustler	Yields moderate to large amounts of slightly to moderately saline water in Culberson, Reeves, and Ward Counties.	Rustler Formation of Permian age	200-500	Vugular and cavernous dolomite, limestone, and gypsum with a basal zone of sand, salt, conglomerate, and shale.
Nacatoch Sand	Yields moderate amounts of fresh to slightly saline water. In some areas, such as Hunt County, the aquifer is overdeveloped and partially dewatered.	Nacatoch Sand of Cretaceous age	350-500	Unconsolidated to indurated, massive, glauconitic, calcareous sand and marl.
Blossom Sand	Yields moderate amounts of fresh to slightly saline water in Fannin, Lamar, and Red River Counties.	Blossom Sand of Cretaceous age	0-400	Unconsolidated, ferruginous, glauconitic sand, interbedded with sandy and chalky marl.

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PART II—INJECTION WELL ASSESSMENTS

CHAPTER 3

INDUSTRIAL WASTE DISPOSAL WELLS

Investigator:

Ben Knape

INDUSTRIAL WASTE DISPOSAL WELLS

Table of Contents

INDUSTRIAL WASTE DISPOSAL WELLS

Introduction

Industrial waste disposal wells are regulated by the Texas Department of Water Resources. These wells are intended to serve as an environmentally safe alternative for disposal of liquid wastes. The receiving stratum, or disposal zone, for these waste disposal wells should be a porous and permeable aquifer containing highly mineralized water, lying significantly below the base of slightly saline ground water.

Regulation of industrial and municipal waste disposal wells originated with the Texas Injection Well Act of 1961. Prior to this date, the development of large-scale projects for the injection of salt water produced from oil and gas activities demonstrated the potential of injection wells as an environmentally sound method of waste disposal. With the success of this technology in the oil field, several chemical companies investigated the feasibility of applying subsurface injection to aqueous industrial wastes. Subsurface disposal of industrial waste in Texas began in 1953 at the E. I. Du Pont de Nemours and Company, Inc. plant located in Victoria County. This well is still in operation, using the Catahoula Formation of Miocene age as a disposal reservoir. By 1961, it was estimated that six industrial waste disposal wells were operating in Texas.

The 1961 Injection Well Act required operators to obtain permits to drill injection wells or to convert existing wells to injection wells for disposal of industrial or municipal waste. Over 200 industrial waste disposal well permits have been issued in Texas. Each of these wells is considered a Class I injection well. Less than ten municipal waste disposal well permits have been issued. Each of these municipal wells is considered to be either a Class I or Class V injection well.

Of the 125 industrial wells in operation in 1983, 114 are noncommercial wells, and 11 are commercial wells which dispose of wastes from off-site generators for a fee. Figure 3-1 shows the locations of industrial waste disposal wells in Texas. Of the 114 noncommercial wells, 92 are used to dispose of hazardous waste. Most of the industrial nonhazardous waste disposal wells are associated with the uranium solution-mining industry, providing the ultimate disposal reservoir for production wastewaters and aquifer restoration waters generated by the uranium solution-mining industry.

The majority of industrial waste disposal wells in the State are located along the Gulf Coast in association with the chemical-petrochemical industrial development of the region. The Class I wells serving the uranium solution-mining industry are confined to south Texas. The remainder of the waste disposal wells are scattered through east Texas, west Texas, and the High Plains regions.

Geohydrology

Proper stratigraphic and structural conditions are important considerations for contained subsurface disposal reservoirs.

Stratigraphy

Most rocks exposed at the surface in Texas are of sedimentary origin. In most areas of the State these rocks extend several thousand feet beneath the land surface. They were deposited in stratified layers, and are generally composed of clay, shale, silt, sand, gravel, and limestone.

The rock units used as disposal zones in Texas range in age from Ordovician to Tertiary (Figure 3-1). More wells use strata of the Miocene Series (Tertiary System) for waste injection than any other age rock because most chemical industries that generate wastewater are located in areas of thick Miocene sediments. The majority of industrial waste disposal well operations inject into sand strata; however, limestone and dolomite are also used. No waste disposal well permit has been issued for injection into fractured shale, igneous rock, or metamorphic rock.

Hundreds of thousands of oil and gas exploratory wells have been drilled in Texas during the past 80 years. From this activity of the petroleum industry, an abundance of information is available concerning subsurface geology. Electric logs, in particular, have furnished sufficient data for detailed mapping of the subsurface in most areas.

Structure

Areas that exhibit great structural deformation should generally be avoided for disposal well operations. Also, highly faulted areas, particularly where strata are composed of consolidated rocks, are not suitable for safe injection. Strata in the vicinity of piercement-type salt domes are subject to considerable deformation and must be thoroughly evaluated before they are used for subsurface disposal.

Structures most favorable to subsurface disposal are gently dipping monoclines, basins, and shelves or platforms. Such structures are the dominant geologic features in Texas. The major structural features of Texas are illustrated in Figure 2-5.

Reservoir Characteristics

A good underground waste injection reservoir must have sufficient permeability to allow injected fluid to penetrate into pore spaces of the rock without need of excessive injection pump pressure which could fracture the rock. Compacted clays have very low permeability. Waste can be injected into clays (or shales) only at an extremely slow rate; thus clays are not suitable for waste disposal. Clays are important, however, as impermeable confining beds which envelop the injection reservoir so as to isolate injected wastes from fresh and slightly saline ground water and from valuable mineral resources. In contrast, sands, gravels, and vugular or fractured limestones may have high permeabilities and consequently are often given favorable consideration as disposal reservoirs.

The thickness and areal extent of a disposal reservoir determine the volume of fluid that can be safely injected. For most injection operations, the reservoir should be large enough to be considered as having infinite lateral boundaries. If a reservoir has finite and known boundaries, it may be suitable for disposal of a limited amount of waste. Figure 3-2 is a map of Texas indicating the generalized suitability of subsurface strata for disposal.

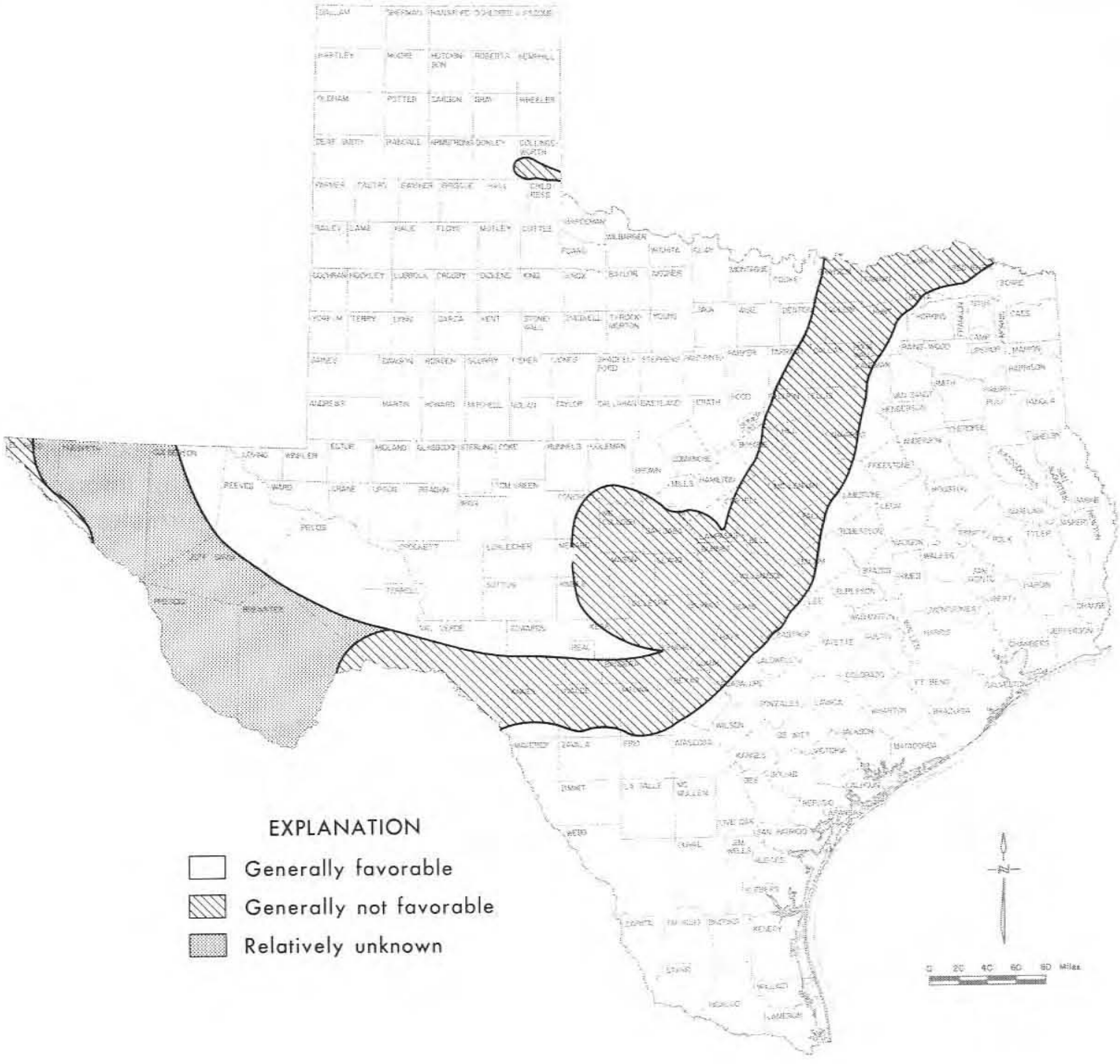

Figure 3-2.—Potential of Subsurface Strata for Waste Disposal (After Greene, 1983)

Project Design

Careful planning is fundamental to the safe design and operation of a waste disposal well. Factors that must be taken into account in evaluating any proposed disposal well project include the number and condition of all wells near the proposed injection project that penetrate the disposal zone, the compatibility of waste fluids with the rock and native fluids of the disposal reservoir, and the proposed materials and methods of well construction.

Artificial Penetrations

The large number of oil and gas wells that have been drilled in Texas present a potential environmental hazard with regard to disposal well operations. If formation pressures are elevated sufficiently by injection operations, inadequately plugged wells that penetrate the disposal zone can provide an avenue for waste fluids or highly mineralized native formation fluids to migrate into and contaminate fresh and slightly saline ground-water zones. To avoid this problem, injection pressures and injection volumes must be limited to prevent excessive pressure buildup in the injection zone. In some instances it may be necessary to reenter and plug inadequately plugged abandoned wells. To enable the Department to set safe controls on injection pressure and rate, a permit applicant must submit drilling, casing, cementing, and plugging records for all wells drilled within a 2½-mile radius of the proposed waste disposal well.

Compatibility

Fluids injected into the subsurface should be compatible with the rock matrix and formation water of the disposal zone. Compatibility tests are therefore routinely conducted to assure that the injection operation will be successful. Some problems that may be encountered are:

1. Acidic waste reacting with carbonate material of the receiving stratum and causing a precipitate.

2. Alkaline waste reacting with clay minerals of the stratum and causing the clay to swell.

Incompatibility reactions involving wastewater in the injection zone have an extremely low potential for impacting fresh to slightly saline ground water because they do not impair the stratigraphic or hydrologic isolation of the disposal zone in a properly constructed well. They may, however, decrease an injection zone's capability to accept waste. Wastewater and injection zone compatibility is, therefore, a concern in protecting the substantial economic investment in a well as an effective and environmentally safe disposal method.

Compatibility problems can be eliminated by preinjection treatment of the waste (e.g., filtering, pH adjustment) or by injecting a buffer fluid to keep the waste and the formation water separate in the immediate vicinity of the wellbore.

Well Construction

Variations in disposal well designs reflect the special disposal requirements for different compositions and volumes of waste. The Department has not adopted standards on well construction, but instead considers each design proposal on an individual basis. The major objectives in the design of a waste disposal well are to protect fresh to slightly saline water resources and to confine injected fluids to the disposal zone.

A typical industrial waste disposal well design is shown in Figure 3-3. Surface casing is set from the surface to a depth below strata containing fresh to slightly saline water, and is cemented in place along its entire length. Long string or protection casing is set inside the surface casing from the surface to either the top or the bottom of the disposal zone. This casing is cemented by

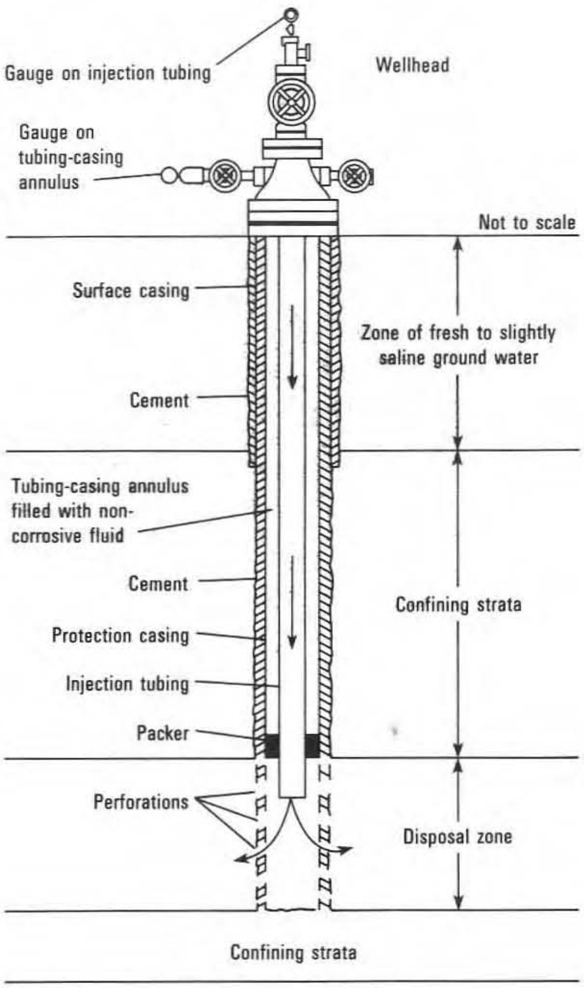

Figure 3-3.—Typical Industrial Waste Disposal Well (Modified from Hill, 1972)

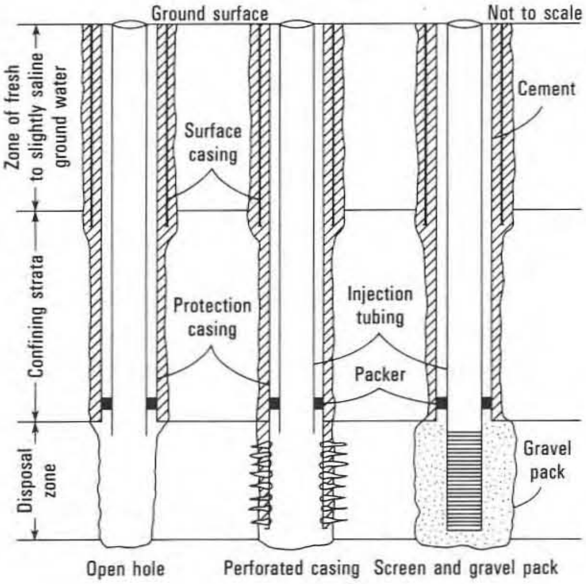

Figure 3-4.—Industrial Waste Disposal Well Completions (After Greene, 1983)

circulating cement from total depth back to the surface. For waste disposal wells in Texas, the average distance from the bottom of the surface casing to the top of the injection zone is approximately 2,900 feet.

Two strings of cemented casing placed through the fresh to slightly saline water zone add strength to the well and protection for the ground water. Protection casing is usually made of carbon steel, but may be made of a special alloy that is not affected by the corrosive nature of the waste. The protection casing is pressure tested to assure that there are no leaks.

Waste fluids are injected into the disposal zone through tubing installed inside the protection casing. At the top of the injection zone, the annular space between the protection casing and injection tubing is sealed by a packer. The packer keeps potentially corrosive wastewater from contacting the protection casing uphole, and allows the sealed tubing-casing annulus to be pressurized to detect leaks in the tubing, or casing. Injection tubing is made of a material that will not be affected by injected waste. Materials commonly used for tubing are carbon steel, plastic-coated steel, stainless steel, and fiberglass.

Bottom-hole completion methods used in industrial waste disposal wells in Texas are of three basic types. Figure 3-4 gives a schematic comparison of the different completion methods.

Open-hole completions are used in competent (hard) formations. These completions are advantageous because the injection zone is maximally exposed to injected fluids. Also, they are the least expensive completions.

Perforated-casing completions are used in formations of only moderate competence, which tend to cave in under injection conditions or under the chemical influence of the wastewater. In this completion method, long-string casing is extended completely through the disposal zone and is perforated to provide waste fluid access to the disposal zone. The casing may be selectively perforated opposite the most permeable sands. The interval of casing through the disposal zone should be of a chemically resistant material. The cost of this completion method is intermediate between those of open-hole and screen and gravel-pack completions.

Screen and gravel-pack completions are used in incompetent, unconsolidated sands. Wells in southeast Texas and along the Gulf Coast use this completion method to control the influx of sand into the wellbore. Well screens are made of stainless steel, fiberglass, or plastic. Gravel packing actually involves filling the space between the borehole and well screen with gravel or sand of a selected uniform grain size.

The Department requires that a pressure gauge be installed on the wellhead to monitor pressure in the tubing-casing annulus. If a leak occurs in the tubing or packer seat during injection, a change in the annulus pressure will be indicated by the gauge, and remedial action can be initiated to correct the malfunction. A gauge on the injection tubing is also required to monitor surface injection pressure in order to prevent fracturing of the disposal formation by excessive injection pressures.

Operational Practices

The basic wastewater pretreatment methods used to achieve trouble-free disposal well operation vary with wastewater properties and geologic conditions in the disposal zone. Pretreatment systems range from temporary wastewater storage facilities to systems involving a complex sequence of treatment steps. Warner and Lehr (1977) have described the basic wastewater pretreatment operations as follows. Not all of these steps are used in every pretreatment system, nor do they always occur in the sequence given.

1. Storage and equalization—to allow an even flow of wastewater to treatment facilities and injection pumps and to equalize wastewater properties.

2. Oil separation—to remove liquid oils.

3. Suspended solids removal—to remove particulate matter.

4. Chemical and biological treatment—to modify wastewater chemistry and make it compatible with the injection system and injection zone.

5. Corrosion and bacterial control—to reduce corrosiveness and inhibit growth of microorganisms.

6. Degasification—to remove undesirable entrained or dissolved gases.

Experience has shown that waste disposal wells operate with fewer problems when they are in constant use, without abrupt start-ups and shut-downs. Such abrupt changes in injection rate may cause pressure surges through a well which jar the tubing and packer and may contribute to sand flow problems in the well completion zone.

In highly permeable aquifers of the Gulf Coast region, many newly completed wells require no positive surface injection pressure. In these situations, the weight of the wellbore column of waste fluid alone is sufficient to drive injection. Gradually, however, most wells begin to require increasing surface injection pressure to maintain a desired disposal rate. An operator may increase surface injection pressure as needed up to the maximum permitted surface injection pressure, which is imposed to guard against fracturing the disposal formation.

Situations that require increasing the surface injection pressure to achieve the desired injection rate are generally caused by obstruction of the wellbore by unconsolidated formation sands or by precipitation of solids in the formation as a result of the mixing of incompatible waste fluids and formation brines. Fine precipitates, in particular, tend to impair formation permeability immediately around the wellbore, decreasing a well's injection capability.

The two most common corrective measures used in waste disposal wells for problems with unconsolidated formation sands and chemical precipitants are acidizing and backflowing with nitrogen gas. Acid will dissolve many chemical precipitants from the interface of the wellbore and disposal formation. Nitrogen gas introduced into well fluids in the completion interval will create a froth of lessened density in the wellbore and cause a backflow of reservoir fluid into the wellbore. By using nitrogen in this manner, sand and other fine particles can be jetted from the wellbore back to the surface. Both acidizing and nitrogen jetting can be performed through the injection tubing of a well.

More elaborate remedial procedures may involve taking a well out of service temporarily and removing the tubing and packer for downhole work. A major workover of this type requires submission of detailed proposals to the Department for approval prior to implementation. Such workovers are usually done to replace leaking tubing or packers, detected by the annulus monitoring system. Major workovers are also done to plug and abandon injection zones that have reached maximum safe pressure limits as a result of past injection, or that have limited injection capability because of irreparable fluid incompatibility problems.

Initial well completions are commonly made only in the lowest portion of a permitted disposal zone, to allow for future recompletions uphole when new disposal reservoirs are needed. The general rationale for using lower potential disposal zones first is that it is easier to plug and abandon a disposal zone and recomplete with casing perforations uphole than to case off an abandoned disposal zone and recomplete in a deeper zone.

Other important operational features of waste disposal wells include gauges, continuous recorders, and alarm and automatic shut-off devices that monitor surface injection pressure and injection rate. Similar instrumentation also monitors the sealed tubing-casing annulus system to detect leaks. Records must be kept and reports made of injection operations as the permit requires, and disposal wells must pass periodic inspections by Department staff. At least every 5 years wells must demonstrate mechanical integrity (absence of leaks) by an approved program of casing pressure tests and down-hole logs.

Nature and Volume of Injected Waste

The typical waste stream in an industrial waste disposal well is: (a) relatively low volume; (b) not readily amenable to alternate disposal methods such as incineration or treatment and surface discharge; (c) within a neutral pH range; (d) very high in total dissolved solids concentration; (e) containing other process-related pollutants; and, (f) essentially without suspended solids. Wastewater is usually filtered prior to injection. Currently, about 6 billion gallons of industrial wastewater are injected into subsurface reservoirs in Texas each year. It is estimated that over 60 billion gallons of industrial wastes have been disposed of by industrial waste disposal wells in the State. Figure 3-5 shows recorded yearly total injection volumes of industrial waste in Texas.

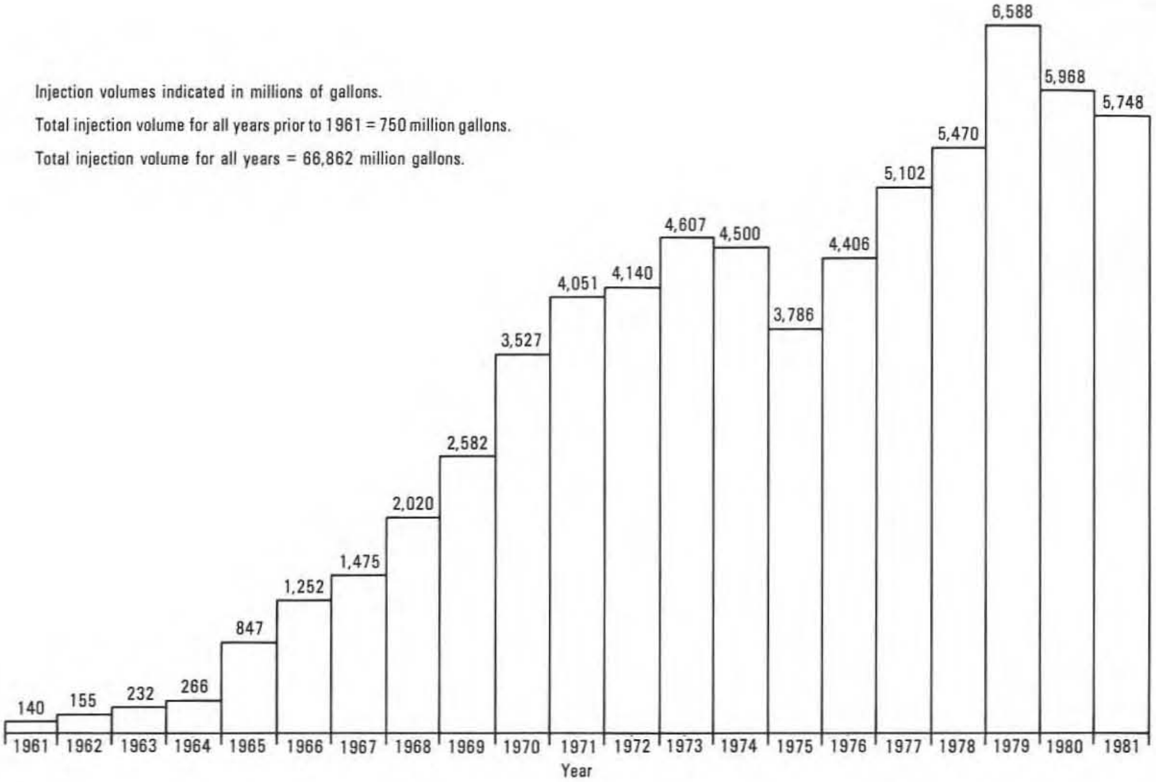

Figure 3-5.—Yearly Total Injection Volumes of Industrial Waste in Texas

Plugging and Abandonment

An abandoned waste disposal well must be plugged with cement in conformity with Department policy. The procedure for plugging an industrial waste disposal well involves prior approval of the proposed plugging operation by the Department. Proper plugging of a well is necessary to confine disposed waste to the injection zone and to prevent future unauthorized disposal in the well. Therefore, waste disposal well permits require the permittee to file a bond or other suitable form of financial security with the Department in order to assure adequate funds for proper plugging and abandonment.

Details of plugging operations vary with types of well construction. However, guidelines constituting minimum criteria for proper well plugging have been formulated by the Department. Basically, three cement plugs should be placed in an abandoned disposal well and the spaces between these cement plugs should be filled with heavy drilling mud. The wellhead, injection tubing, and packer should be removed from the well before cement plug placement. The first plug should be placed in the long-string protection casing through the injection zone to seal off this

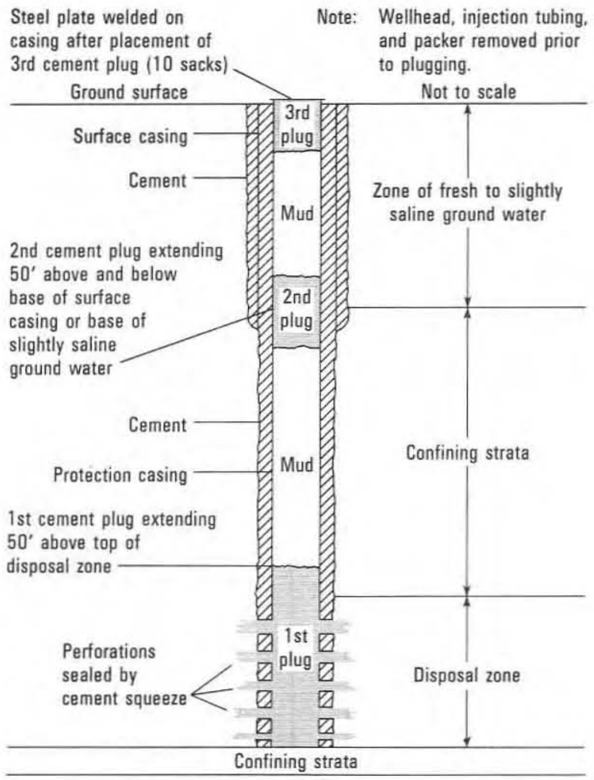

Figure 3-6.—Cement and Mud Placement for Proper Plugging of Industrial Waste Disposal Wells (Modified from Hill, 1972)

zone and prevent backflow of fluids up the wellbore. A second plug should be placed in the protection casing at the depth of the base of the surface casing. This plug should extend approximately 50 feet above and below the bottom of the surface casing in order to protect against upward flow of fluids through casing defects from any lower zone into the fresh to slightly saline water zone. The third plug should be placed at the top of the protection casing, and should extend from the surface to approximately 10 feet below ground. Finally, a steel plate should be welded over the casing head at or just below ground surface. Following abandonment, the well site should be marked with a sign indicating the operator's name, well permit number, dates of operation and plugging, and a statement that complete well records are on file in the Austin office of the Department.

Contamination Potential

Properly designed and operated industrial and municipal waste disposal wells have a very low potential for contamination of fresh ground water. The record of success of these wells in disposing of large volumes of hazardous waste without a single demonstrated case of fresh-water contamination may in large part be attributed to the Department's regulation of these wells by permit. The Department requires:

1. Good casing and cementing practices in well construction;
2. Limitations on allowable surface injection pressure and injection rate;
3. Evaluation of reservoir properties and artificial penetrations;
4. Well integrity monitoring to detect malfunctions or materials failures such as casing, tubing, or packer leaks;
5. Record-keeping and reporting, and periodic inspections for permit compliance; and,
6. Financial assurance for proper plugging of a well upon termination of operations.

Legal and Jurisdictional Considerations

Waste disposal wells are regulated by permit issued by the Texas Water Commission, the Department's judicial arm, under authority of Chapter 27 of the Texas Water Code (the Injection

Well Act). The Railroad Commission of Texas reviews all waste disposal well permit applications to insure that proposed injection projects pose no hazards to oil and gas resources. The Department's staff reviews permit applications for completeness, and where appropriate, drafts proposed permit conditions to protect usable-quality water resources. Proposed permits are filed with the Texas Water Commission. Public notice and opportunity for public hearing precede consideration of proposed permits by the Commission. In order for a permit to be issued, the Commission must determine that a proposed well:

1. is in the public interest;
2. will not impair any existing rights, including mineral rights;
3. will afford protection of surface and ground-water resources under the terms of the proposed permit; and
4. will be properly plugged upon abandonment, as assured by a bond or other form of financial security filed by the permittee with the Department.

If the injection fluid in Class I wells is determined to be hazardous waste as defined in the Texas Solid Waste Disposal Act, the preinjection facilities associated with the waste disposal well must be authorized by a separate solid waste management permit or a consolidated permit, because they constitute hazardous waste storage and processing facilities. Facilities that store or treat hazardous waste must conform to all applicable requirements of Chapter 335 of the Department Rules relating to industrial solid waste. Approximately 80 percent of Class I wells involve hazardous waste disposal.

Concluding Statement

Industrial waste disposal wells that are properly designed, constructed in suitable disposal reservoirs, and strictly regulated by injection pressure and injection rate limitations and by annulus-monitoring requirements, should pose no hazard of pollution to ground water above the disposal zone, including fresh to slightly saline water resources.

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CHAPTER 4

URANIUM SOLUTION MINING WELLS

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URANIUM SOLUTION MINING WELLS

Table of Contents

URANIUM SOLUTION MINING WELLS

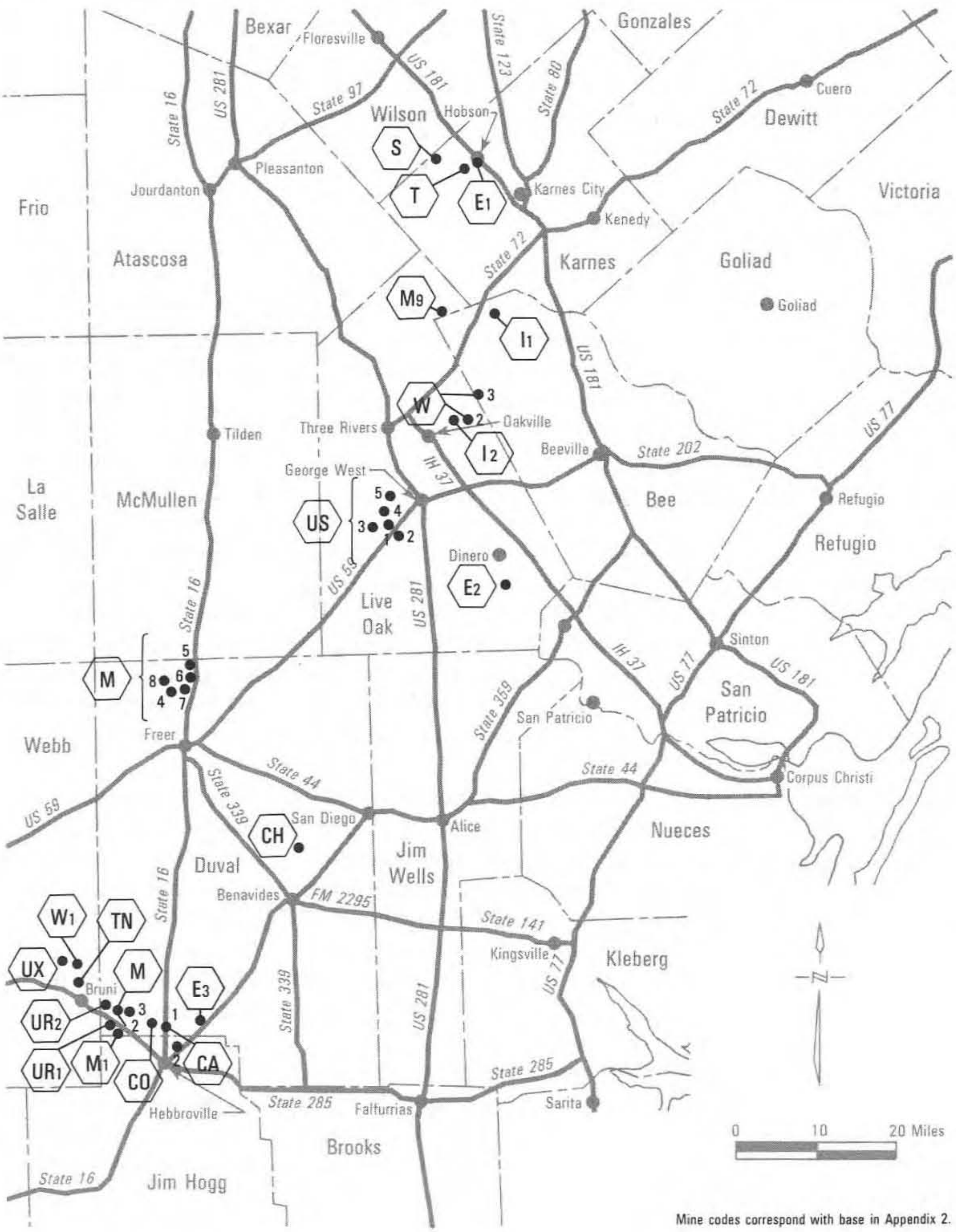
Introduction

There are three major branches of uranium solution mining. These are: heap leaching, solution mining via cavities, and in situ solution mining (Trace Metal Data Institute, 1979). Heap leaching utilizes ore or tailings that have been mined by open-pit or underground methods and placed within a pad to be leached by percolation through the ore. Solution mining via cavities incorporates the use of cavities, fractures, and tunnels as a means to leach the uranium from relatively undisturbed host rock. In situ mining, also known as in-place leach mining, is used to selectively mine the desired mineral from a naturally permeable host rock. This is the type of solution mining with which this chapter is concerned.

At numerous sites in South Texas, principally in Karnes, Live Oak, and Duval Counties, uranium has been produced through the in situ solution mining of shallow ore deposits. In this process, a leaching solution (lixiviant) is injected into an array of wells completed in the ore body. Injected lixiviant dissolves uranium minerals from the intergrain spaces of sands and gravels, then, uranium compounds in solution are pumped to the surface through production wells. At the surface of the mine, the compounds are removed from solution by ion exchange and chemical precipitation, and the product (U_3O_8) is put in containers for shipment.

Uranium deposits in South Texas were first discovered in the Tordilla Sandstone near Falls City in Karnes County in 1954. In the late 1950's, mining of uranium in Karnes County was initiated by several companies using the open-pit method under contract with the U.S. Atomic Energy Commission. But experimentation with in situ solution mining was not begun until 1966 when the Dalco Company (a subsidiary of Sabine Royalty) was organized to carry out uranium research and development (Charbeneau, 1981). In January of 1975, the first state permit for commercial leaching of uranium in the United States was issued by the Texas Water Quality Board (one of the predecessor agencies to the Texas Department of Water Resources) to Atlantic Richfield Company (ARCO) and its partners, U.S. Steel and Dalco, for operations at their Clay West site in Live Oak County. Exploration and development, as well as permitting, of solution mine sites increased steadily with rising prices for uranium until 1979 when several factors, including the nuclear reactor accident at Three Mile Island, Pennsylvania, in March of 1979, sharply lessened demand for uranium in the national market. In many cases, nuclear reactor construction schedules were cancelled or indefinitely delayed. As exploration in the United States began a decline in 1979, exploration in South Texas continued undiminished through that year. But by the end of 1980, drilling for uranium exploration and development in South Texas decreased in conformity with the national trend. In 1984, with at least a 70 percent increase in the market price of uranium required to restore profitability to uranium solution mining, activity in South Texas uranium mines continues to be depressed.

Figure 4-1 shows locations of uranium solution mining sites in Texas. A detailed tabulation of information on these uranium mining operations is given in Appendix 2.



Mine codes correspond with base in Appendix 2.

Figure 4-1

Uranium Solution Mine Locations in Texas, 1982

Geohydrology

Stratigraphy

Almost all of the presently discovered uranium mineralization in South Texas occurs in four geologic formations of Tertiary age: the Whitsett Formation (Jackson Group), the Catahoula Formation, the Oakville Formation, and the Goliad Formation. Figure 4-2 shows stratigraphic relationships of Tertiary and Quaternary geologic units in the South Texas uranium mining district.

Sands of the Whitsett Formation are major hosts of uranium mineral deposits. In many places, these sands are highly indurated and form resistant ridges at outcrops. Lagoonal or shelf muds (for example, the Dubose Clay) were deposited between the strandplain sands of the Whitsett (Henry and Kapadia, 1980).

At least three depositional episodes in semiarid climates are evidenced in the Catahoula Formation. The upper Chusa Tuff and basal Fant Tuff members of the Catahoula represent periods of massive volcanic ash accumulation from west Texas volcanic activity. Between these two tuff members, the Soledad Volcanic Conglomerate contains the major uranium mineralization of the Catahoula Formation.

The Oakville Sandstone was deposited by a major stream system at the transition between the volcanism exemplified by the Catahoula tuff deposits and the relative quiescence represented by the overlying Fleming Formation. The depositional environment of the Oakville was apparently one of high sediment transport energy in stream systems fed by moderate upwarp of the land to the west. The resulting deposition of sand and gravel lenses in the Oakville subsequently became the site of significant uranium mineralization.

The Goliad Sand is the youngest of the major uranium-bearing formations in South Texas. Uranium deposits in the Goliad occur in the medium to coarse sand stream channel deposits in the basal section of the formation.

Occurrence of Uranium

Uranium recovered by solution mining occurs in roll-type deposits. Roll-type, as used here, denotes the general case in which uranium has precipitated from solution in ground water along an oxidation-reduction front in configurations such as the classic crescent shape, or more commonly, in tabular, dish-shaped, or irregular deposits. Various types of uranium ore body configuration are shown in Figure 4-3. Deposits which can be solution mined are usually found at relatively shallow depths (less than 500 feet), and are confined above and below by relatively impermeable strata (Figure 4-4).

Presumably leached from a source material and transported through an aquifer system by ground water in an oxidizing environment, uranium is thought to have been deposited where uranium-rich ground water encountered a chemically reducing environment (relatively devoid of oxygen). The South Texas uranium source material is believed to have been volcanic glass

System	Series	Group	Geologic unit		Description
QUATERNARY	Holocene		Flood-plain alluvium		Sand, gravel, silt, clay.
			Fluvial terrace deposits		Sand, gravel, silt, clay.
	Pleistocene		Pleistocene Deweyville[1] Formation, Beaumont Clay, Montgomery Formation, Bentley Formation, and Pliocene (?) Willis Sand.		Sand, gravel, silt, clay. Montgomery and Bentley comprise Lissie Formation of older reports. Willis Sand not seen on this trip.
TERTIARY	Pliocene		Goliad Formation		Fine to coarse sand and conglomerate. Medium to fine sandstone; gray to pink calcareous clay; basal medium to coarse sandstone. Strongly calichified.
	Miocene		Fleming Formation		Calcareous clay and sand, gray to pink, red, light brown.
			Oakville Formation		Calcareous, crossbedded, coarse sand. Some clay and silt and reworked sand and clay pebbles near base.
			Catahoula Formation (Gueydan Formation of some authors)	Chusa Tuff Member	Light-gray to pink calcareous tuff; bentonitic clay; some gravel and varicolored sand near base. Soledad near middle in Duval County grades into sand lenses in northern Duval and adjacent counties.
				Soledad Volcanic Conglomerate Member	
				Fant Tuff Member	
	Oligocene (?)		Frio Formation (Southwest of Karnes County)		Light-gray to green clay; overlapped by Catahoula Tuff northeast of Live Oak County. Occasional sand-filled channels.
	Eocene	Jackson	Whitsett Formation	Fashing Clay Member	Chiefly marine clay; some lignite, sand, *Corbicula* coquina, oysters.
				Tordilla Sandstone Member. Calliham Sandstone Member west of Karnes County.	Shallow marine very fine sand.
				Dubose Member	Silt, sand, clay, lignite.
				Deweesville Sandstone Member	Mostly fine sand; some carbonaceous silt and clay.
				Conquista Clay Member	Carbonaceous clay.
				Dilworth Sandstone Member	Fine sand, abundant *Ophiomorpha*.
			Manning Clay		Carbonaceous clay and tuff; some fossiliferous sand.
			Wellborn Sandstone		Fine-grained gray sandstone.
			Caddell Formation		Carbonaceous clay and silt. Fossil pelecypods (chiefly oysters) near base.
		Claiborne	Yegua Formation		Medium to fine sand; silt, clay; some glauconitic sand.
			Laredo Formation		Marine clay, glauconitic medium to fine sand; a few thin beds of limestone. Many fossiliferous beds.

Figure 4-2.

Generalized Stratigraphic Section of the South Texas Uranium District (From Eargle, Hinds, and Weeks, 1973)

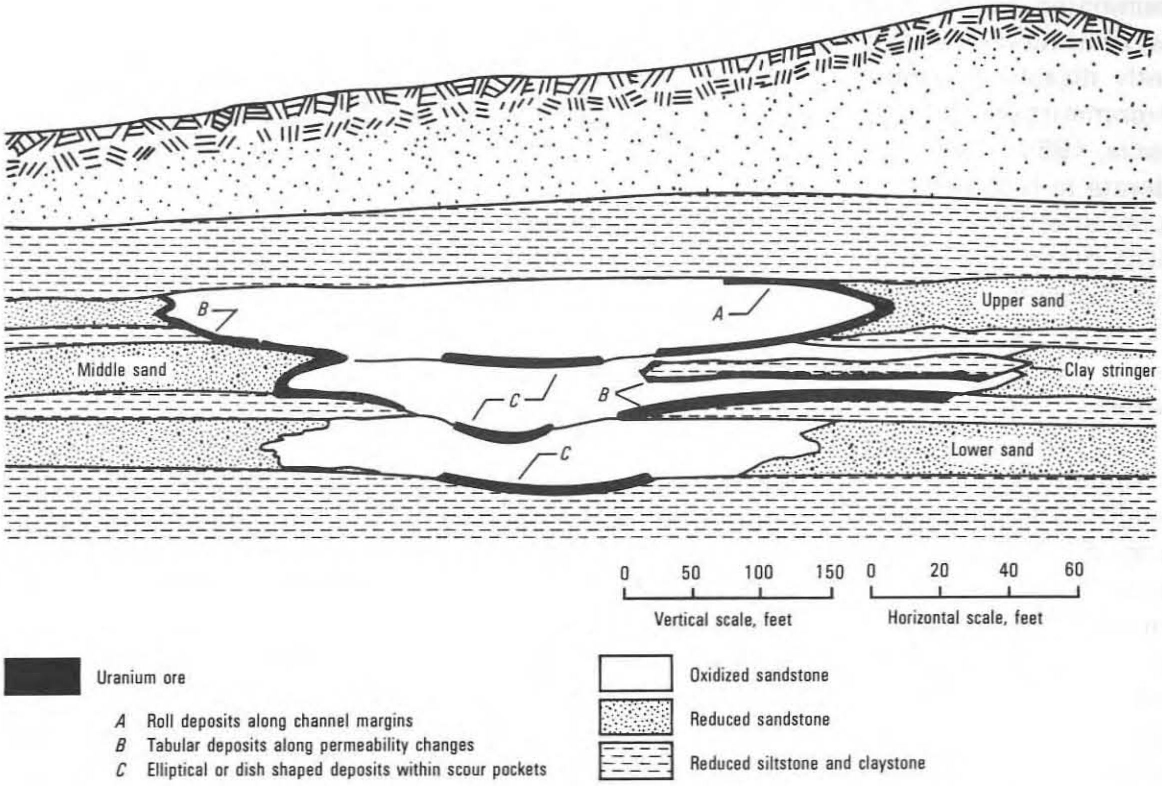


Figure 4-3.—Various Types of Uranium Sandstone Deposits (After Larson, 1978)

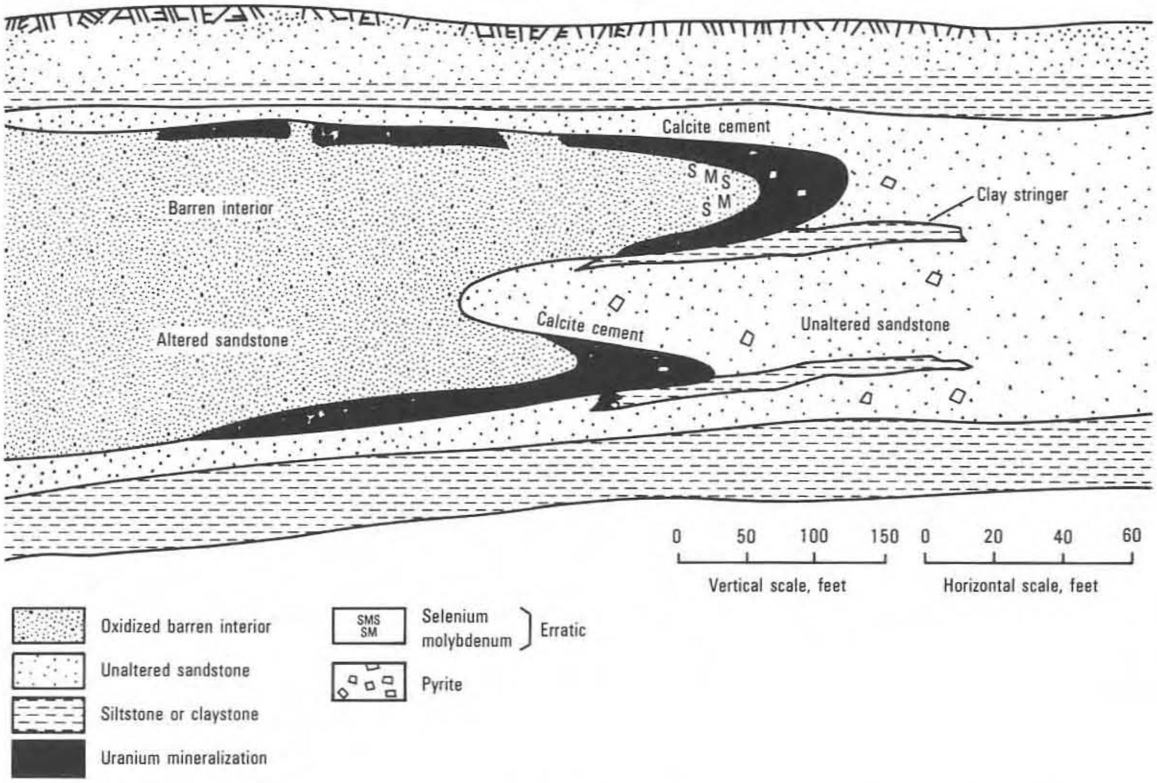


Figure 4-4.—Idealized Uranium Roll Front Deposits (After Larson, 1978)

disseminated mainly in the Catahoula Formation, but also in the Whitsett and Oakville Formations. Alteration of volcanic glass occurred by oxidation. Neutral to alkaline ground water subsequently dissolved uranium from the altered volcanic glass and transported it to reducing environments where concentration of uranium minerals occurred to form an ore body (Henry and Kapadia, 1980). Uranium is highly soluble in the form of uranyl ions (UO_2^{++}) in oxidizing water of moderate to high pH, especially when complexed with carbonate, phosphate, or other negative ions (anions). Reduction to insoluble U^{+4} ions causes precipitation of uraninite (UO_2) or coffinite ($USiO_4$) (Henry and Kapadia, 1980). Usually, uranium occurs as finely disseminated particles within a sandstone matrix or as a black coating on sand grains (Larson, 1978).

Aquifers

Uranium-bearing formations of South Texas lie within the Gulf Coast aquifer (Table 2-2). Throughout the uranium mining areas, ground-water quality varies with depth and proximity to sources of recharge. The ground water is mostly of the sodium bicarbonate and sodium chloride type, with a total dissolved solids concentration generally ranging from 1,250 to 3,000 mg/l. Local areas, however, have ground water dissolved solids levels considerably higher and lower than this range. Trace heavy metal concentrations generally are within accepted public health limits in all uranium mining areas. Levels of radioactive parameters (radium^{226}, gross alpha, and gross beta), however, are commonly above recommended public health standards in samples taken from water in contact with the ore bodies (Thompson et al., 1978).

Ground water in the mining areas is commonly used for domestic supplies, livestock watering, and small municipal systems. Some irrigation with ground water is also taking place near mining areas. Although native ground-water quality may be poor in some parts of South Texas, at many locations there is no other potable water readily available.

Well Construction

Injection wells and production wells for uranium mining are normally of similar design. They differ in the types of pumps used; injection wells use pumps at the surface to drive injection, whereas production wells use submersible pumps on a pipe column in the well to lift water to the surface. Both types of uranium wells are drilled with water well type rotary rigs to total depths of several hundred feet.

Uranium mining wells generally consist of a single string of 4- or 6-inch diameter polyvinyl chloride (PVC) schedule 40 or fiberglass pipe. Pipe joints are attached through threaded couplings or male-female couplings bonded together with glue and metal screws. Makeup of the pipe string begins in most wells with PVC well screen for the ore zone. Immediately above the screen is a joint of pipe which is specially adapted for cementing. The special cementing joint contains a plaster plug to keep cement out of the well screen below, two or more ports for cement extrusion, plus a cement retainer basket on the outside of the pipe. Centralizers to center the pipe string in the borehole are usually placed above the cementing joint and every 100 feet uphole.

The hole is circulated with drilling fluid to remove all cuttings prior to cementing the casing (pipe). Uranium wells are usually cemented with API Class A cement with 4 percent bentonite gel. Enough cement should be on location to get good cement returns at the surface while leaving a

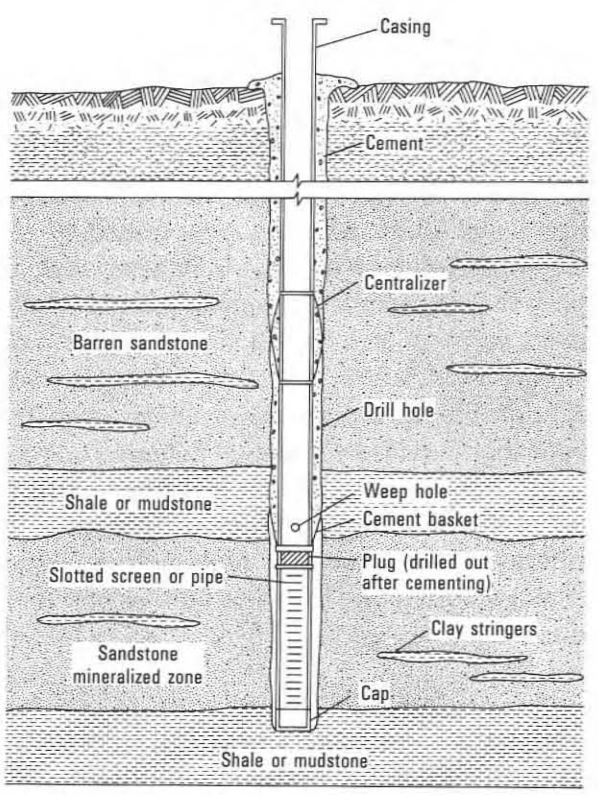


Figure 4.5—Typical Uranium Solution Mining Well Completion (After Larson, 1978)

20-foot plug of cement in the well casing. A wiper plug may be used to separate cement slurry from the displacement water following the slurry during cementing. Once the cement has set, the casing is pressure tested, and the downhole cementing plug is drilled out to complete construction of the well.

An alternate construction method consists of drilling to the top of the ore zone and cementing the pipe string in place. Following pressure tests, the cement plug is drilled from the bottom of the pipe, and the hole is advanced through the ore zone. Well screen is then hung from the bottom of the pipe string to complete the well.

A typical uranium solution mining well completion is shown in Figure 4-5. Other possible completion methods, using retrievable well screen with underreaming, and using casing perforations, are shown in Figures 4-6 and 4-7.

Solution Mining Practices

Solution mining with injection and production wells is a technique in which an ore mineral is selectively leached from a permeable host rock (sand or gravel) using a leaching solution (lixiviant). Lixiviants are formulated by adding chemicals such as ammonium carbonate, $(NH_4)_2CO_3$, or sodium carbonate, Na_2CO_3, to produced ground water. Injected lixiviant which has permeated an ore zone and carries the ore mineral in solution is referred to as "pregnant lixiviant"; this fluid is pumped from the aquifer to the surface by way of production wells. Upon extraction of uranium from the leaching solution in ion-exchange columns, the barren lixiviant is reconstituted by addition of various chemical reagents, and is recycled through the ore zone to recover more uranium. A schematic diagram of an in situ uranium solution mine is presented in Figure 4-8.

The spacing and arrangement of injection and production wells, their pumping rates, and the hydraulic properties of the ore zone are important variables in well field design which affect the production efficiency of the mining operation. The hydraulic response of an aquifer to fluid injection can be estimated if hydraulic properties such as aquifer permeability are known. These properties are usually determined by conducting a hydrologic pump test prior to the drilling of a well field.

Various types of injection-recovery well patterns have been used for in situ uranium mining. The two most common patterns are shown in plan view in Figure 4-9. With the five spot pattern which is used to cover a large area, the distances between the injectors and producers can be adjusted to the permeability conditions of the host aquifer. Ideally, with uniform ore zone permeability, the distances between injectors and producers are equal. The staggered line drive pattern is normally used when there is a long narrow ore zone. With uniform permeability conditions, the distances between injectors and producers in the staggered line drive pattern are equal, and the injectors are arranged in a length to width ratio of two to one.

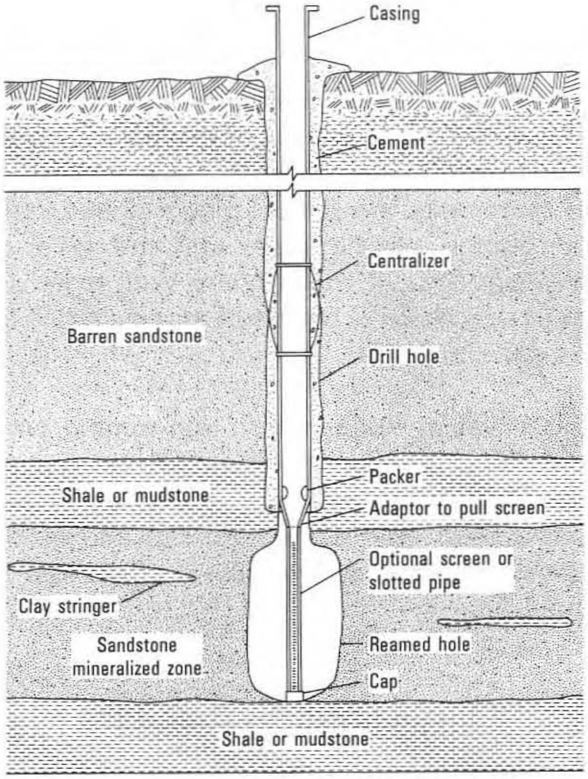


Figure 4-6.—Uranium Mining Well Completion With Retrievable Screen and Underreaming (After Larson, 1978)

A balance between injected and produced volumes of fluid must be maintained at all times in a well field to prevent lixiviant excursions. Model studies show that even a slight excess of injection or a deficit of production at a single well within an otherwise balanced field can create a pressure gradient causing fluid excursions from the well field into potential ground-water supplies. However, unless flow of injected mining fluids occurs along a pathway of anomalously high permeability, the movement away from the field will be very slow.

The driving force which causes lixiviant to permeate an ore body and yet be contained within the ore body results from a pumping technique in which fluid is withdrawn from the ore body at a slightly higher rate than it is injected. Commonly, a volume of produced mining fluids exceeding the volume of injected fluids by 1 percent is maintained during uranium solution mining. This 1 percent excess is considered to be a bleed volume from the aquifer which deepens cones of depression in the aquifer piezometric surface around production wells, accentuating gradients of ground-water flow from injection wells and peripheral parts of the aquifer beyond the ore body, toward the production wells. Care in maintaining ground-water flow gradients toward production wells helps prevent excursions of leaching solutions into the aquifer beyond the boundaries of the ore body. If an excursion of leaching solutions is detected by required aquifer monitor wells which are located just outside the perimeter of the ore zone, pumping rates in producing wells can be increased to recapture excursion fluids. Despite precautions such as the commonly used 1 percent aquifer bleed, excursions may occasionally occur in uranium solution mining because of variability of porosity and permeability in the mining formation.

Successful solution mining of uranium is based on the water solubility of uranium compounds. In tetravalent form (+4), uranium is insoluble in water. However, the oxidized hexavalent form (+6) of uranium has relatively high water solubility. Uranium in most deposits exists in complex tetravalent forms such as uraninite (UO_2), or coffinite ($USiO_4$), with minor amounts of hexavalent forms such as carnotite ($K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$ and autunite ($Ca(UO_2)_2(PO_4)_2 \cdot 10\text{-}12H_2O$). The insoluble forms of uranium have been precipitated within the deposits because of the presence of a chemically reducing environment. A reducing environment is maintained by natural organic compounds such as lignins, tannins, humic acids, petroleum, and sulfides produced by bacteria.

The insoluble tetravalent form of uranium is mobilized (dissolved) by exposure to oxidants. Oxidation must be sufficient to alter the valence of uranium from +4 to +6, and circumvent the reprecipitation of uranium by reductants inherently present in the ore zone. The three most common modes of oxidation are:

1) Oxidation by air or by introduction of free oxygen. (Usually, air lines introduce oxygen to the lixiviant.)

2) Oxidation via chemical application such as potassium permanganate, manganese dioxide, sodium chlorate, or hydrogen peroxide.

3) Oxidation via catalysis based upon a redox vehicle such as ferric iron (+3) or bacteria (endogenous or introduced).

In addition to the oxidation requirement for dissolution of uranium, complexing agents are necessary in solution mining to increase hexavalent uranium solubility and minimize reprecipitation. The complexing agents currently used are sulfate solutions or bicarbonate and carbonate solutions. Use of sulfate in the common form of spent sulfuric acid (H_2SO_4) creates acidic leaching conditions, the benefits of which are easy liberation of uranium from the host rock, and lower lixiviant costs. Also, acidic leaching may at the same time recover other valuable minerals from the ore body. However, disadvantages of acidic leaching include the just described, nonspecific leaching of minerals, and excessive metallic corrosion. At present, no uranium solution mines in South Texas use sulfate as a complexing agent in leaching solutions. Instead, carbonate and bicarbonate are used to create a condition of alkaline leaching in the ore zone, which can be successfully used when ores contain significant amounts of oxides or acid-consuming carbonates such as calcite ($CaCO_3$). Some advantages of using alkaline uranium leaching are an enhanced selectivity in dissolving uranium, and the relatively noncorrosive nature of the leaching solutions. In Texas, use of ammonium carbonate for leaching has largely been discontinued in recent years because of difficulties in restoration of ground-water ammonia levels to pre-mining (baseline) conditions after mining operations terminate. Instead, sodium carbonate has become the dominant leaching reagent for uranium solution mining. Bicarbonate is added to the leach solution to help prevent reprecipitation of dissolved uranium (Merritt, 1971).

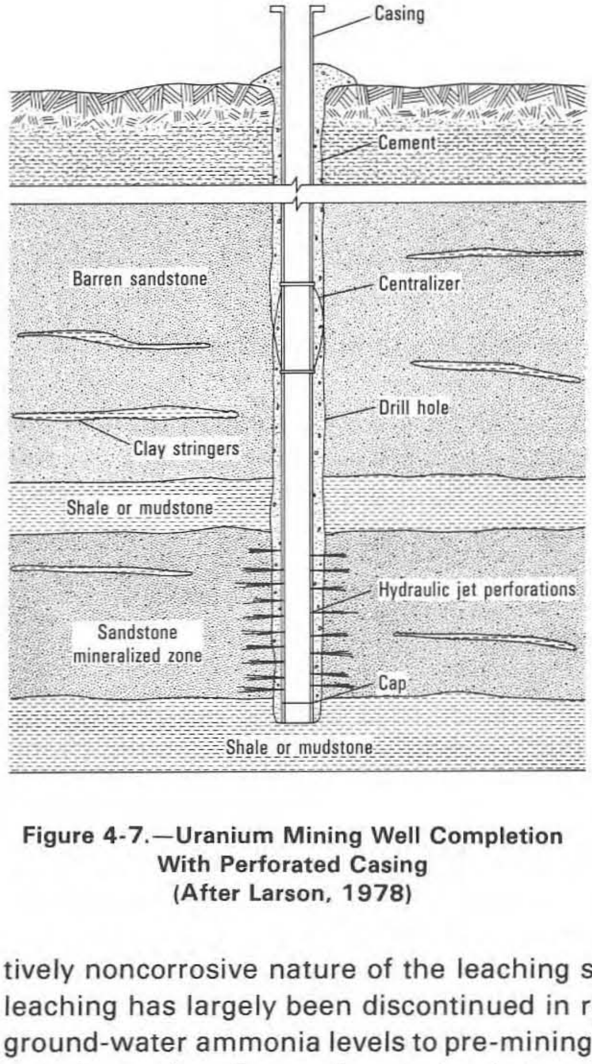


Figure 4-7.—Uranium Mining Well Completion With Perforated Casing (After Larson, 1978)

Composition of the barren leaching solution is adjusted in the mine surface plant to the correct strength before being injected through wells into the mineralized zone. Traveling radially

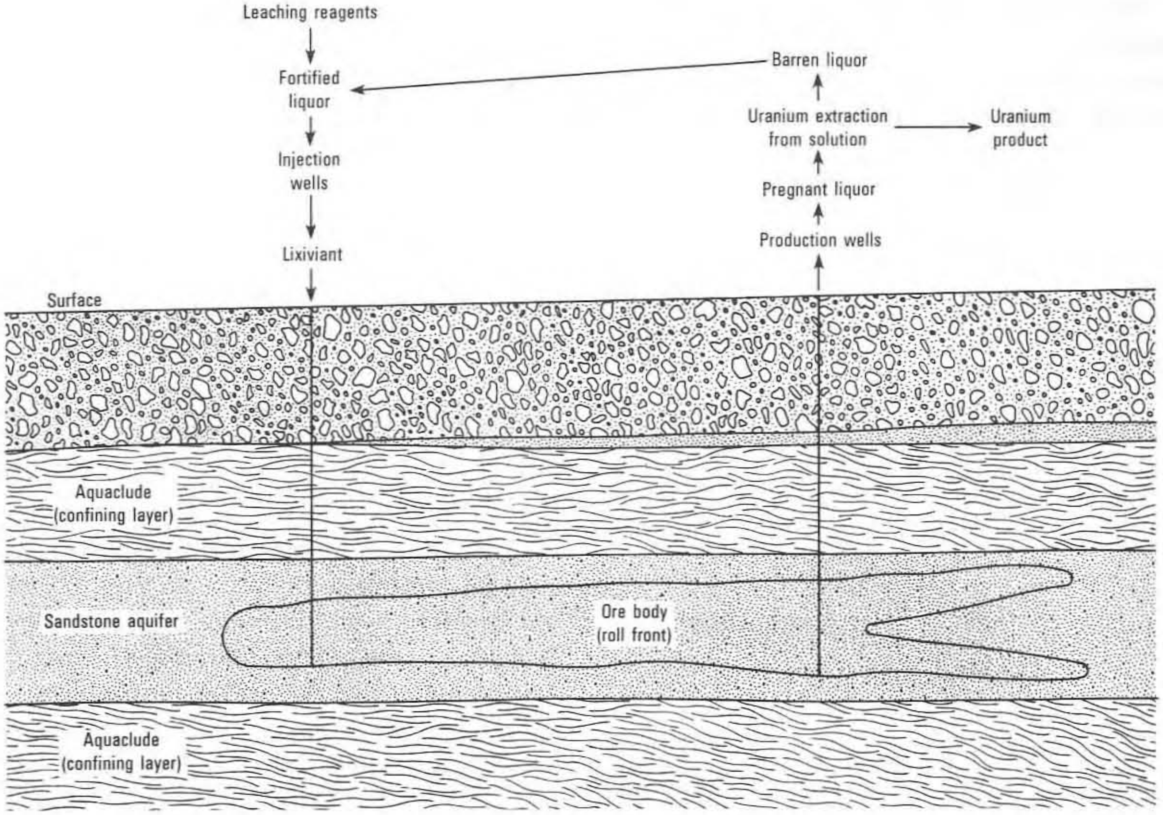


Figure 4-8.—Schematic Depiction of an In Situ Uranium Leaching Site

from injection wells toward the nearest production wells, the leaching solution oxidizes and dissolves uranium minerals, forming the stable complex ion uranyl tricarbonate (or dicarbonate). Uranium in solution is pumped to the surface through production wells and routed to the surface plant for processing at a concentration of about 50 mg/l.

Surface Processing

Adaptation of ion exchange techniques to the recovery process for dissolved uranium has been one of the most significant developments in uranium solution mining processing. Uranyl tricarbonate anions (negative ions) are selectively adsorbed from leaching solutions onto positive ionic sites on synthetic resin beads. The resin beads are contained in a series of fiberglass columns at the surface of the mine site. In the absence of uranium-pregnant lixiviant, the positive ionic surfaces of resin beads are occupied by chloride ions (Cl^-). Each uranyl tricarbonate ion in the pregnant lixiviant, however, has a negative charge and can readily displace chloride ions from a resin surface. By this ion exchange process chloride ions enter the leaching solution as uranium is removed from solution. Each cubic foot of resin can hold from 4 to 8 pounds of uranium (Caithness Mining Corporation, 1981). The concentration of chloride ions in the leaching solution is kept relatively low so that uranyl tricarbonate can successfully compete with chloride ions for sites on the resin surface.

Reversing the ion exchange reactions with resin-washing (elution) reagents subsequently produces a purified and concentrated uranium solution suited for direct precipitation of high-

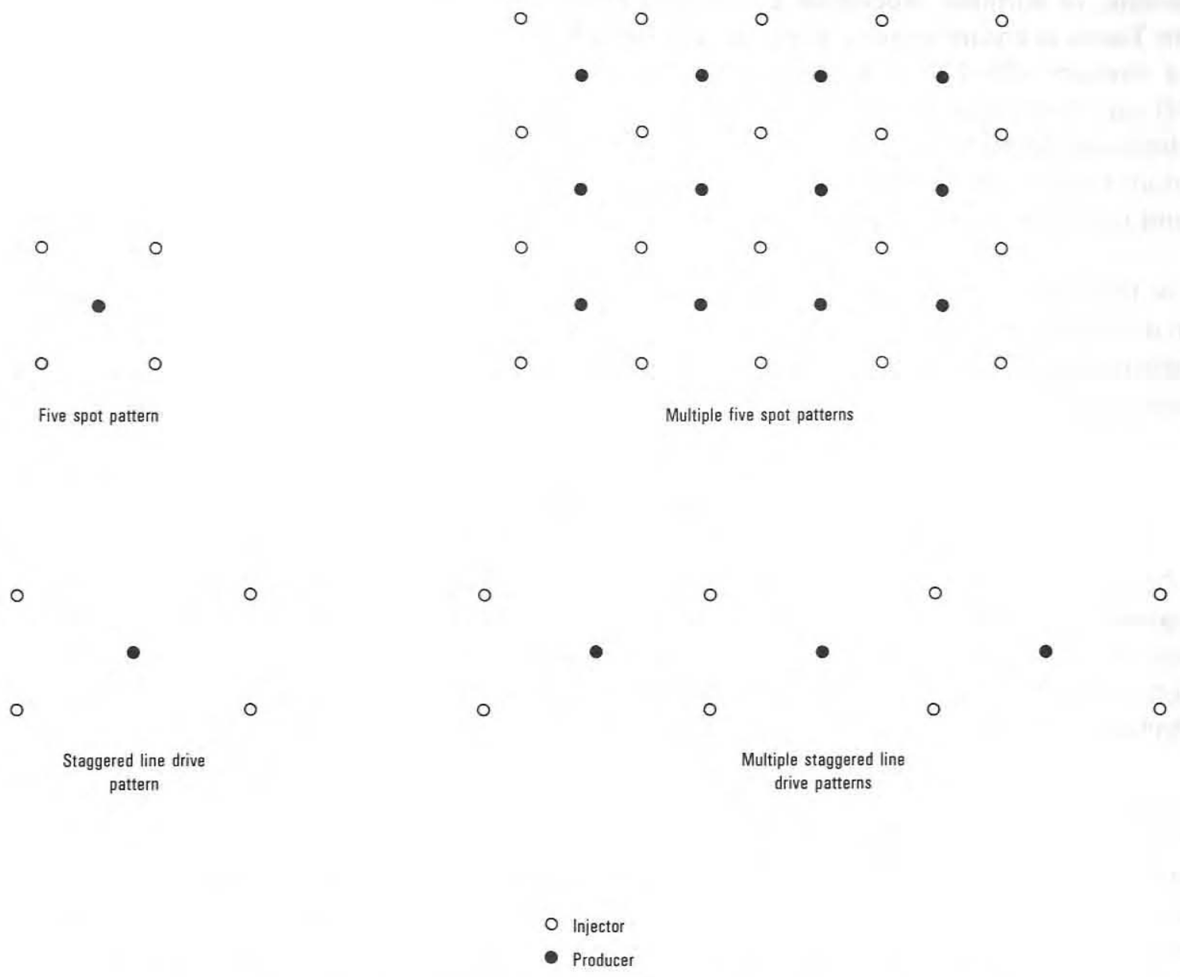


Figure 4-9.—Common Patterns of Injection and Production Wells

grade final uranium products (Merritt, 1971). In alkaline leaching systems, uranium adsorbed onto resin beads in the form of uranyl tricarbonate ions is washed from the resin by addition of a small volume of highly concentrated chloride solution. As resin surfaces begin to display higher affinity for chloride than for uranyl tricarbonate, uranium is progressively returned to solution. This uranium bearing eluate solution is referred to as the pregnant eluate. Uranium concentration in the eluting solution may reach 15,000 to 25,000 mg/l; at such concentrations a solid uranium oxide (U_3O_8) precipitate is produced by adding hydrochloric acid and hydrogen peroxide. This thick slurry of precipitated uranium oxide is either stored in a tank trailer to be shipped or is fed to a dryer. If the yellow cake product is dewatered and dried, it is loaded into drums of 55 gallon capacity, which when fully loaded with yellow cake weigh up to approximately 950 pounds each (Merritt, 1971). The now barren leach solution is usually pumped across sand filters to remove any accumulated particulates and precipitates before it is refortified with lixiviant chemicals and reinjected into the formation for a new leach cycle.

Nature and Volume of Injected Fluids

Leaching solutions injected into uranium mining wells are made up from native ground water produced from the ore body in the local aquifer, with additions of ammonium carbonate, sodium carbonate, or sulfates. Appendix 2 indicates that pre-mining (baseline) ground-water quality at South Texas uranium mining sites ranges from fresh to moderately saline. Mobil Oil Corporation's Brelum 106-200 site has the highest baseline ground-water salinity at approximately 6,110 mg/l total dissolved solids. At this site, the dissolved solids content of the injected lixiviant has been analyzed to be 8,760 mg/l. In a similar way, lixiviants injected at other South Texas uranium solution mines have a dissolved solids concentration elevated over that of the baseline ground water by a few thousand milligrams per liter.

At the time of peak uranium production in 1980, approximately 12 companies were operating at an estimated injection recovery volume of 2 billion gallons per company per year. Accordingly, the estimated 1980 total volume of uranium-mining fluids used in the injection and recovery process was 24 billion gallons.

Potential Problems

Potential environmental problems of uranium solution mining involve three phases of the operation: (1) well construction, (2) excursion control during mining, and (3) surface spill and leak control. Restoration of aquifer water quality to pre-mining (baseline) conditions, which can also be considered a potential environmental problem associated with solution mining, is discussed in the following section of this chapter.

In well construction, casing strength should be adequate to resist collapse failure. Consequently, to withstand casing stresses which increase with depth in a well, deeper mining well completions may justify use of relatively expensive but stronger fiberglass pipe in place of the more commonly used polyvinyl chloride (PVC) pipe. After casing installation, cementing should be done to insure a complete filling of the casing-borehole annulus from the top of the mining zone to the surface of the ground. A good cement job will prevent the spread of mining fluids into strata above the mining zone around each injection and recovery well. Accordingly, casing pressure tests and cementing records should be used to evaluate mechanical integrity of each mining well.

During solution mining operations, excursions of mining fluids into the aquifer may be controlled by keeping production rates in excess of injection rates. This practice accentuates ground-water flow toward production wells and should lessen chances for mining fluid excursions from the ore body. A regular program of aquifer water sampling with monitor wells completed in strata peripheral to, above, and possibly below the ore body will enable detection of these excursions. When detected, excursions can be recaptured by increasing fluid production rates from selected parts of a mine well field. Careful evaluation of abandoned wells and exploratory drill holes near an ore body should be accomplished during the permitting phase of a mining project to eliminate potential avenues for mining fluid migration. Plugging any such abandoned wells or drill holes will preclude the chance of excursion of mining fluids outside of an ore zone through these open holes.

Potential problems of surface facilities of a uranium mine include spills and leaks from fluid processing and storage. Any discharge of contaminated water to the ground surface or shallow subsurface may recharge and contaminate the local aquifer. Accordingly, plant process areas should be paved and curbed to collect all spills and leaks. Wastewater holding (evaporation) ponds should be installed and maintained with impervious synthetic liners; adequate pond freeboard should be maintained at all times to prevent pond overflows. A regularly monitored pond leak detection system will help minimize potential problems of mine surface facilities.

Mine Site Restoration

Regulations

Rules of the Texas Water Development Board (Chapter 27) require that a permittee notify the Department when mining of a permitted area is completed, and where appropriate, proceed to reestablish ground-water quality in the affected mine area aquifers to levels consistent with values listed in the permit or other values approved by the Texas Water Commission and based upon pre-mining (baseline) ground-water analyses for the particular mine area. Beginning six months after starting aquifer restoration, semiannual restoration progress reports are required by the Department until restoration is accomplished. When results of three consecutive ground-water sample sets show achievement of restoration, monitoring and restoration activities may cease. In addition, uranium solution mining permits require a bond or other form of financial security to be filed with the Department of Water Resources to assure that wells will be properly plugged upon closure of the mine.

Surface restoration is also required at each uranium mining site. Surface restoration basically consists of removing all pipelines, plugging and capping all well casings below grade, transporting contents of evaporation ponds to a licensed disposal site, filling in pits, and establishing appropriate revegetation. Financial security is also required for restoration and surface reclamation of the site. This financial assurance must be posted with the Texas Department of Health in accordance with a Memorandum of Understanding between the Texas Department of Water Resources and the Texas Department of Health.

Aquifer Restoration Methods

Some methods of aquifer restoration take place completely within the confines of the contaminated aquifer. With these in situ restoration methods, cost savings are substantial, system complexity is minimized, and objectionable materials are kept remote from the land surface. These in situ restoration methods include natural restoration, biological nitrification, chemical precipitation, and ground-water sweeping. Of these in situ restoration methods, the two most favored by industry are natural restoration and ground-water sweeping.

Natural restoration processes are simply the physiochemical actions that take place within the contaminated aquifer by natural means and without external influence (Riding and Rosswog, 1979). If natural restoration is used, a combination of mechanical pumping and surface treatment of heavily contaminated water from the aquifer followed by natural restoration will result in a more complete restoration (Trace Metal Data Institute, 1979).

Ground-water sweeping, sometimes referred to as "pore-volume flushing" or "pore-volume displacement," has been the most commonly used method of aquifer restoration in the solution mines of South Texas. With ground-water sweeping, water contaminated by leaching solutions is pumped to the surface through the mine production wells, and is replaced by natural inflows of native ground water from the surrounding aquifer, or is replaced by treated water which has been chemically adjusted at the surface plant and reinjected into the aquifer. Figure 4-10 shows a schematic representation of the ground water sweep method of aquifer restoration with recharge by injection.

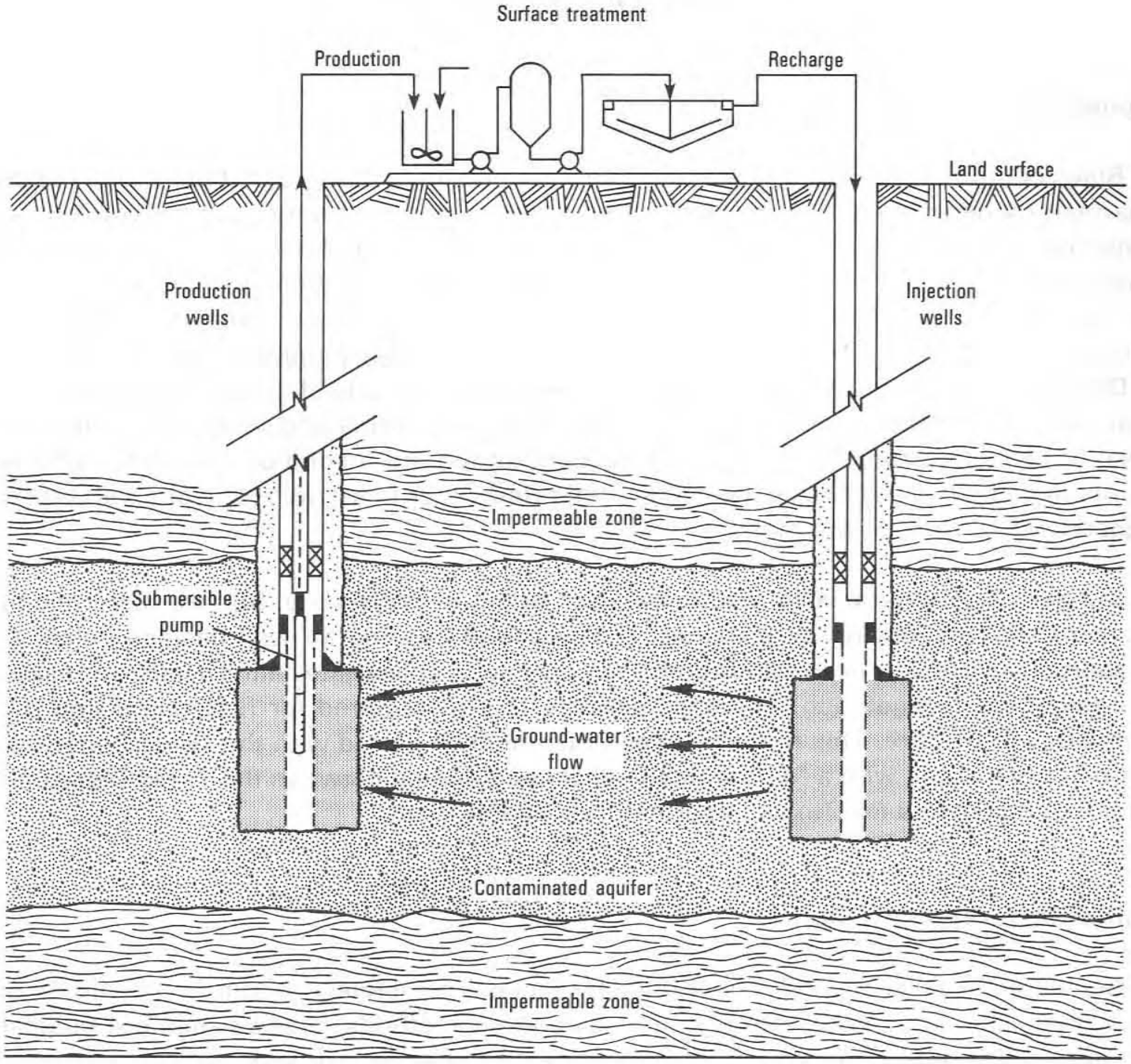


Figure 4-10.—Schematic Representation of Ground Water Sweep Method of Restoration With Recharge (After Riding and Rosswog, 1979)

The estimated number of pore volumes of water required for restoration of a mined aquifer has varied from 3 to more than 30. This high degree of variability results from site-specific differences in ionic competition with a given lixiviant chemistry and formation clay content. A pore volume as used in leaching operations to quantify fluid injection and production is the total fluid volume within the ore zone. But for restoration purposes, a pore volume may be defined to include the total fluid volume within the ore zone and the fluid volume within any zones of lixiviant excursion from the ore body. The time and number of pumped pore volumes required to reach baseline ground-water quality, if baseline can in fact be reached, remain uncertain. Furthermore, the volume of water pumped in pore-volume sweeping to produce a significant improvement in water quality will in most cases be large, and handling such volumes of water presents a major waste disposal problem. Figure 4-11 presents a typical aquifer restoration process, tracking improvement in dissolved solids content of the ground water versus pore volumes swept through the mining zone. The points on the graph do not represent data from an actual case, but rather, they are hypothetical and show a generalized clean-up trend.

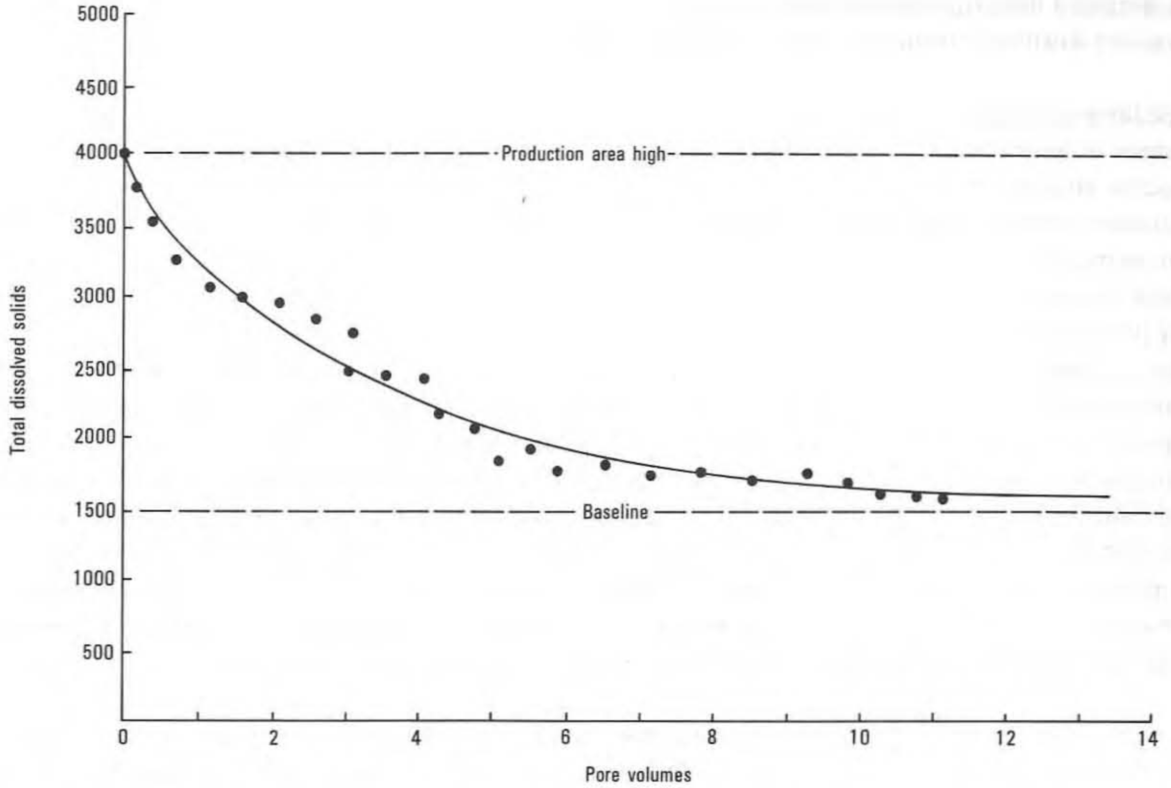


Figure 4-11.—Typical Aquifer Restoration Progress With Pore-Volume Sweeping

Other methods of restoration involve water processing at the mine surface. These surface processes include electrodialysis, distillation, chemical precipitation, adsorption and ion exchange, freeze separation, and reverse osmosis (Riding and Rosswog, 1979). Of these aquifer restoration methods implemented at the mine surface, the most widely used is reverse osmosis.

Reverse osmosis is a physical means of separating dissolved ions from an aqueous stream. This type of treatment uses an externally applied pressure in excess of the solution's inherent osmotic pressure to force water to pass through a semipermeable membrane while the dissolved ions are rejected or not allowed to cross this barrier. The advantages of reverse osmosis are the efficient removal of anionic, cationic, and neutral species, generally low operating costs, and enhanced water recovery (in excess of 90 percent) for environmentally acceptable aquifer recharge or discharge to streams (Trace Metal Data Institute, 1979).

Ultimate Disposal of Waste

A major part of any mine aquifer restoration program is the system for final disposal of contaminated ground water. Four alternatives for disposal of this wastewater are: deep well injection, solar evaporation ponds, solid waste disposal of sludge residues, and irrigation projects.

During restoration, at least the first few pore volumes containing the most heavily contaminated water are usually disposed of through deep wells, as most methods of restoration or surface treatment are generally inefficient in treating such water. Deep disposal wells for injection of uranium solution mining wastewater are permitted by the Department as Class I injection wells.

For a detailed description and assessment of Class I wells, the reader is referred to Chapter 3 of this report entitled "Industrial Waste Disposal Wells."

Solar evaporation ponds reduce the volume of wastewater by providing a large surface area for water evaporation to the atmosphere. This concentration process for wastewater eventually produces sludge residues which must be disposed of by safe methods such as landfills. The precautions which must be taken in construction and operation of evaporation ponds include use of impermeable synthetic pond liners, leak detection underdrain systems, and regular leak monitoring schedules. Heavy metals precipitate from solution as water evaporates from wastewater ponds. Some dissolved gases such as ammonia, carbon dioxide, and hydrogen sulfide may be liberated to the atmosphere from these ponds, but such pond sites in South Texas are generally in remote and sparsely populated areas, and the relatively small amounts of gases produced are dissipated harmlessly (Riding and Rosswog, 1979). Ponds are generally effective in climates where evaporation exceeds precipitation. In South Texas, semiarid conditions exist through much of the year, but hurricanes and tropical storms occasionally bring heavy rainfall to the area which could temporarily limit evaporation pond effectiveness. Evaporation ponds are often used as an intermediate and temporary wastewater holding facility between the surface processing plant and a deep disposal well. Filtration of suspended solids is generally the only required processing step for pond water before the water is injected into a disposal well.

Irrigation projects for wastewater disposal require development of appropriate design criteria and monitoring plans, and evaluation of local site factors. Water application rates must take into account local climate conditions, soil types, topography, geohydrology, and the chemical makeup of the mine wastewater. In some areas the irrigation method of disposal may be a less costly and more resourceful use of reclamation waters than other disposal methods, but more study is needed (Brown and Associates, 1982).

Restoration Effectiveness

At present, no single mine aquifer restoration process is clearly superior in meeting the objectives of aquifer restoration to maximum quality with a minimum volume of treated water. Restoration standards are being developed as technology evolves. For the purpose of ranking various ground-water restoration alternatives, a selected list of techniques is presented in Table 4-1. The areas assessed are costs, processing effectiveness, technological development, and processing limitations.

Ground-water sweeping is time-consuming, expensive, and perhaps even incapable of returning every water quality parameter to the baseline condition (Thompson et al., 1978). However, ground-water sweeping is still the industry-preferred method when used in conjunction with deep well injection or solar evaporation ponds.

In summary, use of different ground-water restoration alternatives may result in different degrees of local aquifer depletion and quality alteration. Evaluation of restoration alternatives for in situ uranium mining operations requires an understanding of the use of water in the area affected by mining activities. Laboratory studies using core sample data from mined aquifers, and computer ground-water dispersion models may be used to evaluate different restoration techniques.

Potential Restoration Problems

One of the major problems encountered when restoring leachate-contaminated ground water is returning the quality of the water to its pre-mining condition. When ammonia is used in the lixiviant, this problem is accentuated. Studies show that the quantities of water required for ammonia-contaminated aquifer restoration are large. Sweeping of ammonia is slow because ammonia is held in the form of ammonium ions (NH_4^+) on the negative sites of the clay fraction of porous formations. To restore ground-water quality, ammonia must be ionically exchanged from a formation anion to an injection fluid anion as the fluid moves through the mining zone. Restoration of ground-water quality after ammonia leaching can be accomplished with much less water if chemical sweeps are used instead of formation water sweeps (Charbeneau, 1981). Currently, few lixiviant solutions in South Texas contain ammonia. However, many of the mines in the area began operations with ammonia lixiviant solutions. Once a site has used ammonia, the restoration problem will be present even if the current lixiviant is ammonia-free.

Another restoration problem can occur from high solids concentrations in the produced restoration stream. When this condition is present, even the normal effectiveness of reverse osmosis for surface treatment of the restoration stream may be impaired. Reverse osmosis is designed to remove dissolved ions, whose diameters exceed 0.0003 micron. Colloids and clay particles in the restoration stream exceed this size, and therefore, are rejected by the reverse osmosis semipermeable membrane and build up at the water-membrane interface. This buildup of clay and other solids forms a solid layer which impedes water flow, requiring the fouled

Table 4-1.—Ranking of Ground-Water Restoration Alternatives (After Riding and Rosswog, 1979.)

	Ranking				
	Cost/1,000 gal*		Nonmonetary		
Restoration scheme	Separation unit	System	Effectiveness	Development	Limitations
1. *In Situ* (Passive or Recirculating)	—	<1	?	None	Not acceptable to regulatory agencies
2. Sweeping, Deep Well Disposal	—	2.50	Very Good	Commercial	Soluble wastes
3. Sweeping, Solar Evaporation Pond Disposal	—	5.98	Good	Commercial	Requires surface storage of wastes
4. Recharge, Reverse Osmosis, Deep Well Disposal	.99	1.78	Good	Commercial	Soluble wastes
5. Recharge, Reverse Osmosis, Solar Evaporation Pond Disposal	.99	2.19	Good	Commercial	Soluble wastes, requires surface storage of wastes
6. Recharge, Electrodialysis, Deep Well Disposal	1.35	2.14	Fair	Commercial	Ionic components
7. Recharge, Distillation, Deep Well Disposal	4.50	5.29	Good	Prototype	Scaling problems
8. Recharge, Direct Precipitation, Solid-waste Disposal	2.82	3.82	Fair	Commercial	Insoluble species only, surface storage of sludge
9. Recharge, Ion Exchange, Deep Well Disposal	3.00	3.79	Fair	Pilot Plant	Ionic component
10. Recharge, Freeze Separation, Deep Well Disposal	.70	1.49	Fair	Bench Tested	Soluble wastes

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*Mid-1978 dollars.

membrane to be cleaned or replaced. If the ground water to be restored has a high percentage of solids (dissolved or suspended), the cost of running a reverse osmosis unit may consequently be high and a less costly water purification process will likely be sought by the mine operator.

Legal and Jurisdictional Considerations

The mining of uranium ore by solution mining techniques began in Texas in the mid 1970's. Because the ore bodies are generally located in formations which contain usable quality ground water, the protection of these water resources has been a major concern of the State. Therefore, from the beginning these mining operations have been regulated by State permits. The first permits issued for the solution mining of uranium were issued by the Texas Water Quality Board, a predecessor agency of the Texas Department of Water Resources, pursuant to the Texas Water Quality Act, Chapter 26 of the Texas Water Code. In 1977 the Texas Uranium Surface Mining and Reclamation Act gave jurisdiction for uranium surface mining to the Railroad Commission of Texas while jurisdiction for the solution mining of uranium remained with the Texas Water Quality Board. In September, 1977, the Texas Department of Water Resources was formed and carried on the responsibilities held by the Water Quality Board. The Department permits consisted of a general permit for each mine site and subsequent production area authorizations issued under the mine site permit. The 1981 Injection Well Act amendments brought uranium solution mining under the injection well permit program of the Department. These permits are now issued pursuant to Chapters 26 and 27 of the Texas Water Code.

Uranium solution mining activities in the State are also under the jurisdiction of the Texas Department of Health. The Texas Department of Health has primary jurisdiction to regulate and license the handling, transfer, transport, storage, and disposal of radioactive materials (V.A.T.S. Article 4590f). The Department of Health evaluates the impact of sources of radiation on the occupational and public health and safety and the environment and, after consultation with appropriate state agencies, adopts rules to require minimization of radiological contamination of surface water and ground water by regulated activities. The mining and production of uranium ore by solution mining techniques involves the handling and disposal of fluids which may contain both radiological and nonradiological contaminants. The Department of Water Resources has permitting authority for the nonradiological contaminants, while the Department of Health has licensing authority for the radiological contaminants.

The licensing and permitting programs of the two agencies have been integrated through a Memorandum of Understanding executed by the agencies on January 27, 1983. The Department of Health has primary responsibility for regulating the aboveground process plant facilities. The Department of Water Resources has primary regulatory responsibility for all wells, wellhead assemblies, and ground-water monitoring equipment. Aquifer restoration parameters will be specified in the Department of Water Resources permit, but the radiological parameters will be established by the Department of Health, while the nonradiological parameters will be established by the Department of Water Resources. Financial security for closure of surface facilities and disposal of radioactive materials will be posted with the Department of Health. The Department of Water Resources will separately require financial assurance for proper plugging and abandonment of wells. Elements of the Memorandum of Understanding are contained in Subchapter B of Chapter 27 of the Department's Rules.

Concluding Statement

Solution mining of uranium with injection and production wells is a less costly and disruptive method of mining uranium as compared to open pit or underground shaft mining. The Texas Department of Water Resources has regulated in situ uranium mining by permit since 1975. Since that time, approximately 30 permits and 45 production area authorizations have been issued to various companies operating in South Texas. Uranium solution mining occurs almost exclusively in four geologic formations of Tertiary age: the Whitsett, Catahoula, Oakville, and Goliad. These formations are subunits of the large Gulf Coast aquifer.

Solution mining of uranium has a significant potential for local aquifer contamination around mine sites. The local effects of uranium solution mining on ground water are to elevate total dissolved solids concentrations, principally by addition of leaching solutions of ammonium carbonate or sodium carbonate, and uranium concentrations. Water quality in the Gulf Coast aquifer near the mine sites investigated ranges from fresh to moderately saline, and in many places exceeds current U.S. Environmental Protection Agency drinking water standards for dissolved solids, chloride, and radium^{226}. However, at many such sites no other drinking water is readily available and, consequently, this water must suffice for a variety of agricultural, domestic, and municipal uses.

Injection and production wells of a uranium solution mine are of essentially similar construction, with polyvinyl chloride (PVC) or fiberglass casing cemented to the surface, and with screened completions through the ore zone. The injection wells use pumps at the surface to drive injection, and the production wells use submersible pumps to lift fluid to the surface. South Texas uranium solution mines also operate numerous aquifer monitor wells to detect possible excursions of mining fluids from the mining zone. Excursions normally can be controlled and recaptured by adjusting fluid production from the mining zone to rates exceeding fluid injection rates.

At the surface of a uranium solution mine, ion exchange, elution, and chemical precipitation are used to recover uranium compounds from mining solutions produced from the ore body. The final yellow cake product (U_3O_8) is dried and loaded into containers or shipped as a slurry.

The Department's regulatory program for uranium solution mines requires aquifer restoration to pre-mining conditions at the termination of mining. The ground-water sweep method of aquifer restoration has been the most favored method in South Texas, but this method may necessitate a system for disposal of large amounts of wastewater. Systems which may be used for wastewater disposal include Class I waste disposal wells, solar evaporation ponds, and irrigation with treated water.

It is recommended that continued research on aquifer restoration be conducted, such as a study of the long-term effects on a mined and restored aquifer. Given the complexity of ground-water movement and geochemical reactions, a limited but long-term post-restoration monitoring program possibly should be maintained, particulary in cases where an ammonia-based lixiviant was used in mining. Also, regulations concerning solution mining of uranium should be periodically reviewed to keep the regulatory program in step with current industry practices and best available environmental protection technology.

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CHAPTER 5

BRINE SOLUTION MINING WELLS

Investigator:

Nancy J. Bolz

BRINE SOLUTION MINING WELLS

Table of Contents

BRINE SOLUTION MINING WELLS

Introduction

Many wells operate in Texas to produce brine by solution mining of subsurface salt deposits. The Department has inventoried a total of 66 brine stations (effective as of July 1984), two of which operate in the Gulf Coast region, with the remainder operating in the Trans-Pecos and High Plains regions. Most of the west Texas brine wells are completed through water-table aquifers that are recharged by infiltration of water from the surface and are susceptible to contamination from surface sources. The locations of the brine wells inventoried by the Department are shown in Figure 5-1. Records of the brine wells inventoried are given in Appendix 3.

It is estimated that Texas produces more than 10 million tons of salt each year. Over 90 percent of this yearly total is produced as brine in contrast with the relatively small amount quarried in the form of rock salt. This tonnage of brine amounts to an annual volume of more than 10 billion gallons. The majority of this brine is used in the petroleum industry. However, some of the brine is used in water softening, highway deicing, or sold to the chemical industry.

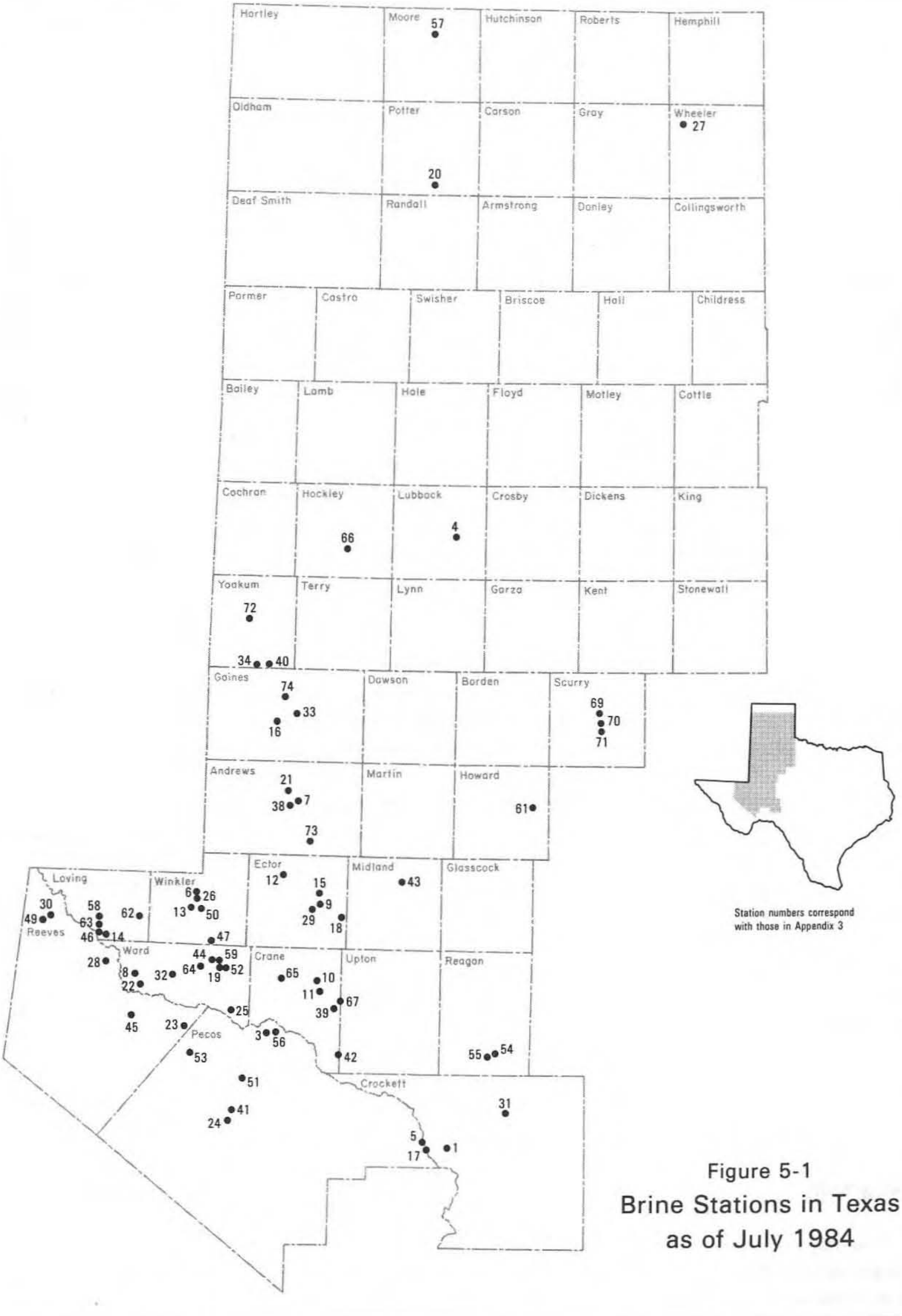
Brine has a number of applications in oil well technology including drilling, workovers, fracturing, and well completion. It is especially used in the petroleum industry in drilling through salt beds of the Salado Formation to minimize drilling problems arising from solution of the bedded salt. In these cases, brine is ideal for displacing mud in well production zones, controlling high bottom-hole pressures, and cleaning holes after fracturing is completed.

The typical brine station consists of one or more water supply wells, a brine well completed in the Salado salt beds, brine and freshwater storage facilities, and other necessary pumps and equipment. Water is pumped from a water well and injected under pressure down the brine well to near the bottom of the brine-filled solution cavity in the salt beds. The injected water dissolves the salt as it rises through the solution cavity and flows as brine to the surface. Brine is either produced from the same well that injects water, or a two-well solution mining system is used in which one well injects water and a second well produces brine from the same cavern. The brine is then stored in tanks and ponds from which it is loaded into trucks and hauled from the brine station for a variety of uses.

Geohydrology

Stratigraphy

The majority of the solution mining of salt occurs in the Trans-Pecos and High Plains regions of Texas where brine is principally obtained from the bedded Salado Formation of Permian age. The second significant source of brine is the salt domes of the Texas Gulf Coast. The deep source



Station numbers correspond with those in Appendix 3

Figure 5-1
Brine Stations in Texas
as of July 1984

of the domed salt along the Gulf Coast is the Louann Salt. This salt formation could range in age from Permian to Jurassic, and is probably on the order of 20,000 to 25,000 feet deep. These salt domes have intruded the Cenozoic age strata, commonly to within a few hundred to a thousand feet of the surface.

Structure

The Salado Formation is a vast salt deposit which extends in the subsurface from near the Big Bend area northward through the High Plains, across Oklahoma, and into Kansas. The bedded salt is primarily sodium chloride, in forms varying from thin stringers to thick beds, and has an east-west width ranging from 150 to 250 miles. The Salado salt is encountered in the subsurface at depths from 200 to 2,000 feet and has a net thickness of up to 1,000 feet.

Texas Gulf Coast salt domes are massive columns of salt with a cap area of as much as 25 square miles. It is generally accepted that the parent salt beds became plastic as the pressure from the overlying sediments increased over time. The relatively low density of the salt then caused it to float or extrude toward the surface, penetrating the overlying sediments and forming the domes. The domes consist of a salt core enveloped by a thin shale sheath. These structures upwarp and pierce the abutting country rock. Many domes are directly overlain by a cap rock consisting of salt, anhydrite, calcite, and sometimes sulfur. This cap rock is believed to accrete at the advancing top of the salt dome by redeposition of minerals dissolved from the salt core into concentrated and segregated mineral zones of the cap rock.

The tops of many salt domes appear to have reached a depth in their upward course of buoyant equilibrium with the enveloping sediments within a thousand to a few hundred feet of the surface. A few domes extend almost to the ground surface. The surface expression of salt domes ranges from low hills of uplifted sediments, such as at High Island in Galveston County, to marshes and bogs associated with solution-collapse sinkholes, such as at Sour Lake in Hardin County. Surface and ground water around salt domes may be slightly saline to saline and may carry an odor suggesting high sulfur mineralization.

Aquifers

Four major aquifers supply water in the regions of the State where brine solution mining occurs. These are the alluvial and bolson deposits in the Trans-Pecos region, the Edwards-Trinity aquifer which extends from the central part of the State into the Trans-Pecos and High Plains regions, the Ogallala Formation on the High Plains, and the Gulf Coast aquifer along the coast. Other water-bearing formations yield small quantities of water in these regions, but because of their limited areal extent, they are considered less significant. The major and minor aquifers are described in greater detail in Chapter 2 titled "General Geology."

Construction Features

Well construction commonly involves setting steel surface casing through the base of usable quality water (dissolved solids content up to about 3,000 mg/l) and cementing the surface casing to the surface. Drilling then continues to a total well depth within the bedded salt. Inside the surface casing, a steel production casing is set to the top of the salt and is cemented in place. Finally, a steel pipe for injection of water is installed inside the production casing. This water pipe extends into the bedded salt section to within about 60 feet of the bottom of the penetrated salt. With this design, water pumped into the well dissolves the bedded salt from the borehole walls and enlarges the hole to form a cavity. The resultant brine is returned via the production casing to the surface. A typical brine well completion is shown in Figure 5-2.

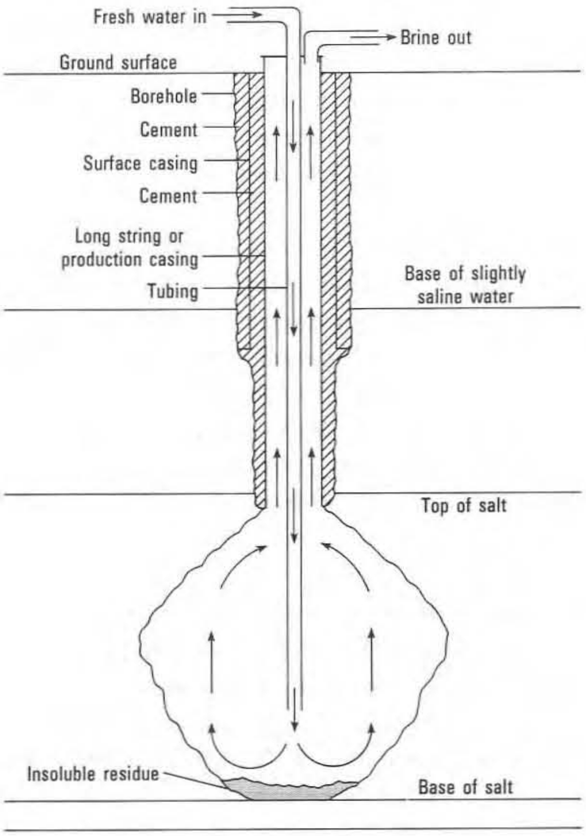


Figure 5-2.—Typical Brine Well Completion

In addition to the systems described, in which a single solution mining well injects water and produces concentrated brine, two-well systems may be used which inject water through one well into an underground salt cavity and produce the resultant brine up a second well completed in the same salt cavity. Such two-well systems are not commonly used in Texas. In two-well brine solution mining systems, both wells are completed in the same salt bed, and salt solution cavities are established around each well. Communication between the two wells is established by fracturing through from one solution cavity to the other.

The generally accepted method for brine well installation in a salt dome is typically more complex than the method used for Salado salt. The wellbore is drilled into the dome and an outer casing is cemented in place. An inner casing is then placed inside this first casing. Tubing which can be progressively lowered into the salt dome as the cavity grows is placed inside the inner casing. After the well casing and tubing installation is completed, an inert fluid such as oil is placed in the outer annulus between the two casings. This fluid prevents contact between the water and the salt near the bottom of the casing and, in turn, prevents salt dissolution in this area which could weaken the casing seat.

Mechanical Integrity

Maintaining mechanical integrity of brine wells is important to avoid ground-water contamination. First, due to high pressures required to pump brine to the surface, long-string and surface casing should be cemented to the appropriate depths. Second, casing leaks and casing cement channels may provide avenues for brine contamination of a freshwater aquifer. Third, abandoned oil and gas wells converted to produce brine may be especially susceptible to corrosion problems and leaks in the casing.

Casing pressure tests and cement bond logs (CBL) are presently considered as the two most efficient methods of evaluating the mechanical integrity of a brine well. Mechanical integrity of an injection well is defined as the absence of casing leaks in the interval between the ground surface and the injection zone, and the absence of fluid movement within the cemented casing borehole annulus. The pressure test is used to check for fluid leaks through casing defects. The cement bond log is run to determine the presence of uncemented channels in the casing-borehole annulus which may be avenues for fluid movement between formations.

Casing pressure tests may be run after casing installation before the cement plug at the casing bottom is drilled out, or any later time during well operation by inserting a mechanical plug in the casing at the top of the injection zone. In both cases, the well is pressurized with air, nitrogen, or water to approximately one and one-half times the operating pressure, and the pressure is monitored for not less than one hour at a gauge installed on the casing head. If there is no significant drop in pressure, the casing is considered to be free of leaks. If the pressure in the casing drops during the test, additional tests are conducted to determine where the leak is occurring, and upon correction the well is retested.

The CBL tool uses acoustic and electronic impulses to determine the quality of cement adhesion to the casing in the well and to the formation. The purpose of well cementing is to isolate the production or injection zones in a well, so that they can be used for a specific purpose. If communication between permeable zones occurs, remedial actions such as cement squeezes must be accomplished. Cement bond logs are subject to a range of interpretation. However, low amplitude levels on the plotted log correspond to zones of good cement quality (no channels, fissures, or fractures), while large amplitude readings indicate the absence of cement bonding and suggest the presence of channels (Pardue, Morris, and Moran, 1963).

Operating Practices

Although brine stations differ considerably in detail, the following generalized description is applicable to most Salado salt brine stations. Each brine station generally consists of one or more water supply wells completed in a relatively shallow aquifer, a brine well completed in the Salado salt beds, brine storage facilities, and other necessary pumps and surface facilities. Typical surface facilities are illustrated by Figures 5-3 and 5-4. Water is pumped from the water well and injected under pressure down the tubing of the brine well to near the bottom of the brine-filled solution cavity in the salt beds. The injection pressure forces brine to the surface through the annulus between the production casing and the tubing. The injected water dissolves salt as it rises through the solution cavity and becomes saturated brine. Analyses of brine water at selected brine stations are given in Table 5-1.

The above procedure may be reversed periodically so that the water is injected through the annulus and the brine is produced through the tubing. Some operators may use the "reversed" procedure as standard practice. The potential for brine contamination of the overlying aquifers through casing leaks is minimized when brine is produced up the tubing. However, dissolution of salt and cavern shape are probably more consistent when the tubing injection method is used.

The majority of stations use steel tanks or ponds lined with at least a 30 mil thick chlorinated polyethylene or Hypalon plastic liner for storage of brine. Occasionally a wooden tank is used for brine storage. Wooden tanks are commonly used for freshwater storage. Many of the steel tanks

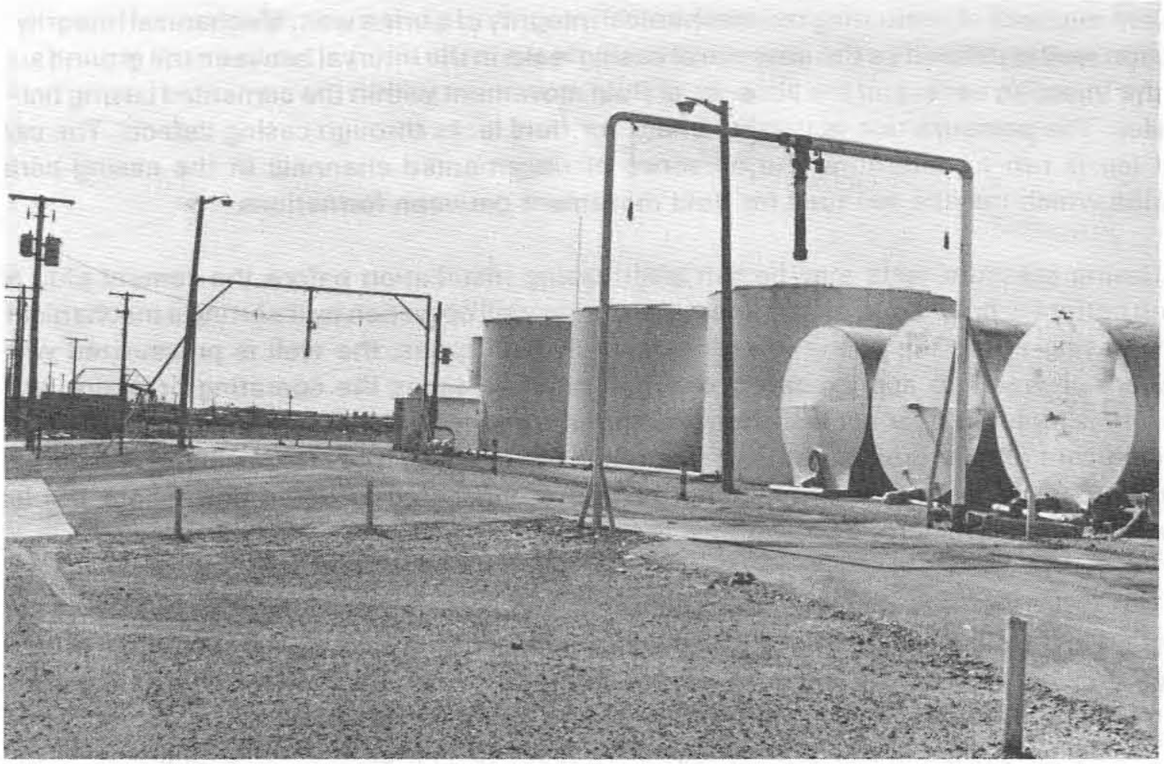


Figure 5-3.—Typical Brine Station

Figure 5-4.—Typical Brine Well

Table 5-1.--Chemical Analyses of Water From Brine Wells
(Analyses are in milligrams per liter except specific conductance and pH)
Analyses performed by the Texas State Department of Health.

Brine station number (keyed to figure 5-1)	County	Date of collection	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (sum)	Total hardness as ($CaCO_3$)	Specific conductance (mmhos at 25°C)	pH	Silica (SiO_2)
15	Ector	June 3, 1982	786	1,292	124,186	3,140	153	9,425	190,512	5.5	32.52	325,300	7,280	3,190	7.2	10
30	Crane	June 3, 1982	1,046	783	111,720	1,562	103	7,258	169,359	0.7	< 0.04	293,400	5,835	12,000	7.4	11

presently being used by brine operators have numerous small holes in the sides which result in a small but constant leakage of brine to the ground surface.

The trend for brine storage appears to be away from steel tanks and toward plastic-lined ponds. Even though there was no evidence of leak-detection systems at many of those ponds visited in 1982, most appeared to be properly engineered and constructed. The plastic-lined ponds represent an improvement over leaking steel tanks; however, any leaks developing in the liner will be difficult to detect.

Nature and Volume of Injected Fluids

The fresh water which is used to dissolve the salt weighs about 8.3 pounds per gallon. The produced saturated brine weighs about 10 pounds per gallon. The degree of saturation depends on the rate of flow through the cavity and the size of the cavity. Assuming production of 10 pound brine, the pressure required to drive the brine to the surface is approximately 8 psi/100 feet of depth. The shape of the cavity and its structural integrity can be controlled by regulating the depth at which the water is injected and the extent of the inert blanket maintained over the brine. Analyses of supply water at selected brine stations are given in Table 5-2.

Potential Problems

The potential for contamination of usable ground water depends on the condition, location, and type of facilities at the brine stations. Almost every brine station visited in 1982 had evidence of minor spills of brine. In addition, major spills are frequently reported despite the presence of signs warning patrons to avoid spilling brine. Some of the spills are due to negligence on the part of truck drivers loading brine, while other spills are due to malfunctioning shut-off switches which allow brine tanks to overflow.

Wells used to produce brine are installed specifically for brine production, or initially for oil and gas production and then are converted to brine wells. Potential ground-water contamination hazards involving wells include unplugged abandoned wells, inadequately cased wells, inadequately cemented well casings, casing leaks, and brine excursions from the solution mining system through solution channels and formation fractures.

Regarding unplugged and improperly cased oil and gas wells, any communication with a brine well by way of casing or cement problems or natural formation fractures may result in contamination of fresh water supplies. Where communication exists between two hydrologic units, water will move from the unit of higher hydrostatic head into the unit having lower hydrostatic head. Plugging records of abandoned wells should be evaluated in order to minimize the potential hazards from other wells in the area.

A final consideration regarding potential hazards of brine wells involves the possibility of overburden collapse into the solution cavity. Such collapse does not appear to be a significant possibility for the single-well brine system in which the solution cavity is almost always tear shaped. This shape transmits the overburden load to the salt around and below the cavity efficiently. Such may not be the case with a two-well brine system, however, where one of the wells must fracture through to the other well and establish circulation and dissolution of salt. The

Table 5-2.--Chemical Analyses of Supply Water at Brine Stations
(Analyses are in milligrams per liter except specific conductance and pH)
Analyses performed by the Texas State Department of Health.

Brine station number (keyed to figure 5-1)	County	Date of collection	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (sum)	Total hardness as ($CaCO_3$)	Specific conductance (mmhos at 25°C)	pH	Silica (SiO_2)
15	Ector	June 3, 1982	292	247	1,016	16.0	212	1,571	1,518	2.5	44.34	5,176	1,747	4,210	7.9	28
26	Reeves	July 6, 1982	1,123	822	5,390	151	175	2,988	10,557	1.4	<0.04	21,080	6,190	9,830	7.4	28
27	Upton	July 6, 1982	254	149	397	--	202	986	657	2.1	28.84	2,750	1,249	2,550	7.9	15
30	Crane	June 3, 1982	580	197	1,960	38	118	3,175	2,240	1.5	<0.04	8,244	2,262	5,770	8.0	13
30	Crane	June 3, 1982	923	205	2,345	27	225	1,232	4,690	1.4	3.04	9,828	3,150	7,180	8.0	68
40	Crane	July 6, 1982	1,171	437	3,416	--	236	3,371	6,056	1.5	94.89	14,850	4,724	32,767	7.8	15
43	Wheeler	Nov. 28, 1979	50	15	20	--	228	10	25	0.4	3.8	269	188	420	8.1	--
51	Crane	July 6, 1982	1,280	270	2,285	--	175	2,758	4,438	1.3	27.33	11,172	4,312	6,830	7.8	23
53	Reagan	July 6, 1982	337	216	3,655	--	335	795	6,031	2.3	<0.04	11,510	1,730	7,550	7.8	12

resulting cavity will not be tear shaped and may be more prone to collapse. Solution cavity collapse could impair well mechanical integrity and contribute to contamination of the fresh water aquifer. Also, in the two-well system, fractures must be controlled to preserve mechanical integrity of the wells and prevent brine from moving into fresh water zones.

Environmental Protective Measures

Ground-water monitoring is necessary to detect contamination from spills and leaks at all brine sites where usable quality ground water occurs. Determination of baseline ground-water quality at a brine station is important to provide data upon which to base a ground-water monitoring program throughout the operation of the brine well. The baseline water quality for existing facilities is determined by sampling all water wells within the area of review which are completed in aquifers overlying the salt. Baseline water quality for proposed brine wells, where there are no existing water wells completed in overlying fresh water aquifers, is determined upon completion and sampling of the solution mining system's water supply wells (Table 5-2).

The number, location, spacing, design, and construction of the monitor wells is based on the geohydrology of the brine station. These wells should be located in a pattern which will detect any excursion of brine from the solution cavity of the brine well into the fresh water of the area. Routine ground-water monitoring consists of sampling the monitor wells at monthly or quarterly intervals and analyzing the samples for specific electrical conductance.

In areas where usable quality ground water exists, corrosion-resistant tanks or ponds lined with suitable synthetic liners with an underdrain leak detection system should be used for brine storage. Examples of suitable synthetic liners include chlorinated polyethylene and Hypalon. The leak-detection systems should be designed to collect all flows resulting from leaks in the liners of ponds. Periodic monitoring of the leak-detection system should minimize the possibility of brine contaminating local fresh water supplies. To prevent surface contamination from pond overflows, at least 2 feet of freeboard should be maintained in all ponds. The installation of pump shut-off switches that will activate when tanks and lined ponds are full may be useful. In addition, tanks and ponds should be protected from accidental damage by adequate fencing, and should be regularly inspected for deterioration. Finally, curbed concrete loading pads with spill catchment basins could be constructed at each brine station to minimize the environmental effects of spills during brine truck loading.

Regarding well and salt cavity integrity, shut-off switches should be installed that will automatically stop injection pumps when there is a significant drop in injection pressure indicating a possible rupture in the casing, or a significant difference in the volume of fluid injected and the volume of fluid returned. Periodic mechanical integrity testing during the life of the brine production well will indicate the condition of the casing and the degree of bonding between the casing and the formation. Should the testing indicate problems, remedial actions must be taken to repair leaks.

Legal and Jurisdictional Considerations

Brine solution mining wells are presently regulated under the Department's Underground Injection Control program pursuant to the 1981 amendments to the Injection Well Act. Prior to the 1981 amendments, such facilities were not regulated by the State.

Brine solution mining wells are classified as Class III wells and in conformance with Department Rules are regulated by permit. The owner or operator of an existing facility must submit to the Executive Director an application for permit not later than January 6, 1984.

The majority of the brine solution mining permits will be issued for sites operating in the Trans-Pecos and High Plains regions. Certain of the Gulf Coast region wells appear to have been developed primarily for the eventual use of the solution cavity as a hydrocarbon storage facility. In these cases, primary regulation as Class II wells under a Railroad Commission Underground Injection Control permit may be more appropriate. Consequently, each brine station associated with salt domes will be evaluated to determine if a Class III permit is needed; however, dual regulation will generally be avoided.

Concluding Statement

Brine solution mining stations have a significant potential to cause ground-water quality problems from surface spills and tank and pond leaks. Brine wells also have the potential to contaminate usable quality ground water when well mechanical integrity is not maintained. This is especially true with improperly or inadequately cased oil and gas wells which have been converted into brine wells. The potential for the contamination of usable quality ground water can be reduced through the use of automatic shut-off switches, lined ponds, monitor wells, properly constructed tanks, and scheduled well maintenance which includes periodic mechanical integrity testing. In addition, scheduled review of the operating data and visual inspections of the sites will help prevent problems. However, experience with the operation of brine wells, as indicated by complaints or problems brought to the attention of the Department, suggest that the actual problems have thus far been minimal.

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CHAPTER 6

FRASCH SULFUR MINING WELLS

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FRASCH SULFUR MINING WELLS

Table of Contents

FRASCH SULFUR MINING WELLS

Introduction

Mining of sulfur by the Frasch process occurs in two general areas of Texas: along the Gulf Coast, and in the Trans-Pecos region of west Texas. On the coastal plain, sulfur mining is associated with salt domes. In 1982 there were three active sulfur mines in this coastal area, located on the Long Point salt dome in Fort Bend County, Boling dome in Wharton County, and Moss Bluff dome in Chambers County. In the Trans-Pecos region, three sulfur mines operate within bedded limestone and evaporite formations of Permian age, in Pecos and Culberson Counties. The Trans-Pecos sulfur-bearing formations include the Rustler, Salado, Castile, Tansil, Yates, and Seven Rivers. Locations of these six Frasch sulfur mining sites are shown in Figure 6-1. Table 6-1 summarizes Frasch sulfur mining operations in Texas.

Frasch sulfur mining began in 1895 in Sulfur Mine, Louisiana, and was first practiced in Texas at Bryan Mound in 1912. Devised by Dr. Hermann Frasch in 1894, the process allows for recovery of liquid sulfur through wells drilled into sulfur-bearing formations. Superheated water at 330°F is injected through a well into the formation where it heats up the host rock and causes sulfur to melt. Liquid sulfur flows to the bottom of the sulfur-mining well and is air lifted to the surface as 99.5 percent pure sulfur.

Sulfur is one of the basic raw materials of the chemical industry. It is used in manufacture of hundreds of products such as fertilizer, paper, fibers, pharmaceuticals, and explosives. Nearly 90 percent of the produced sulfur is converted to sulfuric acid which is essential to industries which produce the above listed products.

Sulfur is an abundant mineral, making up approximately 0.06 percent of the earth's crust, but most of this sulfur is not economically recoverable. The major sources of sulfur are native sulfur produced by the Frasch process, sulfur recovered from natural gases, and sulfur recovered from sulfide ores. Frasch sulfur production currently accounts for more sulfur than any other method of production worldwide, and accounts for 70 to 90 percent of the domestic market.

Origin and Occurrence of Sulfur

Gulf Coast sulfur deposits are associated with salt domes; Trans-Pecos deposits are found in formations altered by faults and folds. Although the two areas are isolated both geographically and geologically, both types of sulfur deposits are thought to have been formed by similar processes.

Origin

Hydrocarbons in oil and natural gas are thought to have been the energy source for anaerobic sulfate-reducing bacteria to convert sulfur in anhydrite ($CaSO_4$) formations to hydrogen sulfide

Figure 6-1.—Frasch Sulfur Mining Sites in Texas, 1982

gas (H_2S), by using sulfate ions ($SO_4^{=}$) in place of elemental oxygen in the respiratory cycle. Hydrogen sulfide migrated upward through fractures in subsurface rocks until it encountered an oxidizing environment where hydrogen sulfide was converted to water and insoluble elemental sulfur. Fractures through which natural gas and hydrogen sulfide moved, and in which sulfur was deposited, were formed by intrusion of salt domes into overlying strata and at anticlinal folds and faults.

Along the Gulf Coast, sulfur occurs in the porous limestone-dolomite portion of salt dome cap rocks which are often vugular and fractured (Figure 6-2). Circulation of oxygenated ground water from shallow aquifers is presumed to have reacted with hydrogen sulfide, resulting in deposition of sulfur in the voids and crevices of cap rocks.

The origin of sulfur deposits in the western part of the State appears to have involved basically the same biogenetic process that occurred in the Gulf Coast salt dome deposits. As solution porosity developed in anhydrite and gypsum formations, petroleum migrated up into

Table 6-1.—Summary of Frasch Sulfur Mines in Texas, 1982

Company	Mine	Discovery date	Mining began	County	Location	Formation	Approx. depth	Average no. of active production wells (1982)
Duval Corporation	Culberson-Phillips	1900	1969	Culberson	42 miles NW of Pecos	Rustler Salado Castile	240-1,000 ft	25
Farmland Industries	Fort Stockton	1900	1968	Pecos	12 miles NE of Fort Stockton on FM Road 1053	Salado Tansil Yates	160- 750 ft	10
Jefferson Lake Sulphur Company	Long Point[1]	1924	1930-38; reopened 1946	Fort Bend	14 miles SE of Rosenburg off State Hwy 36	Cap rock of Long Point Dome	550- 930 ft	8
Texasgulf, Inc.	Newgulf	1922	1928	Wharton	13 miles SE of Wharton on FM Road 442	Cap rock of Boling Dome	380-2,300 ft	20
Texasgulf, Inc.	Moss Bluff[1]	1926	1948	Liberty and Chambers	14 miles S of Liberty on FM Road 563	Cap rock of Moss Bluff Dome	590-1,160 ft	13
Texasgulf, Inc.	Comanche Creek[1]	1900	1975	Pecos	14 miles NE of Fort Stockton on FM Road 1053	Salado Tansil Seven Rivers Yates	250- 800 ft	12

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[1] During the writing of this report, three of the Frasch sulfur miles closed. The Texasgulf, Inc. Moss Bluff mine closed in September 1982, the Texasgulf, Inc. Comanche Creek mine closed in November 1983, and the Jefferson Lake Sulfur Company Long Point mine closed in November 1982. All Class III wells at these three sites have been reported plugged.

these zones from underlying permeable formations. Sulfate-reducing bacteria, present in the petroleum and anhydrite environment, generated large quantities of hydrogen sulfide. As oxygenated ground water mixed with hydrogen sulfide-rich water, sulfur was deposited in formation voids and fracture systems (Davis and Kirkland, 1970).

Geology

The formation of salt domes is thought to have begun with evaporation of salt water, leaving deposits of bedded salt ($NaCl$), gypsum ($CaSO_4 \cdot 2H_2O$), and anhydrite ($CaSO_4$). Following deposition of salt beds, from Permian to possibly as late as Jurassic time, thick layers of sediments were deposited over the salt during the Cretaceous, Tertiary, and Quaternary Periods. Because of the tremendous weight of overburden sediments, the salt became plastic in character and capable of flowing. During Tertiary and Quaternary time, the salt rose through the stratigraphic section by buoyant forces, being less dense than the surrounding sediments. Rising salt deformed and domed overlying sediments on its upward ascent. As the rising salt structure neared the surface, it encountered less saline ground water which dissolved sodium chloride from the salt, leaving insoluble minerals to form a cap rock where sulfur was later deposited. Cap rocks are usually several hundred feet thick and composed initially of anhydrite, which is further acted upon by ground water to form layers of porous limestone, dolomite, and gypsum. This sequence of alteration by ground water forms the typical cap rock stratigraphy shown in Figure 6-2.

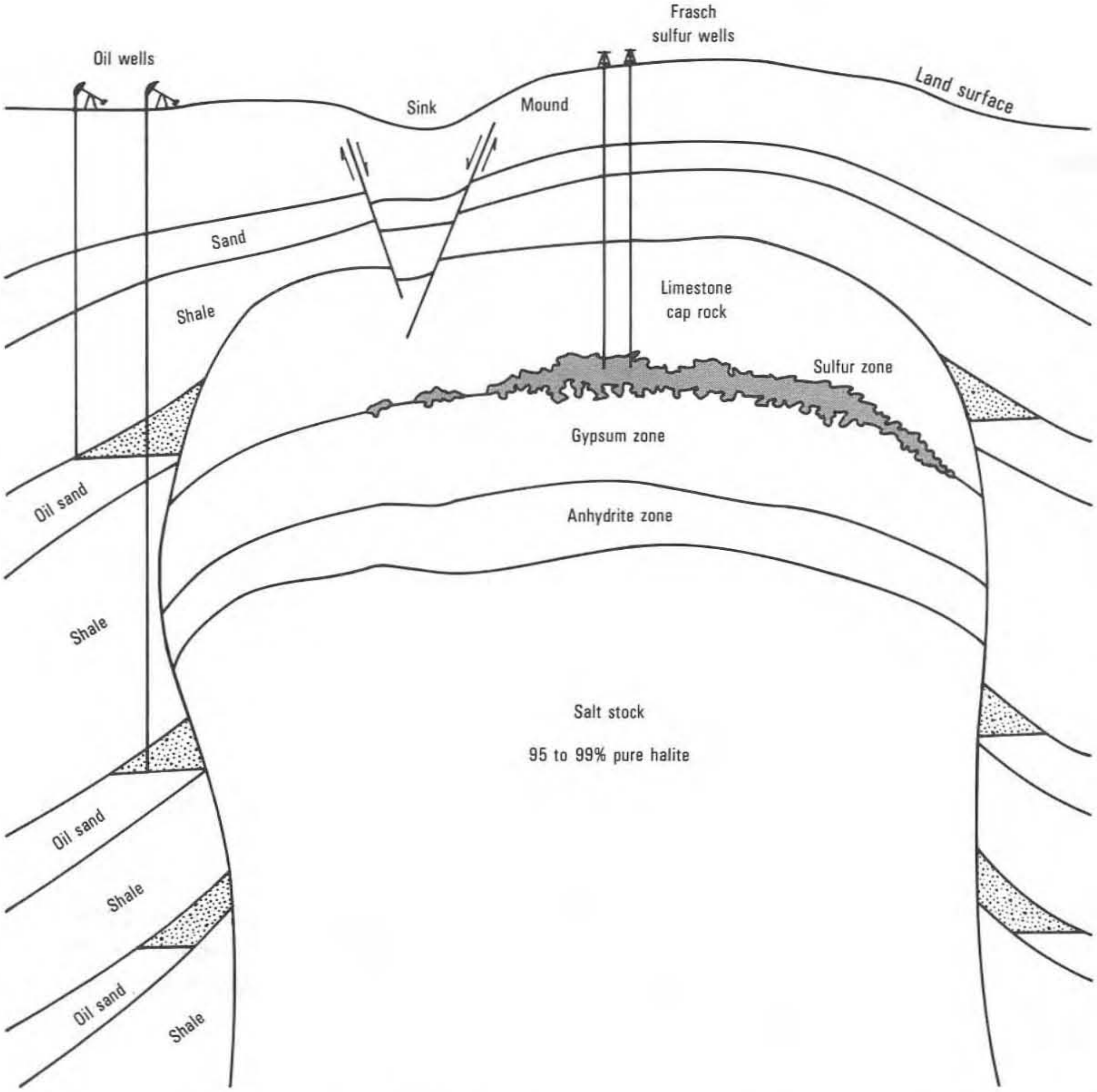

Figure 6-2.—Generalized Cross Section of a Salt Dome

Over 80 salt domes are known to occur in Texas. Fifteen of these domes contain deposits of sulfur that have been mined, and at least 10 additional domes have sulfur deposits which have not been mined. As of 1982, only three sulfur mines were operating in Gulf Coast salt domes (Figure 6-1).

Of the three salt domes recently being mined on the Gulf Coast, the Boling dome in Wharton County is largest and produces the most sulfur. The dome itself is over 5,000 acres in area and contains sulfur-bearing zones up to 200 feet thick in the depth interval between 900 and 2,600 feet. Moss Bluff dome, in Liberty and Chambers Counties, is approximately 1,000 acres in area and sulfur is produced from approximately 600 to 1,600 feet in depth. Long Point dome, located in southern Fort Bend County, is the smallest of the actively mined domes, and covers approximately 750 acres with sulfur-bearing zones between 600 and 1,400 feet in depth.

Sulfur has been found in most west Texas counties beginning with the discovery of surface deposits in Culberson County in 1854. Since this initial discovery, sulfur has been found in nearly all formations of Paleozoic age in wells drilled for oil exploration and recovery. Formations of Permian age contain the most significant deposits of sulfur, and it is in these formations where the current Frasch production of sulfur occurs. The occurrence of sulfur in the Fort Stockton area of Pecos County is illustrated in Figure 6-3.

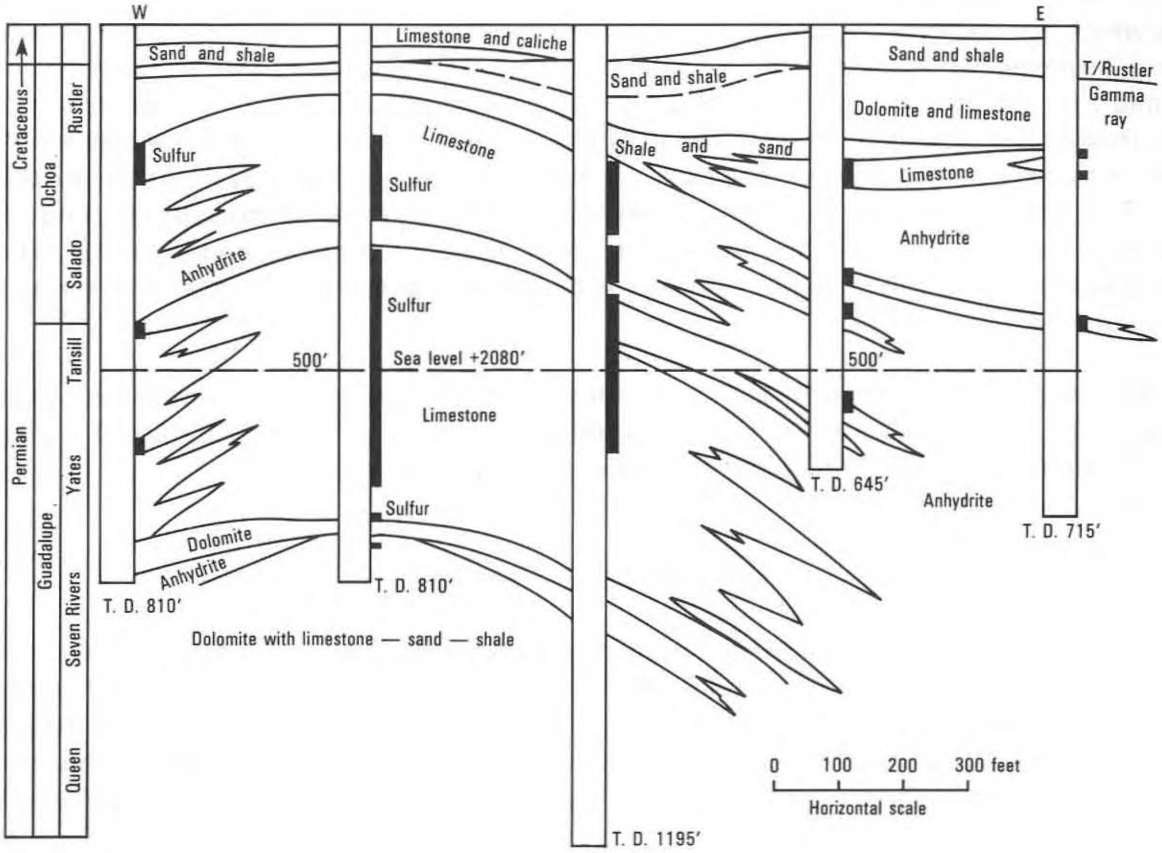

Figure 6-3.—Occurrence of Sulfur in the Fort Stockton Area (After Zimmerman and Thomas, 1969)

In Pecos County, Frasch sulfur is mined approximately 12 miles north of Fort Stockton from the Salado, Tansil, Yates, and Seven Rivers Formations of the Upper Guadalupe and Ochoa Series of the Permian System (Figure 6-3). Depths of these sulfur deposits range from 200 to 900 feet with sulfur occuring in porous limestone and dolomite which vary in thickness from 0 to 460 feet. The sulfur deposits are located on the crest of a regional anticline on the western edge of the Delaware basin and the south end of the Central basin platform.

In Culberson County, sulfur is found in the Rustler, Salado, and Castile formations of the Ochoa Series of the Permian System. Sulfur deposits are mined in the Rustler Springs district, located in northeastern Culberson County. Depths to the Rustler Springs sulfur deposits range from 300 to 2,000 feet below land surface.

Ground Water

Gulf Coast salt domes are generally intruded into formations comprising the Gulf Coast aquifer. There is generally very little or no fresh ground water in the immediate vicinity of salt domes due to communication between highly mineralized zones of the salt dome and cap rock, and the water-bearing formations.

Formations which contain sulfur deposits in west Texas generally yield saline water to oil wells which is unsuitable for human consumption, livestock watering, or irrigation. In Culberson County, however, the Rustler Formation may produce both sulfur and slightly saline water which is suitable for livestock and irrigation. Hydrogen sulfide, which is commonly present in the water of the Rustler Formation, is dissipated soon after the water is exposed to the atmosphere. Most water produced from the Rustler is used to repressure oil and gas fields by injection into Class II wells. The major aquifers in the Trans-Pecos region of west Texas, which sulfur mining operations may penetrate, include the Edwards-Trinity (Plateau) aquifer extending as far west as eastern Culberson County, and the alluvial and bolson deposits which are scattered throughout the region.

Major and minor aquifers of the State are described in this report in Chapter 2 titled "General Geology". Figures 2-6 and 2-7 show the areal extent of these aquifers; Tables 2-2 and 2-3 describe their stratigraphy, lithology, and water-bearing properties.

Construction Features

Frasch sulfur wells are constructed by using a rotary drilling rig to drill down to the top of the sulfur-bearing zone. Most mine operators take core samples of the ore zone and overlying strata using a core barrel in place of a drill bit to remove sections of strata intact. These cores are logged and used to construct models of the mine area stratigraphy to more accurately define the ore zone and overlying strata. From core samples, ore-grade determinations and host-rock lithologic studies may also be made.

After the well is drilled and cored, 8- to 10-inch diameter steel surface casing is lowered into the borehole. In west Texas where wellbores are generally drilled into hard consolidated rocks, cementing is necessary to fill the space between the casing wall and the downhole formations. However, Frasch sulfur wells along the Gulf Coast are installed with uncemented casings. In these coastal areas, the space between the borehole and casing is occluded soon after casing emplacement by clay strata which squeeze tightly against the casing. Inside the casing another string of pipe, 6 to 8 inches in diameter, is hung from the casing head through the sulfur-bearing zone. This hot-water string is perforated at two levels, one interval near the bottom of the pipe and another interval slightly higher. Through the upper set of perforations superheated water is injected into the sulfur formation, and molten sulfur enters the well through the lower perforations. Inside the hot-water string is the sulfur string of 3-inch diameter pipe, open at the end and extending nearly to the bottom of the well. A ring-shaped seal or collar is placed around the sulfur string and seals off the annular space between the hot-water and sulfur strings between the two sets of perforations. Through the sulfur string, molten sulfur is lifted back to the surface for processing and recovery. A sulfur well is completed by suspending a 1-inch diameter air line inside the 3-inch diameter pipe, to air lift molten sulfur to the surface. A typical sulfur well is illustrated in Figure 6-4.

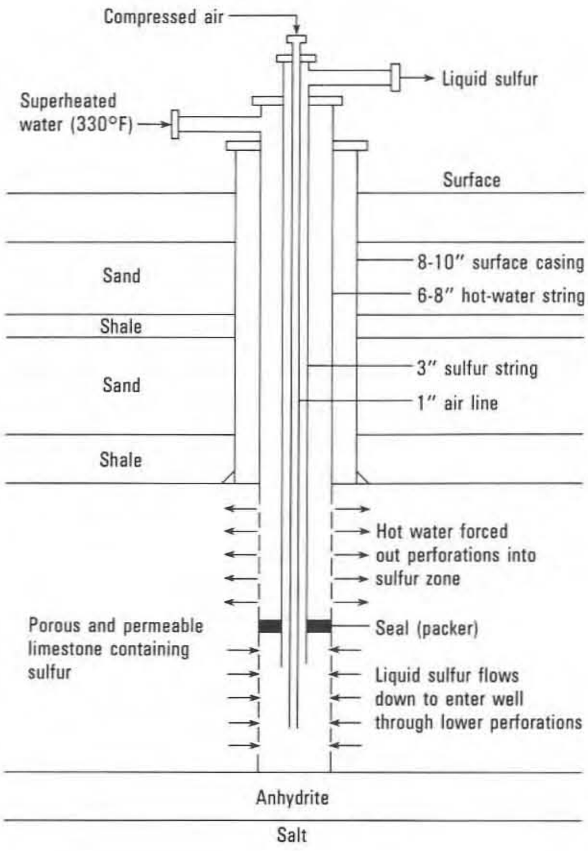

Figure 6-4.—Diagram of a Frasch Sulfur Well

Operating Practices

Production of sulfur by the Frasch process consists of three basic operations: (1) collecting and heating large quantities of water; (2) injecting heated water into sulfur-bearing formations to melt the sulfur; and (3) returning liquid sulfur to the surface for storage and shipment.

Elemental sulfur has an unusual property which is critical for the economic recovery of sulfur using the Frasch process. Sulfur melts between 235° and 248°F, and as temperatures are raised above the melting point, liquid sulfur increases in viscosity up to a temperature of 370°F. At temperatures above 370°, viscosity of liquid sulfur progressively decreases. Thus, temperature of the sulfur must be carefully regulated in a Frasch operation to remain at a temperature just slightly above the melting point. Any additional heating beyond the melting point of sulfur results in increased heating fuel costs and less profitable recovery of sulfur.

Operation of a sulfur well begins with injection of superheated water under a pressure of 125 to 200 pounds per square inch at a temperature of approximately 330°F This superheated water is forced down the annulus between the hot-water string and sulfur string and enters the sulfur-bearing formation through the upper set of perforations. Injected hot water flows through the permeable host rock mixing with and displacing the formation water. As the formation rock heats up, the sulfur melts, and because its density is greater than water, it flows down toward the bottom of the well. Liquid sulfur enters the lower perforations in the hot-water string and then moves up the sulfur string towards the surface. Compressed air released from the air line at the bottom of the sulfur string mixes with the liquid sulfur, reducing its weight by aeration, and airlifts it to the surface. Sulfur remains in a liquid state as it travels up the well because the hot water being injected downhole surrounds the sulfur string and keeps the liquid sulfur above its melting point.

When molten sulfur reaches the surface it travels through steam heated lines to collecting stations located between the well field and sulfur storage tanks. All surface tanks and pipelines are insulated and heated to maintain sulfur in a liquid form. Pipelines usually have a 1-inch diameter steam line inside them which prevents sulfur from solidifying and plugging the pipe. Storage tanks are lined with steam coils which maintain a temperature of approximately 270°F.

Virtually all Frasch sulfur produced today remains in liquid form from the time it is initially melted through the periods of storage and shipment. From the liquid storage tanks, sulfur is loaded into insulated railroad cars which are equipped with internal heating coils to re-melt the sulfur if it has solidified during shipment.

Surplus sulfur, or sulfur that is not shipped in liquid form, is stored in solid sulfur vats. The vats are formed by pouring sulfur in thin layers over an area enclosed by aluminum walls. When one layer cools, other layers are successively poured over it until a solid block of sulfur is formed. The walls are then removed and what remains is 99.5 percent pure sulfur which may be re-melted for shipping or sold as solid sulfur with no further processing. The sizes of solidifying vats vary; a normal-sized vat measures approximately 200 feet wide, 1,250 feet long, and 50 feet high.

The life of a sulfur well varies from only a few weeks to a year or more, depending upon factors such as: (1) local permeability of the ore zone, (2) actual amount of sulfur in the well's area of influence, (3) degree of confinement of injected water, and (4) amount of subsidence. In order for profitable amounts of sulfur to be produced, injected hot water must be able to travel out into the ore zone and heat up the host rock to melt the sulfur. If the host formation has low permeability, injected hot water is confined to a small area around the wellbore, decreasing efficiency of the operation. However, if channeling occurs, heated water may move out from a sulfur well too rapidly and in very restricted directions, also resulting in less efficient sulfur production. In order to confine the heated injection water within the sulfur formation, the overlying and underlying strata should seal off the mining zone to keep the heated water in contact with the sulfur-bearing rock.

In sulfur zones which have good permeability and good containment (isolation) from adjacent formations, the life of a well may still be shortened by subsidence. As sulfur is removed, the host formation is weakened, and overburden collapse occurs which often shears off well casing strings, thus ending production. Overburden collapse into the mined sulfur zone is manifested at the land surface by subsidence in surface elevation. At some mines, up to 50 feet of subsidence has occurred. Though often a cause of sulfur well failure, subsidence is desirable in Frasch mining because as depleted strata and overlying material collapse, the volume of porous formation in which hot water can circulate is kept low. The collapsed material is generally less permeable than the mined zone, and consequently helps to confine hot water to the objective zone for optimum sulfur recovery.

Another method used to help seal the sulfur zone is to inject mud, either through special mud wells or through the outer casing of the sulfur well. The injected mud fills cracks and voids left after sulfur has been removed, and thus decreases the amount of hot water needed to reach productive areas of the sulfur zone.

Some mines use bleed wells located around the periphery of the mining-well field to withdraw water from the injection zone and reduce the injection pressure required to circulate heated process water. This "cold" formation bleed water is either recycled through the plant for softening treatment and heating prior to injection, or is disposed of by way of Department-regulated discharge.

Whereas assurance of mechanical integrity is normally of great importance for safe injection well operation, there are several factors associated with Frasch sulfur wells which make mechanical integrity impractical and unnecessary: (1) the relatively short production life of a sulfur well imposed by the frequence of well disruption from subsidence collapse, (2) the nonhazardous nature of fluids which are injected and produced from the wells, and (3) the common absence of protectable water resources in areas of sulfur mining. Accordingly, Department Rules allow waiver of mechanical integrity testing requirements for sulfur wells installed in areas of high subsidence or substantial risk of collapse.

Sulfur wells should be properly plugged as soon as possible after they have been permanently taken out of service, to prevent movement of formation fluids out of the intended mining zone. In most cases, plugging of abandoned wells is a normal practice with mine operators.

Monitoring

Aquifers which overlie a Frasch sulfur mining formation may be of sufficient quality to require monitoring. However, because formations directly overlying sulfur production zones are susceptible to subsidence collapse, monitor wells cannot be completed within the area of subsidence without a high risk of crushed or sheared well pipes and casings. Consequently, aquifers with water of potentially usable quality should be monitored outside of the area of subsidence around Frasch sulfur mining sites, through existing water wells or new wells drilled specifically for monitoring at selected locations.

At the six mine sites in the State which were active in 1982, the production zone formation water contained dissolved solids concentrations much greater than 10,000 mg/l, ranging up to 50,000 mg/l. Because of the nature of sulfur deposition in salt domes or flat-bedded evaporite sequences, sulfur-bearing zones usually are underlain by impermeable zones, or aquicludes, of dense anhydrite and salt which would prevent the downward escape of mining waters from the sulfur zone. Therefore, monitoring of aquifers underlying mined sulfur deposits is in most cases unnecessary. Geohydrologic conditions at each mine site should be evaluated to determine the extent of monitoring necessary to insure containment of mining-zone fluids.

Nature and Volume of Injected Water

Frasch process water for injection is obtained from water wells or from surface water impoundments. Before the water is heated it must be softened to remove minerals which cause scaling in boilers and pipelines. Calcium, magnesium, and silica are the major minerals which must be removed from the process water before it enters boilers for heating. There are two basic methods of water softening used in the Frasch sulfur industry. One method is the hot process where lime and soda-ash are added in large vertical softening tanks, causing a chemical reaction which precipitates minerals out of the water. After softening, sand and gravel filters are used to clarify the water. Another water softening method is the cold process where water is first clarified and then passed through ion (zeolite) softeners at ambient temperatures (communication from Texasgulf, Inc.). After softening, the water is heated to approximately 330°F and piped under pressure to the sulfur well field. Table 6-2 presents a comparison of Frasch sulfur mine injection waters before and after water-softening treatment. Table 6-3 presents estimated water injection volumes at Frasch sulfur mines in Texas.

Contamination Potential

Although the sulfur mining industry has existed for more than 60 years in Texas, there has been no documented contamination of ground water from the Frasch sulfur process. It should be noted that sulfur deposits are usually found in conjunction with salt deposits and hydrocarbons which tend to make poor water quality in the area a natural condition. Figure 6-5 shows areas adjacent to salt domes in Fort Bend County with sands containing ground water with more than 1,000 mg/l in total dissolved solids concentrations.

Table 6-2.--Comparison of Injection Water Quality Before and After Treatment
(Constituent concentrations in mg/l.)

Mine	Water source	Total dissolved solids		Calcium		Magnesium		Silica		Sodium		Chloride		Sulfate	
		Before treatment	After treatment	Before treatment	After treatment	Before treatment	After treatment	Before treatment	After treatment	Before treatment	After treatment	Before treatment	After treatment	Before treatment	After treatment
Jefferson Lake Sulphur	Freshwater reservoir	452	386	61	1	12	1	19	12	93	127	105	146	7	9
Long Point Mine															
Farmland Industries, Inc.	Rustler well water	5,460	5,198	500	--	166	--	44	--	1,078	1,856	1,319	1,240	2,027	1,870
Fort Stockton Mine															
Duval Corporation	Toyah Lake	2,446	15,840	332	1	61	6	20	50	388	6,104	525	8,310	902	1,103
Culberson-Phillips Mine	Recycle water (bleed wells)	19,110		206		165		59		6,926		10,164		1,198	
Texasgulf, Inc.	Rustler well	4,916	2,928	647	16	137	39	26	9	760	1,039	994	685	2,205	1,042
Comanche Creek Mine	Choate Ranch wells	1,626		182		54		14		292		408		471	
Texasgulf, Inc.	Chicot or Evangeline well	568	--	95	3	16	.1	20.8	--	98	--	195	170	23	--
Newgulf Mine															

Table 6-3.—Estimated 1982 Frasch Sulfur Mine Water Injection Volumes (From company data, 1983.)

	Average number active wells	Mine water injection (thousands of gallons per day)	Injection per well (thousands of gallons per day)
Duval Corporation			
Culberson-Phillips	25	7,000	280
Texasgulf, Inc.			
Newgulf Mine	19	3,500	184
Comanche Creek Mine	12	2,000	166
Farmland Industries			
Fort Stockton Mine	8	1,000	125
Jefferson Lake Sulphur Company			
Long Point Mine	8	2,500	312.5

The activity with greatest potential for contamination of ground or surface water is the disposal of industrial wastewater from the Frasch sulfur mining sites. These wastewater streams are largely made up of bleed water withdrawn from mining zones and wastewater from mine water treatment facilities. Bleed water from the sulfur-bearing zone is usually high in concentrations of sodium, chloride, calcium, and sulfate (Table 6-4). Most water quality complaints involving sulfur mining which have been filed with the Department have been related to the discharge of industrial waste from storage reservoirs. These wastewater streams are currently regulated by the Department through industrial waste discharge permits issued pursuant to Chapter 26 of the Texas Water Code.

Table 6-4.—Chemical Analyses of Bleed Water From Frasch Sulfur-Mining Process (Constituent concentrations in mg/l.)

Constituent	Texasgulf, Inc. Newgulf Mine	Duval Corporation Culberson-Phillips Mine
Silica	112	59
Calcium	1,330	206
Magnesium	195	165
Sodium	19,300	6,926
Carbonate	0	0
Bicarbonate	138	1,343
Sulfate	2,930	1,198
Chloride	30,900	10,164
Flouride	1.6	8.6
Dissolved solids	54,800	19,110
pH	—	8.0

There are several aspects of the Frasch process which make it an environmentally protective mining method:

Table 6-3.—[illegible]

[illegible]

There [illegible]

[illegible]

There are [illegible] mining method [illegible]

1) Water that is injected is softened before heating and injection to remove scale-forming minerals which could clog boilers and pipelines. This generally produces an injected fluid which is of better quality than the native ground water in the production zone and overlying aquifers (Table 6-5).

Table 6-5.—Frasch Process Injection Water Quality* Versus Formation Water Quality**
(Constituent concentrations in mg/l.)

Parameter	Duval Corporation Culberson-Phillips Mine		Texasgulf, Inc. Comanche Creek Mine		Farmland Industries Fort Stockton Mine		Jefferson Lake Sulphur Long Point Mine		Texasgulf, Inc. Newgulf Mine	
	Injection water	Formation water (1)	Injection water	Formation water (2)	Injection water	Formation water (3)	Injection water	Formation water (4)	Injection water	Formation water (5)
Silica	50	25	9	26	—	44	12	19	—	20.8
Calcium	1.0	338	16	47	—	500	1	61	3.0	95
Magnesium	6	257	39	137	—	166	<1	12	.1	16
Sodium	6,104	9,232	1,039	760	1,856	1,078	127	93	—	98
Carbonate	259	0	159	0	712	0	37	0	33	0
Bicarbonate	506	1,672	132	155	866	464	1	317	19	278
Sulfate	1,103	1,221	1,042	2,205	1,870	2,027	9	7	—	23
Chloride	8,310	14,034	685	994	1,240	1,319	146	105	170	195
Fluoride	3.2	9.1	1.1	3.9	4.8	3.6	0.3	0.3	—	0.3
Nitrate	0.04	<0.04	<0.1	<1.0	0.22	1.0	0.09	<0.04	—	<0.01
pH	10.4	7.5	10.8	7.9	10.5	8.3	10.2	8.1	10.0	8.2
Total dissolved solids	15,840	25,454	2,928	4,916	5,198	5,450	386	452	—	568

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*The injection water quality values are from analyses of water samples taken at the water treatment plant.
**The formation water quality values are from analyses of samples taken from wells located at the mine site or from water reservoirs.
(1) Sample collected from bleed well completed in the Salado Formation, uneffected by mine operations.
(2) Sample collected from a well completed in the Rustler Formation located near the plant.
(3) Sample collected at the plant from a well completed in the Rustler Formation.
(4) Sample collected from holding reservoir at plant.
(5) Sample collected from City of Newgulf water supply well (607 ft depth).

2) Sulfur is insoluble in water, and thus does not dissolve in the injected water as in true solution-mining operations. Consequently, in Frasch sulfur mining, sulfur itself is not as much a potential contaminant as are salts and other mineral constituents making up the formation waters.

3) Liquid sulfur solidifies as soon as it is cooled to a temperature below 235°F, and therefore is self-sealing if a leak occurs in well casings, pipelines, or storage tanks.

4) Subsidence which occurs with the extraction of sulfur collapses overlying zones and helps to seal off the injection zone and confine formation fluids to the sulfur-bearing zone.

In contrast, the negative aspects of Frasch sulfur mining which may contribute to contamination of fresh water supplies are as follows:

1) Although water is treated to an overall improved quality before it is injected, the softening process generally increases the pH of the water and increases some dissolved

mineral constituents. As concentrations of silica, calcium, and magnesium are reduced, concentrations of sodium, chloride, carbonate, and bicarbonate are generally increased. The total dissolved solids concentration, however, is usually lower after treatment (Table 6-5).

2) Hot water injected to melt sulfur also dissolves some minerals which make up the host rock. This may result in an increase of calcium, sodium, sulfate, and chloride concentrations in the formation water. Sulfur-bearing rock formations, as discussed previously, are composed chiefly of calcite ($CaCO_3$), gypsum ($CaSO_4 \cdot 2H_2O$), anhydrite ($CaSO_4$), and the associated salt (NaCl) of salt domes and bedded salt deposits. Table 6-4 shows water quality analyses of bleed water from Duval Corporation's Rustler Hills Mine and Texas Gulf's New Gulf Mine on the Boling dome. These samples are representative of the quality of water in sulfur-bearing formations.

3) Injected hot water heats up the sulfur-bearing formation, and this heat remains in the formation due to the poor heat conducting properties of the host rock. Formation water temperatures of greater than 120°F have been reported at mines inactive for more than 10 years. The rate of cooling of heated mine water and extent of movement out of the mining zone have not been accurately determined.

Another aspect of Frasch sulfur mining which might be considered detrimental to the environment, although not necessarily detrimental to quality of ground water, is the subsidence which normally occurs with the mining process. At the surface of a Frasch sulfur mine, subsidence appears as a surface depression of several acres in area and up to 50 feet or more below the original land surface. Subsidence of the land surface is generally a slow, gradual process rather than a catastrophic-type movement that is frequently associated with natural sink-hole collapse. Gradual subsidence may continue to occur for years after mining in an area has ceased. It is possible, particularly in the Trans-Pecos region, for large cracks to occasionally appear at the surface when catastrophic collapse does occur. Steam from heated sulfur formations has been observed at the surface escaping through these cracks.

Legal and Jurisdictional Considerations

Frasch sulfur mining wells are presently regulated under the Department's Underground Injection Control program pursuant to the 1981 amendments to the Injection Well Act. Prior to the 1981 amendments, these injection activities were not regulated by the State. The amendments provide that the Department may not impose any requirements more stringent than those promulgated by the U.S. Environmental Protection Agency concerning Frasch mining activities unless the Department determines that more stringent regulations are necessary to protect human health or the environment.

Frasch sulfur mining wells are classified as Class III injection wells. Department Rules require that Class III wells be regulated by permit. The owner or operator of a preexisting facility must have submitted a permit application to the Department not later than January 6, 1984.

Concluding Statement

After more than 60 years of Frasch sulfur mining in Texas, contamination of ground water by this mining process has never been documented in the State. The greatest potential for contamination to surface or ground water which may be associated with the Frasch process appears to be from discharge of saline industrial wastewaters from the mine sites. These wastewater streams are currently regulated by the Department through industrial waste discharge permits. The Department will regulate Frasch sulfur mining wells by injection well permits. Regulatory recommendations for Frasch sulfur wells include monitoring of freshwater wells located outside the area of subsidence to detect any degradation of water quality, and properly plugging abandoned sulfur wells upon completion of mining to prevent movement of production zone fluids into adjacent or overlying aquifers or to surface waters.

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CHAPTER 7

SODIUM SULFATE SOLUTION MINING WELLS

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SODIUM SULFATE SOLUTION MINING WELLS

Table of Contents

SODIUM SULFATE SOLUTION MINING WELLS

Introduction

The only known injection wells which are operated in Texas for solution mining of sodium sulfate are located in eastern Terry County at Brownfield Lakes and Mound Lake (Figure 7-1). The sources of hydrous sodium sulfate are the mineral mirabilite ($Na_2SO_4.10H_2O$) and associated brine ground waters found in "crystal beds" in shallow subsurface deposits beneath the saline playa lakes.

Solution mining of hydrous sodium sulfate was initiated in the late 1930's at Brownfield Lakes in eastern Terry County using steam as injection fluid. Use of this method of solution mining was discontinued in the early 1940's because the operations were unprofitable.

About 1957, operations were reestablished at Brownfield Lakes using highly concentrated sodium chloride brines as the injection fluid to more effectively solution mine the hydrous sodium sulfate deposits. Use of high sodium chloride ($NaCl$) brines as the injection fluid increases the solubility of hydrous sodium sulfate ($Na_2SO_4.10H_2O$), and therefore, enhances recovery of anhydrous sodium sulfate (Na_2SO_4) from subsurface deposits. Feed brine pumped from production wells is piped to the processing plant where it is chilled to precipitate hydrous sodium sulfate. Within the processing plant, bound water is removed by a drying process to form anhydrous sodium sulfate or salt cake, which is the final product for marketing.

At the Brownfield Lakes operation, the source of high sodium chloride brines for injection is the effluent or "mother liquor" from the processing plant. Excess "mother liquor" from the processing plant is disposed of in saline playa lakes at the Brownfield Lakes operation. Supplies of plant feed brines and "mother liquor" are supplemented with high sodium chloride brines produced (1) by circulation of brine and dissolution of sodium chloride by two injection wells completed in deep Permian salt beds, (2) from Rich Lake, a saline playa nearby, and (3) from production wells completed in shallow deposits beneath Mound Lake which is another saline playa nearby. Brine produced from the Mound Lake deposits is not only high in concentration of sodium chloride but also has a high productive concentration of hydrous sodium sulfate. Plant feed brine waters are also supplemented with small amounts of slightly saline water supplied by a nearby well field completed in the High Plains aquifer.

Since about 1980, approximately 20 to 40 injection wells completed at depths from 50 to 60 feet have been used at the Brownfield Lakes mining operation, and two injection wells each completed at a depth of 100 feet have been used at the Mound Lake operation. At Brownfield Lakes, two types of injection wells have been used. One type is a gravity flood well and the other type is a pressure injection well. At Moun~~t~~d Lake, the two injection wells are gravity flood wells. In the operation of gravity flood wells, the water level is maintained at or just below land surface. Operation pressures of 13 to 30 pounds per square inch have been used in the pressure injection wells at the Brownfield Lakes operation.

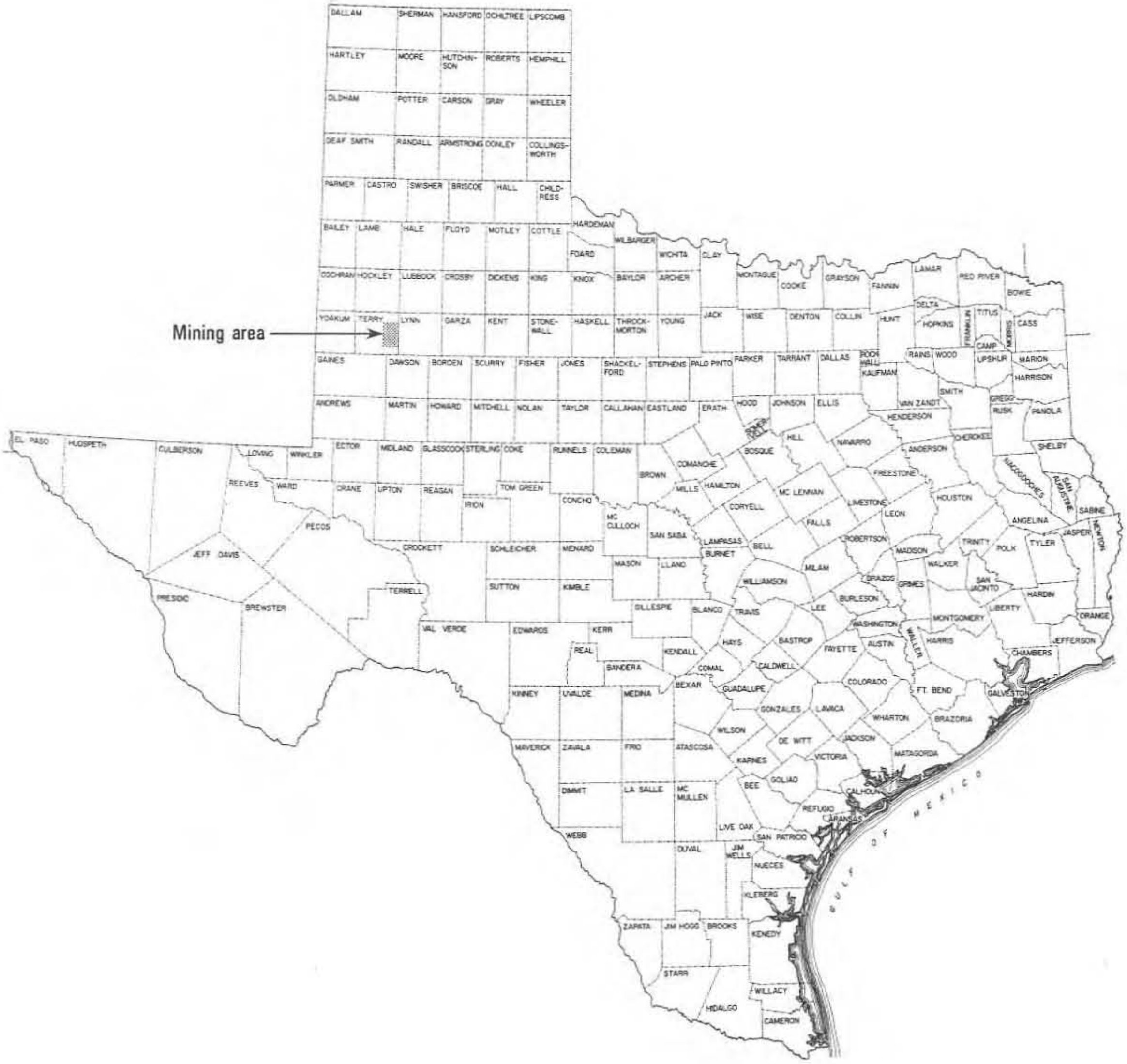

Figure 7-1.—Location of Sodium Sulfate Solution Mining Area Where Injection Wells Are Used

Moderately saline water produced from wells completed in the Edwards-Trinity (High Plains) aquifer is used as injection fluid at Mound Lake. As many as 20 production wells at Mound Lake pump brine which is piped to the Brownfield Lakes operation. The brine content of this water is such that it provides significant amounts of hydrous sodium sulfate for production of salt cake in the Brownfield Lakes processing plant, and significant amounts of sodium chloride to supplement sodium chloride requirements of the "mother liquor" used as injection fluid in injection wells at the Brownfield Lakes operation.

At the Brownfield Lakes operation, use of gravity flood injection wells has been discontinued. In the future, all injection wells to be used in the solution mining operation will be pressure injection wells. In May 1983, 24 pressure injection wells were being used on an operating and standby basis. Pressure injection wells are easier to monitor, do not have pathways for leakage of brines, and can inject more water per well than the gravity flood type of injection well. Since the original, natural subsurface brine has been essentially removed from the Brownfield Lakes mirabilite deposits, pressure injection wells can force sufficient amounts of high sodium chloride brine into the mirabilite deposits to efficiently solution mine profitable amounts of hydrous sodium sulfate.

Approximately 20 production wells are used at the Brownfield Lakes operation to pump brine from the mirabilite deposits which received and transmitted brine from the injection wells. During its passage through the mirabilite deposits, brine becomes highly saturated with hydrous sodium sulfate. The June 1981 locations of the injection well and production well systems at the Brownfield Lakes operation is shown in Figure 7-2.

The total amount of reserves of mirabilite at Brownfield Lakes and Mound Lake is unknown. Approximately 200 tons per day of anhydrous sodium sulfate is being produced by the processing plant at the Brownfield Lakes operation. About half of this amount comes from feed brines from the Brownfield Lakes mining operation and about half from feed brines from the Mound Lake mining operation. As of 1981, a 10-year supply of anhydrous sodium sulfate is believed to be available from mirabilite deposits at Brownfield Lakes.

Anhydrous sodium sulfate produced at the processing plant as the result of solution mining with injection wells at Brownfield Lakes and Mound Lake is shipped by rail from Brownfield, Texas, to many users throughout the United States. Anhydrous sodium sulfate or salt cake (Na_2SO_4) is used in manufacture of detergents, paper, glass, textiles, dyes, paint, explosives, and fertilizers. Its major uses are for manufacture of detergents, paper, and glass. Sodium sulfate is also mined at Cedar Lake in Gaines County, Texas, where from 15 to 20 production wells are used without use of injection wells. Very large reserves of sodium sulfate are mined in northern Mexico and southern Canada.

Geohydrology

Stratigraphy

The most important geologic units within the mining area shown on Figure 7-1 are, from oldest to youngest, the Duck Creek Formation of Cretaceous age, the Ogallala Formation of Tertiary age, and the Tahoka Formation of Quaternary age (Table 2-1). Sodium sulfate deposits occur mainly in the lower portion of the Tahoka Formation and are found in a "crystal bed" composed of gray sandy clay with very abundant crystals of mirabilite and some crystals of gypsum. In the Brownfield Lakes area, the Tahoka Formation, which is composed of lake deposits, is underlain by dark gray marine clay which probably belongs to the Duck Creek Formation and contains gypsum, glauberite, and polyhalite crystals. Beneath the Brownfield Lakes, the dark gray clay in the very upper part of the Duck Creek Formation may contain high concentrations of mirabilite crystals which may be considered part of the "crystal bed" being mined by solution mining operations. The Tahoka Formation is flanked by the Ogallala Formation composed of nonmarine clay, sand, and gravel which in most of the area overlies the Duck Creek Formation. The west-east geohydrologic cross-section A-B shown in Figure 7-3 illustrates stratigraphic relationships of (1) the three important geologic units, (2) an approximate delineation of the "crystal bed" of mirabilite, and (3) the June 1981 water-table and ground-water depression caused by the Brownfield Lakes solution mining operation. Similar relationships exist at the Mound Lake mining operation north of Brownfield Lakes.

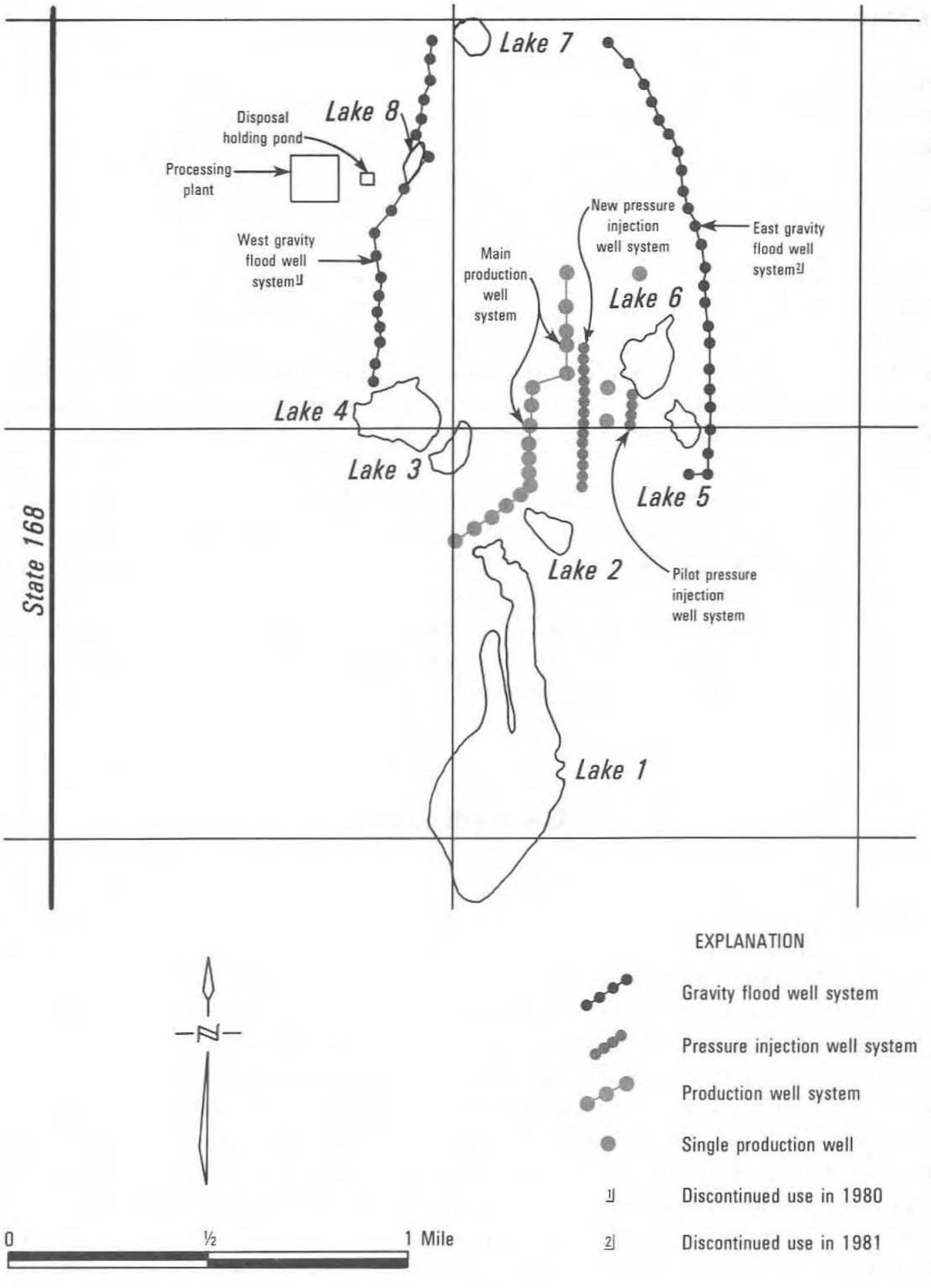

Figure 7-2
Sodium Sulfate Solution Mining Operation at Brownfield Lakes, Eastern Terry County, Texas, June 1981

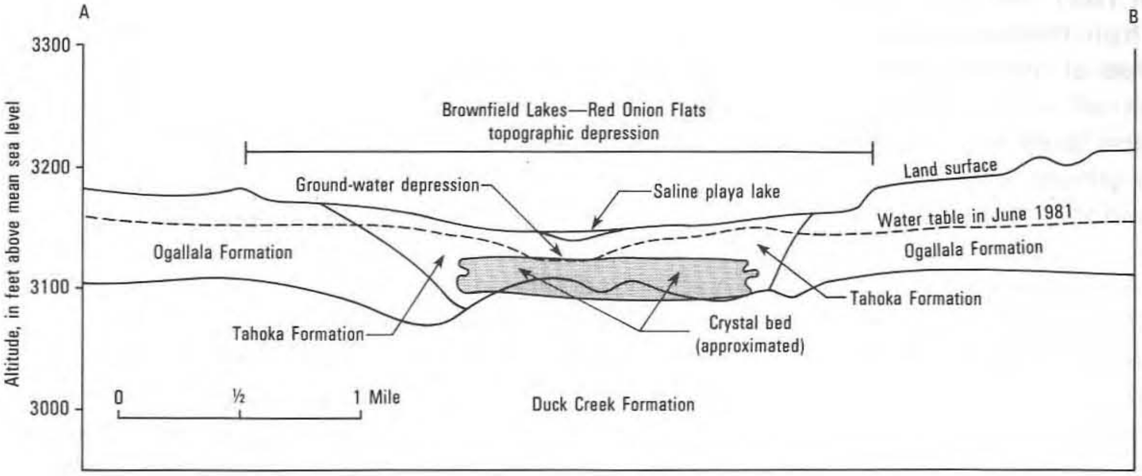

Figure 7-3.—Geohydrologic Cross-Section A-B Through the Brownfield Lakes Sodium Sulfate Solution Mining Operation (View Looking North)

Structure and Geologic History

The sodium sulfate solution mining area at Brownfield Lakes and Mound Lake occurs in the northeastern portion of the Midland basin which is a structural trough trending southeast from southern Hockley County through Terry County to eastern Reagan County (Figure 2-2). During Pennsylvanian time (Table 2-1), thick sequences of shale and limestone were deposited in a sea which covered much of west Texas. This deposition was followed by extensive regional downwarping or subsidence and deposition of a great thickness of Permian age (Table 2-1) sand, shale, limestone, anhydrite and salt to form the Midland basin. Regional subsidence continued during Triassic time (Table 2-1) when sequences of nonmarine shale, sand, and gravel were deposited in the basin. Deposition of Triassic deposits was followed by a period of erosion. During Cretaceous time (Table 2-1), the sea advanced from the south and sand, limestone, silt, and clay were deposited. During late Cretaceous time, the sea receded to the south. During Tertiary and Quarternary time (Table 2-1), nonmarine gravel, sand, and clay of the Ogallala Formation and lake sediments (mostly clay and sandy clay) of the Tahoka Formation were deposited on the Cretaceous clays. Most of the mirabilite deposits and associated brines in the Tahoka Formation and Duck Creek Formation at Brownfield Lakes were probably formed during Pleistocene time (Table 2-1) by evaporation of mineral laden runoff waters and decomposition of algal material which occurred simultaneously in the Brownfield Lakes-Red Onion Flats topographic depression (Figure 7-3) with deposition of the lake deposits of the Tahoka Formation.

Aquifers

The most important water-bearing unit within the mining area is the High Plains aquifer (Figure 2-3 and Table 2-2) which is under water-table (unconfined) conditions and is composed of hydrologically connected saturated rocks of the Ogallala, Tahoka, and upper Duck Creek Formations (Figure 7-3). During a dry year within the western portion of the mining area, approximately 14,000 to 15,000 acre-feet of fresh to slightly saline ground water has been withdrawn from the aquifer for irrigation purposes. Fresh to slightly saline ground water is also used from the aquifer for livestock watering and rural domestic purposes in the western portion of the mining area.

In 1981, solution mining operations at Brownfield Lakes withdrew about 234 acre-feet of brine from the saline water body within the High Plains aquifer. During the same year, about 194 acre-feet of "mother liquor" was injected at the Brownfield Lakes operation. The difference in the amount of brines produced and injected (about 40 acre-feet) is made up from leakage of brines from the lakes within the solution mining area at Brownfield Lakes, and from the underflow of saline ground water due to the hydraulic gradient of the essentially steady-state ground-water depression (Figure 7-3) created and maintained by solution mining operations.

The amount of brines withdrawn at Mound Lake in 1981 was about 234 acre-feet from the High Plains aquifer. The moderately saline injection waters used at Mound Lake are from wells completed in the Edwards-Trinity (High Plains) aquifer (Figure 2-4 and Table 2-3). The amount of ground water pumped from the aquifer for use in the two Mound Lake injection wells is about 12 to 20 gallons per minute during the colder months of the year. The Edwards-Trinity (High Plains) aquifer in the mining area is under artesian conditions, and is hydrologically separated from the High Plains aquifer by relatively thick sequences of confining Cretaceous clays and limestones with very low permeability.

At both Brownfield Lakes and Mound Lake, the brine ground-water body in the Tahoka and Duck Creek Formations is not overlain by an underground source of drinking water. The ground waters found beneath the mining operation areas in the Tahoka Duck Creek Formations is extremely mineralized, having total dissolved solids in excess of 300,000 mg/l. Adjacent to the mining operation areas, underground sources of drinking water are found in the High Plains aquifer (Ogallala Formation) at significant lateral distances from the mining operation areas, and in the Edwards-Trinity (High Plains) aquifer (Antlers Formation) which is separated from the brine ground-water body and the Ogallala Formation by a thick sequence of Cretaceous clays and limestones, having very low permeability.

Construction Features

A typical pressure injection well for solution mining of sodium sulfate at the Brownfield Lakes operation is about 50 feet in depth. First a 15-inch borehole is drilled to a depth of about 19 feet and 14-inch OD steel casing is set to about 20 feet. The 14-inch casing has to be forced or driven to the casing point depth at 20 feet, because a bed of "quicksand" is usually encountered in the upper part of the Tahoka Formation, and also, the 15-inch borehole is purposely drilled to a depth (19 feet) less than the casing point depth (20 feet). A 12-inch borehole is then drilled to about 50 feet through the "crystal bed" of mirabilite. A string of 2½-inch blank steel tubing with the bottom 25 feet torch slotted is set to the bottom of the 12-inch borehole. A gravel pack of sufficient size gravel is then placed in the annulus between the slotted tubing and the 12-inch borehole. A bentonite plug of about 3 feet in length is then placed on top of the gravel pack. This plug is packed or tamped into position and is of final sufficient thickness so that it extends up into the 14-inch OD casing. If there has been a washout of formation material just below the bottom of the 14-inch OD casing during drilling of the 12-inch borehole, packing or tamping of the bentonite as it is placed in the well will cause it to fill the washout void and any voids in the annulus between the 14-inch OD casing and the 15-inch borehole. The bentonite plug serves as a seal to prevent injected brines from leaking upward to the upper Tahoka Formation and the land surface. A cement plug is then set from the top of the bentonite plug inside the 14-inch OD casing to the land surface. The base material used for this plug which is installed in the annulus between the 14-inch casing and the blank 2½-inch tubing is a Class 4, sulfate resistant cement. At the land surface, the 2½-inch injection tubing of each injection well is equipped with a "Christmas tree" which has a pressure meter, a vent to the atmosphere, a dump valve, and a throttle valve. A diagram of a typical pressure injection well completed at the Brownfield Lake operation is shown in Figure 7-4.

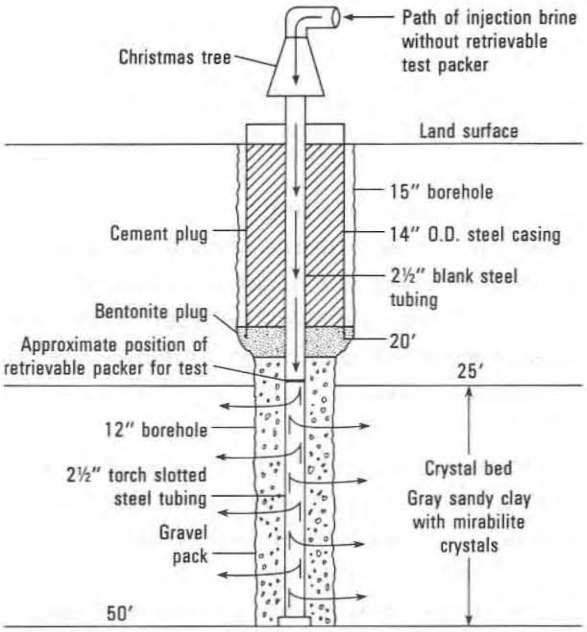

Figure 7-4.—Diagram of Pressure Injection Well for Sodium Sulfate Solution Mining Operations

Mechanical Integrity

Mechanical integrity of each existing injection well is very important to prevent leakage of highly concentrated, mineral laden brines which can destroy crops and natural vegetation and seriously harm wildlife habitat on the land surface in the areas of solution mining operations. The older injection wells were generally constructed without the current plug shown in Figure 7-4, creating a potential avenue for leakage to migrate to the surface. Subsurface leakage of injection fluid into the upper Tahoka Formation poses less hazard because the formation contains natural brines, and the ground-water depression caused by brine withdrawals from the brine water body prevents migration of brines into the fresh ground-water body of the High Plains aquifer. However, since sodium sulfate solution mining is a low volume brine use operation, leakage from the injection well system is immediately stopped when detected because any leakage seriously decreases the efficiency of the solution mining operations, and therefore, the productivity of salt cake for marketing.

The primary means of preventing leakage from a new injection well is to conduct an initial pressure test of the upper 25-foot section of blank 2½-inch steel tubing. This can be accomplished by setting a retrievable packer inside the 2½-inch blank steel tubing at a depth below the base of the bentonite plug and just above the lower torch slotted section of the tubing (Figure 7-4). Water should then be placed under pressure inside the 2½-inch blank steel tubing. The initial test should be conducted for a sufficient duration at pressures approximately two times greater than the projected initial operating pressure. If these pressures cannot be maintained over a specified time period, then the injection well should be reworked and retested. Any well not passing pressure tests should be plugged and abandoned. Mechanical integrity of operating and abandoned injection wells can also be assured by requiring the mining operator to keep accurate well construction and abandonment records on each well, particularly on the volumes, composition, method of installation, and position of cement and bentonite plugging material. To date no problems have been experienced by the operator in use of bentonite as plugging material in pressure injection wells (Figure 7-4). Under certain conditions bentonite has been found to not hydrate properly in some highly mineralized waters. Sodium sulfate solution mining injection wells must be plugged and abandoned in a manner approved by the Department.

Operating Practices

As indicated on Figure 7-2, sodium sulfate solution mining wells are operated on a system basis. At the Brownfield Lakes operation from about 1957 to 1980, the injection wells were operated in two systems, a west gravity flood well system and an east gravity flood well system. The main production well system located essentially midway between the two gravity flood injection well systems pumped brine from the subsurface deposits for delivery to the processing plant. The solution mining operator discontinued use of the west gravity flood well system in 1980. Use of the east gravity flood well system was discontinued in 1981 (Figure 7-2).

Since 1957, the original, natural hydrous sodium sulfate brines have been removed from the subsurface deposits at Brownfield Lakes. The only remaining in-place source of hydrous sodium sulfate is the "crystal bed" of mirabilite. To effectively mine these in-place mirabilite deposits, the solution mining operator has decided that pressure injection well systems be used. Pressure injection wells are a much safer means of injecting brines, are easier to monitor, and are capable of injecting more brine per well than the gravity flood injection wells.

When the mirabilite deposits in the area of influence of an injection well system are sufficiently mined by dissolution, a new pressure injection well system will be established in another strategic location to remove additional hydrous sodium sulfate from the deposits. Under these conditions, most of the abandoned pressure injection wells will be plugged, while a few will be retained as water-level observation wells. In the future, it also may be necessary to strategically relocate the production well system relative to relocated pressure injection wells in order to effectively solution mine the mirabilite deposits.

Since pressure injection wells have been used at the Brownfield Lakes operation, operating pressures have ranged about 13 to 30 pounds per square inch. It has been the experience of the operator at Brownfield Lakes that the initial operating pressures of a newly established pressure injection well system are high, usually from 25 to 30 pounds per square inch. As brine injection continues, operating pressures have gradually decreased and in May 1983 attained a level as low as 13 pounds per square inch. Reductions in operating pressures with time can be expected due to dissolution of the mirabilite deposits which causes an increase in the permeability of the host rock (clay) and opens more pathways for injected brines to eventually reach the area of influence of the production wells.

With time, the mirabilite deposits and associated brines at Mound Lake probably will be mined in essentially the same manner. Also, the mirabilite deposits beneath the Rich Lake playa probably will be exploited in the same manner, when the supply of hydrous sodium sulfate approaches depletion in the Brownfield Lakes mirabilite deposits.

Solution mining operations at Brownfield Lakes and Mound Lake within the mining area (Figure 7-1) vary from day to day, month to month, and season to season within any given year. This is due to comparable variations in (1) market demand for sodium sulfate, (2) depletion of the sodium sulfate deposits, (3) air and water temperatures, and (4) ground-water quality and quantity conditions of the aquifers in and adjacent to mining areas.

Nature and Volume of Injected Waters

The nature or chemical characteristics of the various waters associated with solution mining and processing of sodium sulfate at the Brownfield Lakes and Mound Lake operations are given in

Table 7-1. Representative chemical analyses of injection waters used are given in Table 7-1 as sample numbers 1, 2, and 3 for the Brownfield Lakes operation and sample number 10 for the Mound Lake operation.

In June 1981, approximately 70 to 165 gallons per minute of plant effluent or "mother liquor" was being injected into the Brownfield Lakes mirabilite deposits by gravity flood and pressure injection wells. The heads (water levels) in the east gravity flood injection well system (Figure 7-2) were being maintained at or just below land surface, and the pressures used to operate the new pressure injection well system (Figure 7-2) were about 20 to 25 pounds per square inch. The east gravity flood injection well system was injecting about 30 to 60 gallons per minute, while the new pressure injection wells were injecting about 40 to 105 gallons per minute. In the Fall of 1981, the use of the east gravity flood injection well system had been completely discontinued. From January to mid-May 1983, the pressure injection well system was operated at pressures of about 13 to 28 pounds per square inch, and was injecting about 85 to 120 gallons per minute.

From January to mid-May 1983, approximately 12 to 20 gallons per minute of moderately saline water was injected into mirabilite deposits at the Mound Lake operation by two gravity flood injection wells. Injected water was being supplied by three wells completed in the Edwards-Trinity (High Plains) aquifer.

Potential Problems

Destruction of vegetation and wildlife habitat is a potential problem related to solution mining operations with injection wells at Brownfield Lakes and Mound Lake. Brine and moderately saline waters used for injection fluids should be kept in adequately monitored, confined distribution and injection systems to avoid leakage or spills. All potentially operative gravity flood injection wells at Brownfield Lakes and Mound Lake should have a cement plug of about 2 feet in thickness installed on top of the gravel pack at or near the land surface in the annulus between the injection tubing and surface casing. All gravity flood and pressure injection wells that do not have any potential use should be properly plugged and abandoned in a manner acceptable to the Department. Continuous use of high pressures greater than normal maximum operating pressure (30 psi has been used in the past) should be avoided in the pressure injection well system.

Leakage of brine from the pipelines from Rich and Mound Lakes to the Brownfield Lakes processing plant is a potential problem which threatens fresh to slightly saline ground water in the High Plains aquifer within the mining area. Pressures used in this pipeline are monitored closely by the operator in order to detect brine leaks. Every effort should be made in the future to continue pipeline pressure monitoring, because only a very small amount of brine leakage from this pipeline could cause serious and extensive damage to the fresh to slightly saline ground-water resources of the aquifer.

An unknown but significant amount of very local land-surface subsidence has occurred at Brownfield Lakes due to compaction of clays caused by mining of sodium sulfate. At any given time, this subsidence is probably restricted to the area of influence of the production well system. Since this subsidence is very localized within the solution mining area, subsidence probably will not cause any structural damage at the processing plant. However, it possibly could cause apparent upward movement of abandoned properly plugged injection wells which may be located within the area of influence of the production well system. Therefore, permanent markers should

Table 7-1.--Chemical Analyses of Injection, Production, and Effluent Waters Associated with the Solution Mining and Processing of Sodium Sulfate in the Mining Area of Eastern Terry County, Texas.
(Analyses are given in milligrams per liter or parts per million except diluted conductance and pH).

Identification of water sample	Date of collection	Silica (SiO_2)	Strontium (Sr)	Calcium (Ca)	Magnesium (Mg)	Sodium* (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Diluted conductance (Micromhos at 25°C.)	pH
1/ 1. Brownfield Lakes processing plant effluent or "mother liquor." Used as the injection brine in the Brownfield Lakes injection wells. Excess amounts are disposed of in Lakes 3, 4, 5, and 6 at the Brownfield Lakes operation.	Apr. 13, 1977	13	--	179	26,400	29,400	8,000	730	28,200	109,100	1.4	3.4	--	201,656	457,856	7.1
2/ 2. Same as above in 1.	Oct. 25, 1979	--	29.5	448	36,649	52,000	9,100	866	61,297	147,503	.8	.7	61	307,872	--	7.2
3/ 3. Same as above in 1.	June 11, 1981	11	--	298	21,860	41,395	12,152	399	27,283	116,346	1.2	4.8	--	219,547	470,400	7.1
1/ 4. Slightly saline ground water from well field in High Plains aquifer near Brownfield Lakes. A very small supplemental water supply for make up of feed water to Brownfield Lakes processing plant. Not used as drinking water.	Apr. 13, 1977	62	--	106	95	214	15	354	494	221	4.2	40	--	1,425	2,528	8.0
3/ 5. Same as above in 4.	June 11, 1981	62	--	120	82	223	17	365	465	234	4.3	50.5	--	1,437	2,609	8.2
3/ 6. Composite sample of feed brines to Brownfield Lakes processing plant. Represents combined supply from Mound Lake and Brownfield Lakes production wells.	June 11, 1981	5	--	290	19,158	84,672	9,878	306	119,952	107,251	1.2	.1	--	341,358	667,968	7.2
1/ 7. Brine supply from Brownfield Lakes production wells for feed brines to Brownfield Lakes processing plant.	Apr. 13, 1977	4	--	252	23,700	63,700	8,620	455	126,100	82,300	1.3	.4	--	304,901	624,064	7.0
4/ 8. Same as above in 7.	Dec. 4, 1978	--	6.4	216	18,800	66,667	13,600	488	121,473	79,500	1.9	0	34	300,836	--	--
3/ 9. Same as above in 7.	June 11, 1981	18	5.7	108	29,145	67,424	8,938	431	144,883	92,198	1.3	.1	--	343,362	684,208	7.0
2/ 10. Moderately saline ground water from supply well in Edwards-Trinity (High Plains) aquifer at Mound Lake. Supply used for injection water in gravity flood injection wells at Mound Lake operation. Not used as drinking water.	Apr. 7, 1981	86	13.7	384	317	1,032	20	262	2,559	1,149	2.1	60.7	2.1	5,676	--	7.2
3/ 11. Brine supply from Mound Lake production wells for feed brine to Brownfield Lakes processing plant.	June 11, 1981	4	2.1	256	12,200	96,197	10,597	150	107,878	108,819	.6	0	--	336,658	663,264	7.2
2/ 12. Same as above in 11.	June 15, 1981	17	3.0	64	11,727	90,000	9,500	170	101,147	109,918	.2	22.8	1.1	322,538	--	7.0
2/ 13. Intermittent brine supply from surface water in Rich Lake.	Sept. 27, 1979	--	41	145	23,230	74,000	7,080	1,390	148,634	69,497	2.0	1.0	2.9	323,753	--	7.7
1/ 14. Composite sample of water from Rich Lake and ground water from well field at Rich Lake.	Apr. 13, 1977	6	--	510	15,400	40,400	4,800	1,800	86,900	46,400	--	.4	--	195,306	392,582	8.0
1/ 15. Brine supply from water circulated through deep Permian salt beds by injection well no. 2 at Brownfield Lakes processing plant.	Apr. 13, 1977	6	--	228	23,800	77,700	8,500	590	64,600	146,100	1.1	.4	--	321,225	680,512	6.9
3/ 16. Surface of lakes 3 and 4 (connected) used for disposal of excess "mother liquor" from Brownfield Lakes processing plant.	June 10 [illegible]	2	--	616	28,607	39,514	10,534	533	42,336	124,499	1.1	1.1	--	246,372	523,712	7.9
3/ 17. Surface of lake 5 used for disposal of excess "mother liquor" from Brownfield Lakes processing plant.	June 10, 1981	2	--	[illegible]	48,798	31,997	19,051	1,736	84,672	147,706	.9	.7	--	333,721	715,008	7.3
3/ 18. Surface of lake 6 used for disposal of excess "mother liquor" from Brownfield Lakes processing plant.	June 10, 1981	1	--	[illegible]	43,916	50,803	15,464	969	62,093	174,048	.7	.2	--	346,825	752,640	7.1

1/ Analyses given in parts per million. Analyzed by Texas Department of Health Laboratory, Austin, Texas.
2/ Analyses given in milligrams per liter. Analyzed by Southwestern Laboratory, Midland, Texas.
3/ Analyses given in milligrams per liter. Analyzed by Texas Department of Health Laboratory, Austin, Texas.
4/ Analyses given in milligrams per liter. Analyzed by laboratory of operator of solution mining operation.

be located at abandoned injection well sites, so that the sites can be visually inspected periodically. If evidence of protrusion of an abandoned well site is observed, it may be necessary, especially in cultivated areas, to reexcavate the site and reestablish the top of the cement plug at a depth acceptable to the Department. Also, all brine delivery pipelines within and adjacent to potential areas of subsidence may have to be placed on the land surface instead of being buried. If differential subsidence occurs, it can break buried pipelines and cause brine spills, thus contaminating the land surface and shallow subsurface.

Environmental Protective Measures

Since the fresh to slightly saline ground-water users (irrigators and others) and the solution mining operator within the mining area (Figure 7-1) withdraw ground water from a common aquifer, it is essential that a meaningful network of water-level and water-quality observation wells be established to periodically monitor geohydrologic conditions of the High Plains aquifer. A recent detailed Department investigation of the area (Bluntzer, 1982) recommended that 14 additional water-level observation wells and six water-quality monitoring wells be used by the Department to periodically monitor geohydrologic conditions in and near the Brownfield Lakes-Red Onion Flats topographic depression (Figure 7-3). Similar monitoring programs should be established in and near the topographic depressions associated with Rich Lake and Mound Lake. The purpose of water-level observation well networks is to detect changes in the hydraulic gradients associated with the shape and extent of the ground-water depressions within the mining area. Data collected on the changes of the ground-water depressions can perhaps be used to explain any changes in ground-water quality indicated by the ground-water quality monitoring wells.

The recent Department investigation (Bluntzer, 1982) indicated that historically saline-water encroachment has occurred from the brine water body of the aquifer into the fresh to slightly saline water body due to relatively heavy irrigation pumpage nearby, and that encroachment probably would have been more serious in extent and degree if the solution mining operation and its associated ground-water depression had not existed at Brownfield Lakes. Also, in certain respects the mine operator's brine withdrawals and the irrigator's fresh to slightly saline ground-water withdrawals are beneficial to each other. The irrigators benefit from the mine operator's ground-water depression, because during the nonirrigation season it induces inflow of fresh ground water to the irrigation area, and during the irrigation season it helps prevent more serious saline-water encroachment. Irrigation pumpage benefits the mine operator, because it helps prevent significant amounts of fresh water from entering the ground-water depression and diluting the mined brine waters. Meaningful networks of water-level and water-quality monitoring wells should be established and maintained to substantiate these geohydrologic conditions in the future.

A significant, unmeasured amount of land-surface subsidence has occurred at Brownfield Lakes since 1957 due to solution mining of sodium sulfate from the clays of the Tahoka and Duck Creek Formations. Since 1957 subsidence has not caused any problems because it probably has been limited to the production well area of influence within the solution mining area. However, the solution mining operator should closely observe abandoned injection well sites and properly place and monitor brine delivery pipelines within known subsidence areas of the solution mining operation.

Other important measures which should be followed by the solution mining operator to protect the environment are as follows:

1. Continuously monitor operating pressures of injection wells and all pipelines associated with sodium sulfate solution mining and processing operations.
2. Be capable of substantiating required injection well construction, particularly concerning methods and procedures of cementing.
3. Be capable of substantiating required pressure tests on new injection wells.
4. Be capable of substantiating required plugging of abandoned injection wells.
5. Report all brine leaks or spills which occur on or below the land surface in the mining area.

Measures which should be followed by the Department to protect the environment are as follows:

1. Periodically monitor water levels and water quality in the mining area.
2. Periodically conduct a field inspection of the mining area.
3. Periodically inspect the operator's records concerned with injection well and pipeline operations.
4. Periodically obtain geohydrologic data collected by the solution mining operator.
5. Investigate all brine leaks and spills reported by the operator or discovered during field inspections.

Legal and Jurisdictional Considerations

The 1981 amendments to the Injection Well Act (Chapter 27 of the Texas Water Code) brought solution mining of minerals under direct State regulation. The industries immediately affected by this action include existing sulfur, brine, and sodium sulfate solution mining operations. The sodium sulfate solution mining wells will be regulated by injection well permits issued by the Department and are immediately subject to interim status standards. These operations have been investigated over a period of time by Department staff.

Concluding Statement

Sodium sulfate solution mining injection wells and associated brine delivery pipelines have a significant potential to cause damage to vegetation and wildlife habitat on the land surface and ground-water quality problems caused by brine leakage and spills. However, actual experience with the operation of sodium sulfate solution mining injection wells and associated pipelines indicate that the problems have thus far been minimal.

Use of the environmental protective measures described in this chapter, by the Department and the solution mining operator, should adequately minimize any adverse effects of sodium sulfate solution mining activities on the surface and subsurface environment in and adjacent to the mining area.

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CHAPTER 8

ARTIFICIAL RECHARGE WELLS

Investigator:

Guy Grant Cleveland

ARTIFICIAL RECHARGE WELLS

Table of Contents

TABLE OF CONTENTS—Continued

ARTIFICIAL RECHARGE WELLS

Introduction

Texas has many valuable aquifers which provide water for irrigation and municipal and domestic needs. However, because of increasing demand for ground water, excessive pumping of some aquifers is depleting underground supplies of water. Replenishment of ground water usually occurs through natural recharge where surface water enters pores and fractures on the outcrop of an aquifer, or percolates through overlying sediments to enter the aquifer. Where water has been produced from an aquifer faster than the rate of natural recharge to the aquifer, methods have been sought for replacing the depleted water supply. These methods have usually involved operation of wells which inject surplus volumes of surface water into the underground aquifer.

In the last 20 to 30 years, farmers throughout the High Plains of Texas have been using the injection well method of artificial recharge with "dual-purpose" wells which can alternately produce ground water for irrigation and inject surface runoff water back into the underground aquifer. With advances in technology, the basic artificial recharge well has been applied to other ground-water problems including secondary recovery of capillary ground water, flood control and storm water drainage, and control of subsidence and salt water intrusion. Artificial recharge wells, in their various applications, are Class V wells under the regulatory jurisdiction of the Texas Department of Water Resources, local water districts, and city and county governments.

Following are descriptions of various types of wells used for artificial recharge of aquifers in Texas. Assessments are presented by geographic area and well type. Figure 8-1 shows the locations of artificial recharge wells investigated by the Department.

Trans-Pecos Region

El Paso Area

Geohydrology

The principal ground-water supply of the City of El Paso is the Hueco Bolson, which together with other bolson deposits of the Trans-Pecos region constitutes a major aquifer (Table 2-2). Hueco Bolson lies east of the City of El Paso and the Franklin Mountains (Figure 8-2). In Hueco Bolson, ground water occurs under water table conditions. As ground water moves into the city artesian area, it passes beneath relatively impermeable sediments and becomes confined under pressure exerted by the higher elevation of the water surface underlying the mesa. Ground-water movement in the Hueco Bolson deposits in and adjacent to the city artesian area is predominantly

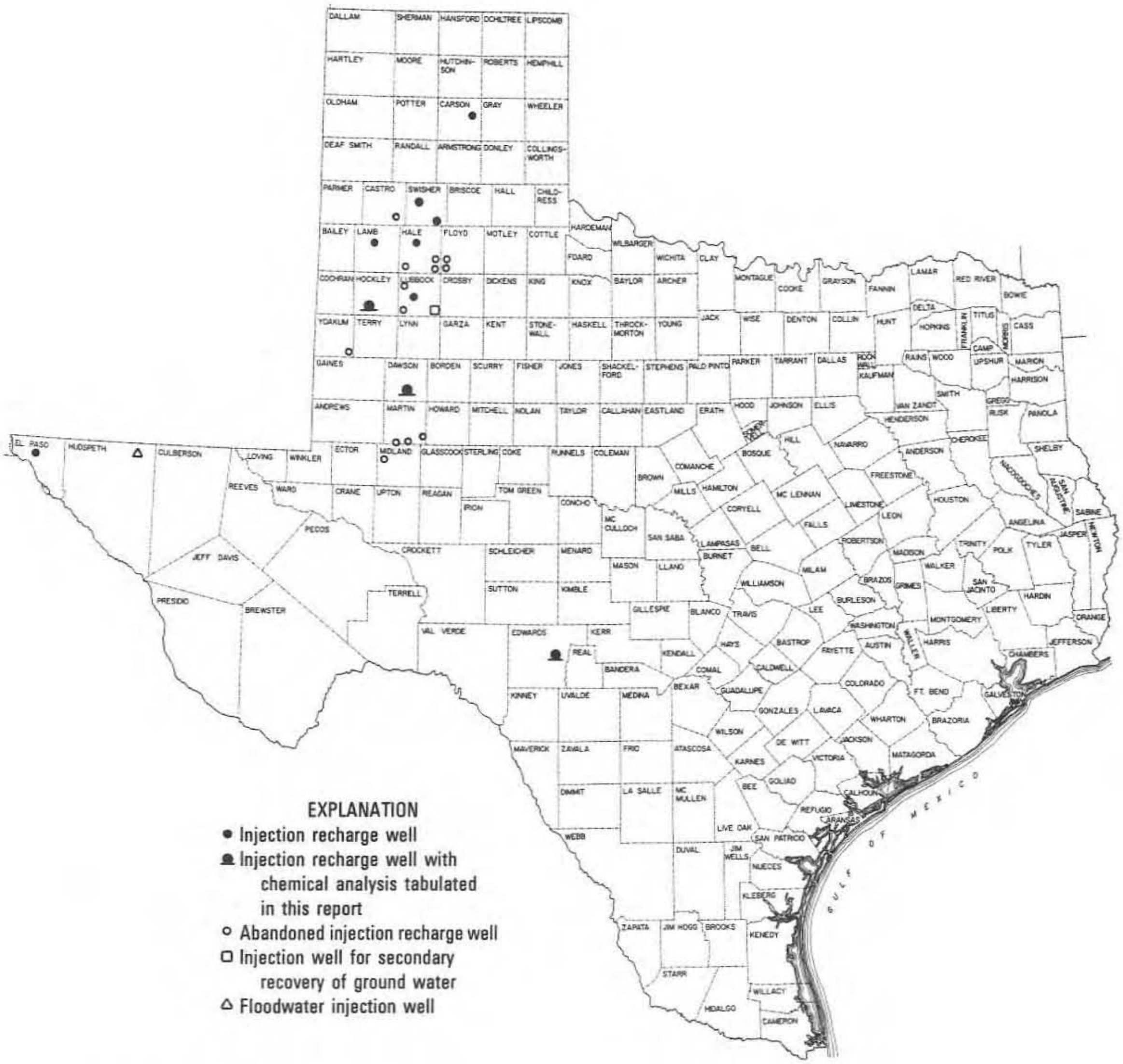

Figure 8-1.—Locations of Artificial Recharge Wells in Texas, 1982

toward centers of water-well development and pumpage. Earlier studies suggested the same condition of ground-water movement toward producing well fields, and showed that the direction of regional ground-water movement in 1936 in Texas and Mexico was generally to the south and southeast toward the Rio Grande and other areas of natural discharge.

Assessment of Treated Effluent Injection Wells

The City of El Paso Water Utilities began construction of a 10 million gallons per day sewage treatment facility in 1983. The facility, located just northeast of the city, should be operating by 1985, with treated wastewater to be injected into Hueco Bolson. Presently, two pilot injection wells are in operation, with ten injection wells proposed for the treatment facility. Figure 8-3 shows the wellhead of one of the operating injection wells. Figure 8-4 shows a diagram of Hueco Bolson recharge well design. The Hueco Bolson project will treat wastewater to drinking water standards before injection into the local aquifer. Treated effluent will be injected into wells for

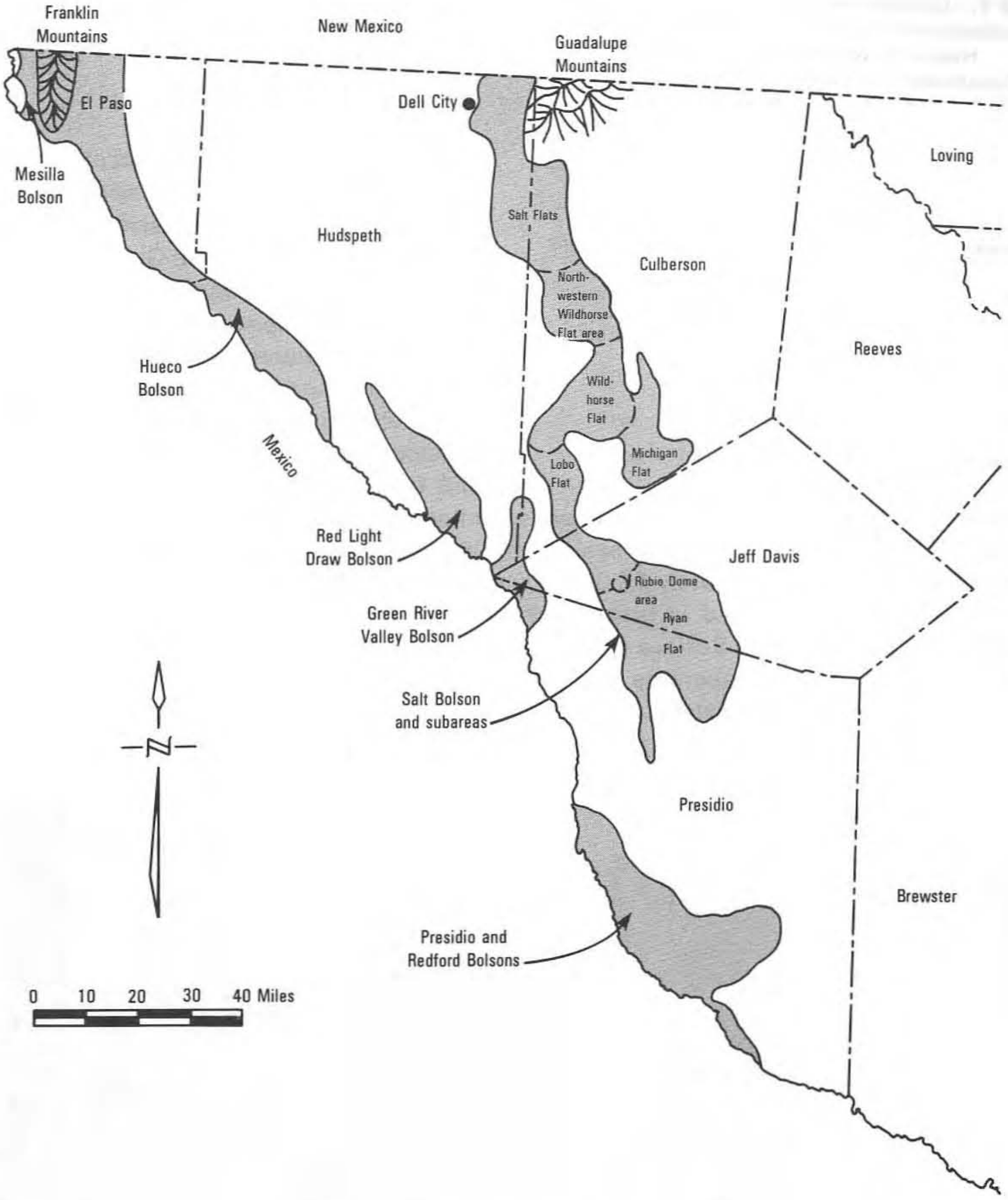

Figure 8-2.—Alluvium and Bolson Aquifers of the Trans-Pecos Texas Region

recharge of Hueco Bolson or directed to a nearby power station for industrial use. Table 8-1 compares the water quality standards of the El Paso injected effluent with the water quality of the Hueco Bolson aquifer in the vicinity of the injection well project. From these data (Table 8-1) it is concluded that the El Paso recharge wells should have very low potential for contaminating the local ground-water supply, and that the ground water will be maintained at drinking-water quality.

The Hueco Bolson Recharge Project in El Paso is authorized by a wastewater permit issued by the Department. The permit consolidates regulation of the treatment facilities and injection wells, under the authority of Chapter 26 of the Texas Water Code.

Table 8-1.—Comparison of Injection Water Quality Standards with Aquifer Water Quality for the Hueco Bolson Recharge Project (Constituent concentrations are in mg/l.)

Parameter	Injection water requirements of El Paso municipal wastewater discharge permit 10408-07 (values not to exceed)	Hueco Bolson Aquifer, well JL-49-05-604, sample Oct. 30, 1963
Nitrate (N)	10.0	4.9
Iron (Fe)	0.3	0.05
Sulfate (SO4)	300.0	25.0
Chloride (Cl)	300.0	168.0
Dissolved solids	1,000.0	434.0

Dell City Area

Geohydrology

Dell City is located just west of Guadalupe Peak and approximately 90 miles east of El Paso (Figure 8-2). An extensive salt basin lies between Dell City and the Guadalupe Mountains. The Permian age Bone Spring Limestone is the principal water-bearing formation in the Dell City area. Natural recharge of the Bone Spring Limestone occurs at the outcrop in the upland areas surrounding Dell Valley. Pleistocene and Recent alluvial deposits up to 150 feet thick cover the Bone Spring Limestone in the valley. Lake-bed sediments of undetermined thickness, containing large amounts of gypsum and other salts occur in the basin along the eastern side of the valley. According to Goerdel (1968, p. 2), approximately 25,000 acres of cropland are irrigated within the elongated basin of Dell Valley. The land is irrigated from relatively shallow wells pumping from the cavernous limestone aquifer. Surface runoff flows into shallow lakes and broad flats in the lowest part of the basin and then evaporates. The slope of the hydraulic gradient of ground water of the entire basin was toward the salt lakes before irrigation developed. Under these conditions, ground water discharged into the salt lakes through springs such as Crow Springs on the east side, and

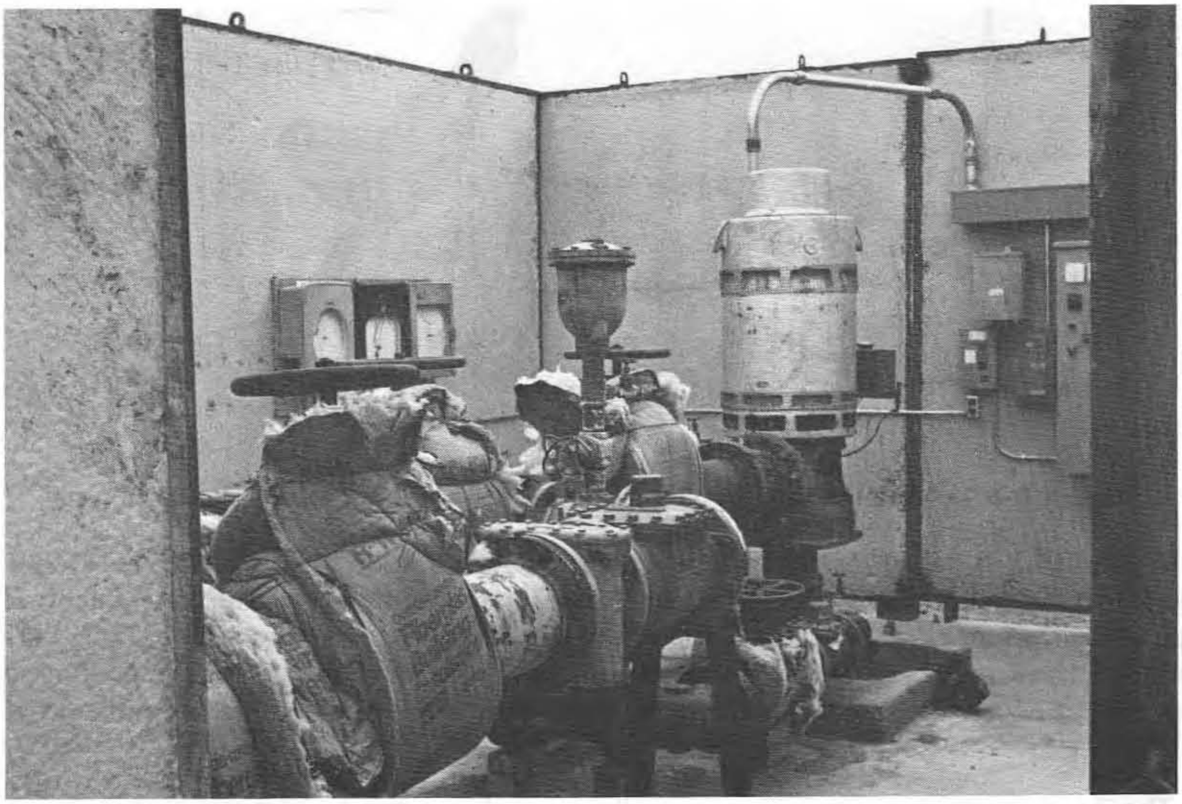

Figure 8-3.—Pilot Well for Hueco Bolson Recharge Project, El Paso County

from the lake beds and flats by capillary movement. Extensive irrigation with water from the Bone Spring Limestone has, however, altered the hydraulic gradient to cause an influx of more saline water from the salt lake area into the Bone Spring Limestone aquifer.

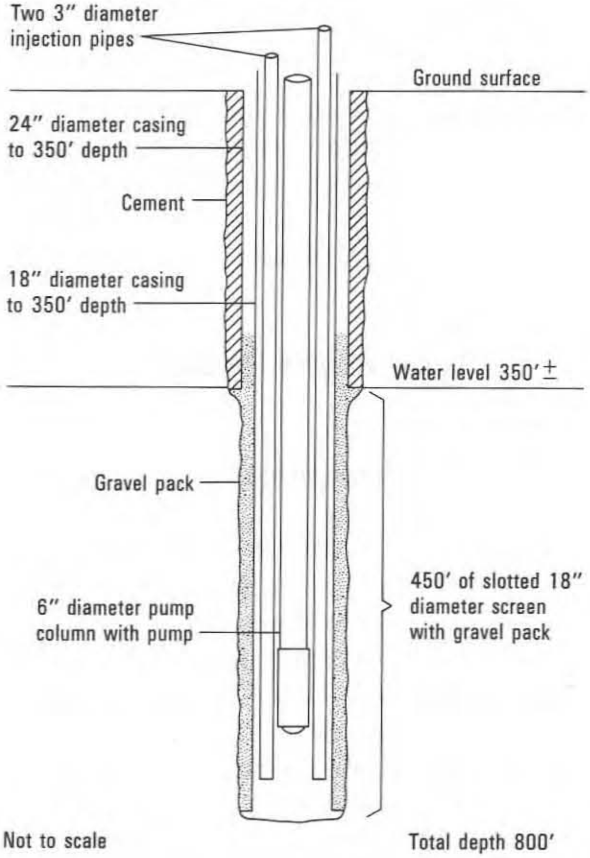

Figure 8-4.—Diagram of Recharge Well in El Paso (Modified from Knorr, 1979)

Assessment of Floodwater Injection Wells

Flood control impoundments to be used in conjunction with recharge wells are under construction in Dell City, Texas as of April 1982. Prior to initiating flood control in the area, floodwaters flowed through this agricultural area as sheet-flow, and drained into local depressions called salt lakes. As of April 1982, the two floodwater-retarding dams which have been completed and the additional four dams which are proposed will collect rainfall runoff for injection into the Bone Spring Limestone. Impounded drainage will be injected into 20-inch diameter wells which are approximately 1,000 to 2,000 feet deep (Figure 8-5). Figure 8-6 shows a diagram of the Dell City recharge well design. At present, five of these floodwater injection wells have been constructed. The wells are located downstream from each dam, enabling impounded water to travel through conduits with control gates and through filtering systems for silt and debris removal, to enter wells by means of gravity flow. The first dam to be completed is approximately 1 mile long and 40 feet high.

The estimated average annual volume of floodwater to be released from the six proposed floodwater impoundments and injected into the Bone Spring Limestone is about 6,000 acre-feet or 261 million gallons. The feasibility study by Goerdel (1968) indicates that owing to the highly permeable, cavernous nature of the injection formation, the rates of injection will be limited only by the rate of water conveyance into the wells. Therefore, the well injection rates will depend primarily on the rates of floodwater release from the impoundments, and the sizing and design efficiency of transmission lines and filters.

The data presented in Table 8-2 suggest that injected floodwaters will lower salinities in the Bone Spring aquifer, improving the quality of ground water for use in irrigation. In addition to improvements in water conservation and ground-water quality, recharge by floodwater injection wells will cause an increase in the ground-water level under Dell City. This recharge will decrease movement of highly saline water out of salt lake sediments into the Dell Valley aquifer (Bone Spring Limestone) by changing the hydraulic gradient back to its pre-irrigation condition. Ground water from the Bone Spring Limestone is used mainly for irrigation and is generally of poor quality (2,000 to 4,000 mg/l dissolved solids). This ground water must be desalted for municipal use.

Table 8-2.—Comparison of Injected Water Quality with Aquifer Water Quality at Dell City (Constituent concentrations are in mg/l.)

	Water sample from floodwater impoundment	Well water sample from the Bone Spring Limestone
Date Sample Collected	Sept. 29, 1983	Apr. 1, 1981
Well Depth (feet)	—	1,200
Nitrate	(NO_3) 4.43	(N) 4.0
Silica (Si)	9.0	17
Calcium (Ca)	45	308
Magnesium (Mg)	6.0	119
Sodium (Na)	10	126
Potassium (K)	19	—
Sulfate (SO_4)	38	1,000
Chloride (Cl)	27	205
Fluoride (F)	0.44	1.8
pH	8.72	7.48
Dissolved solids (sum)	253	2,005
Specific conductance (micromhos at 25°C)	425	2,400

With addition of better quality waters by way of floodwater injection wells, ground water will be of higher quality and will cost less to treat for municipal use. The Dell City flood control wells should have a very low potential for contamination.

Dell City floodwater injection wells are operated and maintained by the Hudspeth County Commissioners Court with assistance from the City of El Paso and the Hudspeth Water Conservation District No. 1.

High Plains Region

Geohydrology

The Ogallala Formation (Pliocene) of the High Plains aquifer overlies rocks of lower permeability of Cretaceous and Triassic age. Triassic rocks, principally shale, serve as a nearly impermeable floor for the High Plains aquifer, but buried mesas or buttes of Cretaceous rocks generally yield water to wells. At

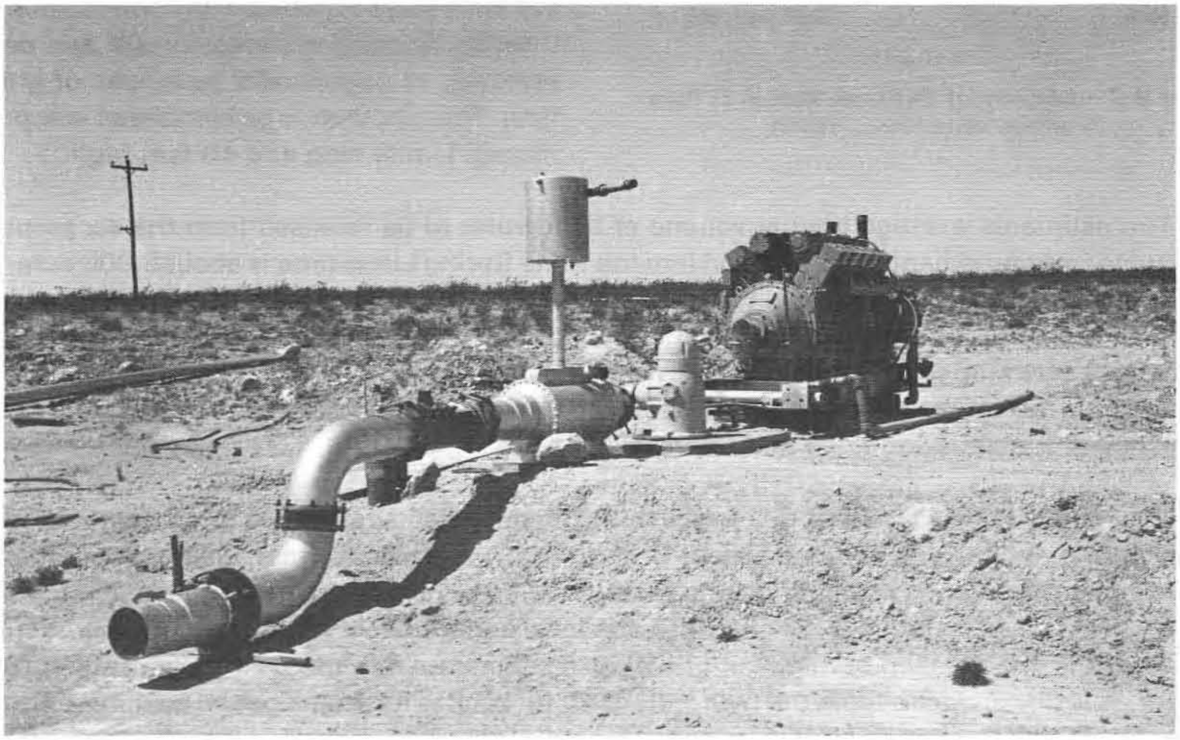

Figure 8-5.—Dell City Floodwater Injection Well, Hudspeth County

the locations of buried mesas, the Ogallala and Cretaceous waters are in hydrologic continuity. Therefore, Cretaceous rocks yielding water are also considered to be part of the High Plains aquifer.

Erosion has removed the Ogallala from much of its former extent east and west. As a result, the southern High Plains, although relatively flat, stand in high relief and the Ogallala here is hydraulically independent of other aquifers. For this reason, coupled with the scarcity of rainfall and large agricultural and municipal demands for ground water, water is being withdrawn from the aquifer more quickly than natural recharge can replenish the aquifer. The ground water is, in effect, being mined. The impact of aquifer depletion upon a water well operator is first noted in decreased yields from water wells, and ultimately may necessitate costly recompletions of wells at greater depths in response to the lowering of the water table.

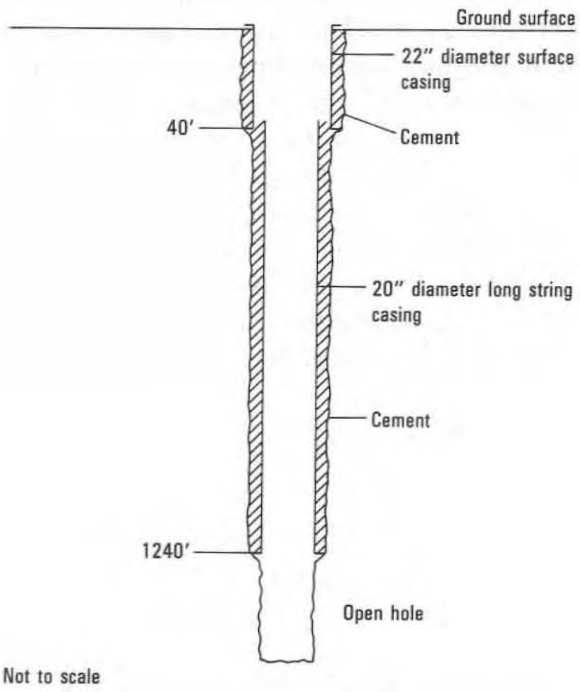

Figure 8-6.—Diagram of Floodwater Injection Well in Dell City, Hudspeth County

After significant rainfall, numerous gentle depressions in the extremely flat topography of the High Plains become apparent as they fill with water. These surface depressions with rainwater are referred to as playa lakes. Bottoms of playa lakes are covered with natural accumulations of impermeable clays; thus most playa water is eventually lost by evaporation, and natural recharge of the High Plains aquifer from playas is minimal. As a consequence, artificial recharge well projects on the High Plains have developed in attempt to conserve and store playa water for domestic and agricultural use.

Assessment of Irrigation Dual-Purpose Wells

Dual-purpose wells, the most common type of artificial recharge installation in the State, are found throughout the High Plains of Texas. This type of well is used to recharge ground-water aquifers when surface water is in surplus, but may also be used to pump water from an aquifer to meet municipal and agricultural needs. Since the 1950's, recharge wells have also aided farmers in draining standing water from playa lakes. When these lakes are drained, additional fertile land is made available for farming. The wells are drilled so that lake water that is normally lost to evaporation is allowed to pass through the impermeable clay layer at the bottom of the playa lake and recharge the aquifer.

During the early 1970's, there were approximately 200 artificial recharge wells in existence. However, only a few are presently operating. The few remaining dual-purpose wells in operation generally inject water by gravity flow. When needed, pumps may be used to increase recharge rates and remove excess water from playa lakes. Ten existing wells were inventoried in the High Plains; two of the wells were sampled to analyze water being injected into the aquifer. Wells

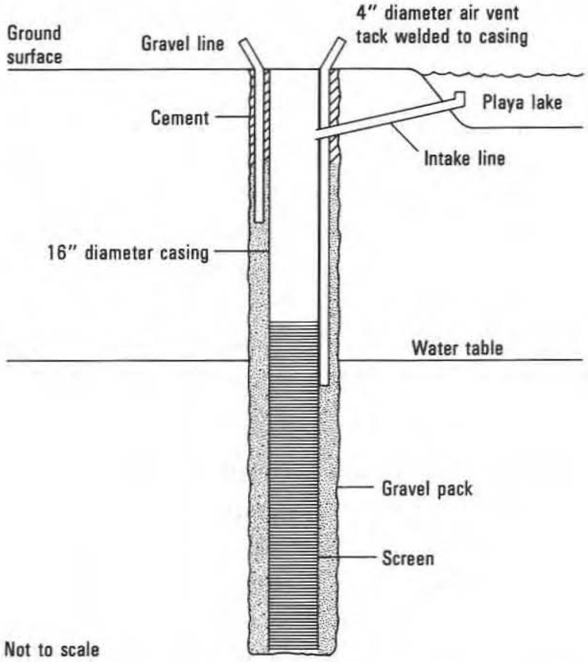

Figure 8-7.—Diagram of a Typical Dual-Purpose Well (Modified from Johnson, Crawford, and Davis, 1976, and High Plains Research Foundation, 1974)

investigated by Department staff are considered representative of recharge wells on the Texas High Plains.

The decline in use of recharge wells can be attributed to problems with sediment-laden water found in playa lakes. Due to these sediment problems, many privately owned and operated dual-purpose wells failed within 5 to 10 years. Preventative measures in well construction are required to control the clogging effect caused by sediment. Figure 8-7 shows the common cased hole design for construction of dual-purpose wells for irrigation and recharge use. The casing is perforated or a screen is used, depending upon the subsurface geology or individual operator's preferences. The well is commonly equipped with a valve to control recharge flow through the intake line, down the casing and into the aquifer. In addition, water can be pumped back to the surface for irrigation use. Figures 8-8, 8-9, and 8-10 show surface installations of High Plains dual-purpose wells.

Figure 8-8.—Recharge Well for Playa Water in Lamesa, Dawson County

Figure 8-9.—Recharge Well in Playa Lake 6 Miles Southwest of Tulia, Swisher County

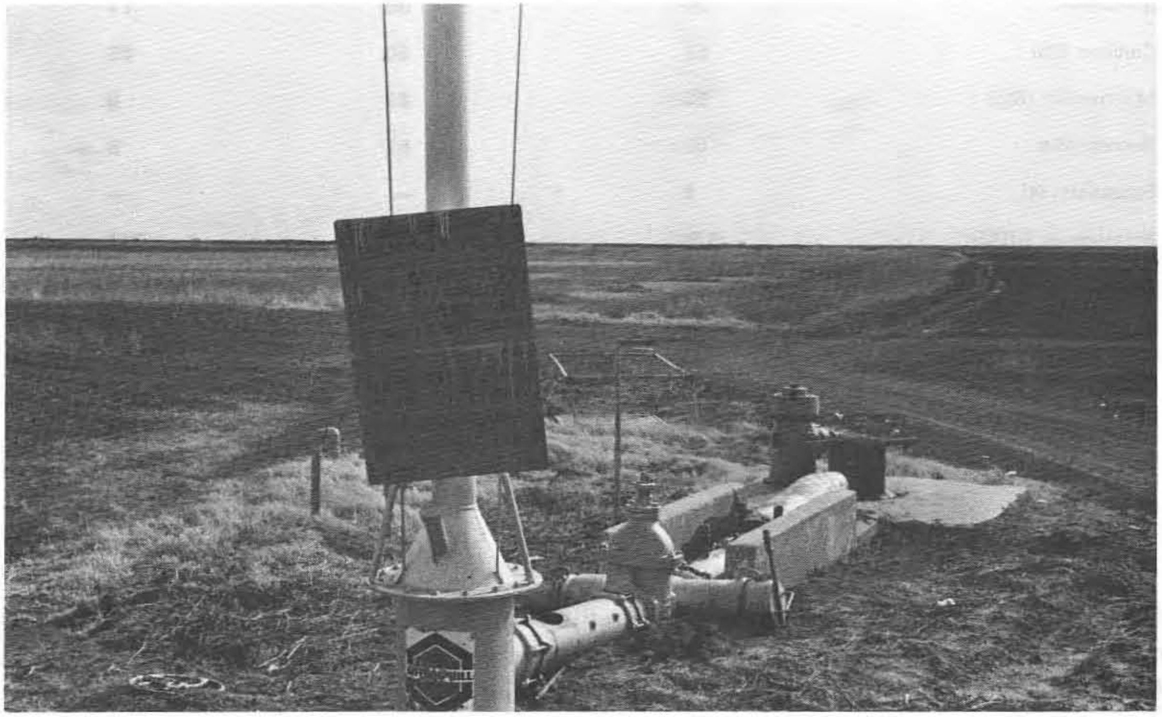

Figure 8-10.—Recharge Well Near Halfway, Hale County

No data are available on the injection volumes of dual-purpose wells. These injection volumes will depend upon rainfall runoff, the efficiency of the well design, and the permeability of the injection formation.

Chemical analyses of water samples taken from the High Plains aquifer are shown in Table 8-3. The High Plains aquifer was sampled near Lamesa in Dawson County and in Levelland in Hockley County. Comparison of aquifer water samples with corresponding recharge water samples (Table 8-4) suggests that injected water may often be of better quality than that of the receiving aquifer. Table 8-5 indicates very low levels of organic chlorides in the two High Plains recharge water samples, and this suggests a very minimal impact on the aquifer locally from agricultural pesticides. Dual-purpose irrigation and recharge wells on the High Plains are therefore assessed to have very low potential for contamination of underground supplies of drinking water, provided that care is taken to keep agricultural and industrial pollutants and domestic and municipal wastes out of playas which collect recharge water.

Table 8-3.—Chemical Analyses of Aquifer Waters
(Constituent concentrations are in mg/l.)

	Dawson Co. Well (near Lamesa)	Hockley Co. Well (in Levelland)	Edwards Co. Well (in Rocksprings)
Injection zone	Ogallala	Ogallala	Edwards
State well number	28-17-103	24-30-401	55-63-701
Date sample collected	July 17, 1975	July 7, 1980	June 18, 1979
Well depth (feet)	156	211	563
Nitrate (NO_3)	43	8.4	7.2
Silica (Si)	70	50	11
Calcium (Ca)	61	60	63
Magnesium (Mg)	53	88	8
Sodium (Na)	65	61	8
Potassium (K)	8	—	—
Bicarbonate (HCO_3)	375	337	211
Sulfate (SO_4)	81	218	7
Chloride (Cl)	68	86	15
Fluoride (F)	4.5	4.4	0.2
pH	7.8	8.4	8.1
Dissolved solids (sum)	637.8	741.5	223.1
Specific conductance (micromhos at 25°C)	935	1,002	368

Presently, a permit must be obtained from the High Plains Underground Water Conservation Districts to drill and operate recharge wells in areas where underground water districts have been established. The only permit requirement for artificial recharge injection is that no pollutants enter the fresh water aquifer through these wells. In addition, a well completion report must be furnished to the local district by the owner of the well.

Table 8-4.—Chemical Analyses of Recharge Waters
(Constituent concentrations are in mg/l.)

	Dawson Co. Well (near Lamesa)	Hockley Co. Well (in Levelland)	Edwards Co. Well (in Rocksprings)
Injection zone	Ogallala	Ogallala	Edwards
Water level (feet)	70	130	—
Date sample collected	Apr. 27, 1982	Apr. 27, 1982	Mar. 4, 1982
Well depth (feet)	250	225	150
Nitrate (NO_3)	0.04	0.04	0.04
Silica (Si)	2	2	11
Calcium (Ca)	39	27	60
Magnesium (Mg)	3	7	1
Sodium (Na)	25	15	6
Potassium (K)	6	6	12
Carbonate (CO_3)	0	6	0
Bicarbonate (HCO_3)	113	87	183
Sulfate (SO_4)	32	24	10
Chloride (Cl)	33	20	15
Fluoride (F)	0.3	0.5	0.1
pH	8.3	9	8
Dissolved solids (sum)	206	154	222
Specific conductance (micromhos at 25°C)	331	251	338

Assessment of Wells for Secondary Recovery of Ground Water

Artificial recharge to the High Plains is also being used in tests on secondary recovery of ground water. This is being studied by High Plains Underground Conservation District No. 1 and Texas Tech University in Lubbock, Texas. These field and laboratory ground-water studies involve use of injected air to pressurize an aquifer to enhance recovery of ground water.

Pressurization tests of the High Plains aquifer have been conducted near Slaton, Texas. The testing, performed from January 23 until February 1, 1982, ran for 217 hours. Approximately 1,000 cubic feet per minute of air was injected into the formation to determine whether air pressure would force residual capillary water in the unsaturated zone of the aquifer to move away from the injection well and migrate downward to the saturated zone of the aquifer (Figure 8-11). The design of the test wells is shown in Figures 8-12 and 8-13.

Six wells were constructed for the air injection test. Placement of a centrally located air injection well was based on the assumption that air would disperse radially. In this central well, a 6-inch diameter air injection hole was completed at a depth of 116 feet. The remaining five wells were air pressure monitor holes strategically located over the test area. Wells were drilled with

Table 8-5.—Organic Chloride Concentrations in Recharge Waters (Concentrations are in micrograms per liter [μg/l.])

	Dawson Co. Well (near Lamesa)	Hockley Co. Well (in Levelland)
Aldrin	0.02	0.02
Chlordane	1	1
DDD	.25	.25
DDE	.2	.2
DDT	.27	.27
Diazinon	.3	.3
Dieldrin	.1	.1
Endrin	.2	.2
Heptachlor	.02	.02
Heptachlor epoxide	.06	.06
Lindane	.03	.03
Methoxychlor	.5	.5
Methal parathion	.25	.25
Parathion	.25	.25
Toxaphene	5	5
PCB	1	1
Malathion	.4	.4
Diethylhexyl phthalate	50	50
Dibutyl phthalate	5	5
Guthion	10	10
Ethyl parathin	.25	.25
Trifluralin	.06	.06

Analyzed by the Texas Department of Health.

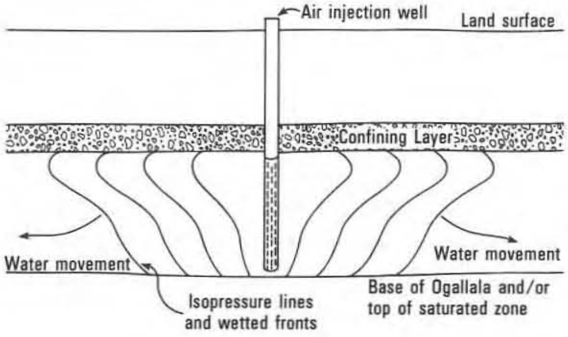

Figure 8-11.—Illustration of Secondary Recovery of Ground Water by Air Injection (From Rauschuber, Wyatt, and Claborn, 1982)

either air, water, or foam. Air drilling was preferred, because it caused the least amount of formation damage. Figures 8-14 and 8-15 show the wellhead and surface equipment of the test air injection well.

It is estimated that over 12 million cubic feet of air was injected into the formation during 217 hours of testing. The formation responded rapidly to pressure build-ups and water level changes upon initiation of air injection. Analytical procedures including development and verification of mathematical models are underway at the time of this writing. The results of the testing will be presented in a future report by the High Plains Underground Water Conservation District No. 1.

Artificial recharge wells injecting air for secondary recovery of ground water are assessed to have a very low potential for contamination of underground supplies of drinking water.

Edwards Plateau Region

Geohydrology

An artificial recharge well in Rocksprings in Edwards County is completed in the Edwards Limestone. This formation is the major unit of the Edwards-Trinity (Plateau) aquifer (Table 2-2) in the area. The Rocksprings area is marked by poor surface drainage resulting from clayey soil, impervious surface rock, and flat topography. Accordingly, there is little natural recharge of the Edwards-Trinity aquifer in these impervious clayey areas. The Edwards Limestone conducts fluids throughout its thickness from the surface to a depth of approximately 650 feet. The local production zone for good-quality water occurs at a depth of approximately 400 feet.

Assessment of Rocksprings Drain Well

On the south side of Rocksprings, recharge is accomplished through a drain well into the Edwards Trinity aquifer. The main function of the well is to drain water standing after heavy