plicability and limitations of the underground disposal of liquid industrial wastes by observing installations at industrial plants, cities, and oil fields. About 10 million b/d of oil-field brines are being injected into formations from which no fluids are withdrawn. In addition, about 175 deep wells are being used by the chemical process industry to inject approximately 1 million b/d of aqueous waste solutions that may be classified in 5 distinct categories: (1) inorganic salt solutions, (2) mineral and organic acids, (3) basic solutions, (4) chlorinated and oxygenated hydrocarbons, and (5) municipal sewage. In many cases, underground disposal is the most economical method for disposal of liquid wastes that are not amenable to surface treatment.

The wells, ranging from 1,000 to 8,000 ft deep, are completed in 4 general types of formations: (1) unconsolidated sand, (2) consolidated sandstones, (3) vugular carbonate rocks, and (4) fractured granite. The hydrology and physical characteristics of the disposal formation often dictate the design of the underground disposal system and govern its operation. Because of the widely diverse parameters, almost every new system presents unique problems of design and operation. For a given rate of waste injection, the wellhead pressure usually depends on the reservoir permeability and fluid pressure. Some wastes can be injected at 20,000 b/d with zero pressure at the wellhead, whereas others require a 1,000-psi wellhead pressure for the same rate of waste injection.

Unconsolidated sands tend to enter the casing and restrict fluid flow. Suspended solids may plug sandstone and sandy carbonate formations that have small pores. Injection into fractured granite under tectonic stress may lead to earthquakes. Thus, each waste-disposal system must be considered separately, although a few general principles of design and operation are applicable to all underground systems.

One primary indicator of well behavior is the injectivity index. It is specific for an individual well, remaining the same as long as the permeability and porosity of the formation do not change. The injectivity index is used to distinguish between plugging and the normal pressure buildup within the formation, and to examine the effectiveness of well-stimulation procedures.

There are many advantages of subsurface over surface methods of waste disposal. Capital investment and operating costs are lower, the surface area required for the plant is less, seasonal temperature variations have less effect on the system, chemical treatment of the waste is minimal, and generally the only physical treatment required is filtration. However, inadequate knowledge of how the waste constituents interact with the subsurface formation imposes a potential for the creation of a severe environmental hazard. The safety hazards of underground waste disposal should receive careful consideration in the planning stages of a waste-disposal well.

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ROLE OF BIOTA IN UNDERGROUND WASTE INJECTION AND STORAGE

Biologic activity can clog waste injection wells and produce gas in aquifers. Beneficial effects such as solubilization of particulate matter are also possible.

Some organisms, particularly Protozoa, fungi, and bacteria of the biotic kingdom *Protista*, thrive under extreme conditions. Therefore, the potential for problems of biologic origin must be evaluated carefully in every situation. Exclusion of biota is to be expected only under the most hostile conditions.

Versatility in adaptation to unusual environments and size limitations imposed by typical aquifer materials suggest that *Protista* will be the predominant biota in the waste injection regime. The composition, size, and activity of a protistan population depends upon many factors. These include temperature, pH, salt content, concentration and types of nutrients and micronutrients available, oxygen concentration, and aquifer lithology among other things. All chemical elements necessary for cell building such as carbon, nitrogen, phosphorous, sulfur, and numerous trace elements must be present.

Past experience with artificial recharge wells suggests that public-health jeopardy by microorganisms introduced by injection of certain types of waste is not great. Bacterial travel in confined aquifers is negligible and survival time is short. Exceptions may exist in highly permeable strata.

Microbial growth supported by nutrients in the injectant occurs near the well screen. Addition of disinfectants to control microbial growth may be useful but certain biocides may become nutrients under some circumstances. The biocide may be ineffective in the waste injection regime. Slime control measures must be carefully selected.

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HYDROLOGIC SYSTEMS

The increasing tempo of ecologic crusades for the cleanup of lakes and streams is driving pollution underground, in more than a manner of speaking. There is in prospect a veritable explosion in the use of sanitary landfills for disposal of solid wastes, in the use of spray irrigation for disposal of partly treated sewage effluent, and in the use of deep-well injection for disposal of certain industrial wastes.

Citations of the astronomical volume of storage space within the earth's crust, the very small velocity of groundwater motion, the evidence of entrapment of hydrocarbons and brines, and the presence of very fine-grained confining rocks, intrigue proponents of subsurface storage with the potential for resolving our waste-disposal problems. What gives cause for concern is the recognition that groundwater reservoirs or aquifers are not static environments, but represent dynamic flow systems that undergo change whenever a new stress is imposed.

Attendant upon the injection of fluid into an aquifer is a consequent increase in hydraulic head which ultimately influences the hydrologic regime throughout the entire flow system, howsoever distant its boundaries may be. Disposal to shallow aquifers, which are generally sources of water supply, poses a threat not only to present and future well developments, but also to lakes and streams that are sustained by groundwater seepage. In deep-lying confined aquifers, where overburden pressures are large, the hydraulic transmissivity is generally small and consequently the pressures required for significant rates of injection are large. In marked contrast to the very slow migration of the cylinder of injected waste, the cone of pressure increase is propagated outward in a confined aquifer with the velocity of sound in the medium. Thus, to evaluate the consequences of waste injection requires not only consideration of the effects of the advancing cylinder of waste, but also the far-reaching effects of the cone of pressure increase.

Profile sections of hypothetical systems illustrate the nature, form, and extent of hydrologic system response to the stress of subsurface waste storage. Representative values of travel time for advances of the waste cylinder versus the cone of pressure increase are given for selected values of injection rate and aquifer diffusivity.

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CONTROL OF UNCONSOLIDATED SANDS IN WASTE-DISPOSAL WELLS

Sand control methods were first used in water wells, and later, modified methods were applied to oil and gas wells. The most recent application for sand control is in waste-disposal wells. The increasing use of unconsolidated sands as disposal zones has created a need for better sand-control systems.

We suggest that the primary causes of sand control problems in disposal wells are: (1) greater completion intervals, (2) intermittent operation of the well, and (3) chemical characteristics of the injected effluent. Therefore, successfully to prevent sand production in disposal wells, consideration must be given to: (1) formation characteristics, (2) completion fluid, (3) type of completion, and (4) completion method.

Two universally used methods of sand exclusion, with suggested modifications when applied to disposal wells, are the method of in-place sand consolidation with plastics, and the use of gravel packs in conjunction with sand screens. Sand consolidation has limited application owing to the large completion intervals normally used in disposal wells, and to possible chemical reactions with injected effluent. However, a gravel-packed–sand-screen completion generally eliminates the three primary causes of sand production in disposal wells. Factors of prime importance are (1) the drilling and completion fluids, (2) formation grain size and composition, (3) size and amount of gravel, (4) pumping rate, (5) pressure, and (6) gravel concentration.

Field and laboratory data show that the method of gravel-packed–sand-screen completions can be used successfully over intervals as large as 500 ft in unconsolidated Frio sands.

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GEOLOGIC FRAMEWORK FOR SUCCESSFUL UNDERGROUND WASTE MANAGEMENT

Geologic requisites for successful underground waste management include: (1) porous and permeable reservoir rocks, in which the storage space may be caverns, intergranular pores, or fracture crevices; (2) impermeable seals to prevent escape of fluid wastes; (3) adequate understanding of hydrologic parameters, and planning to prevent undesirable migration of fluids; and (4) compatibility between waste materials and the reservoir rocks and their natural fluids.

Layered sedimentary rocks, rather than igneous or metamorphic rocks, provide the most suitable reservoir space, for both geologic and hydrologic reasons, but they must lie below, and be well shielded from, fresh groundwater aquifers. If wastes are hazardous to the biosphere, objective reservoir zones must be located deep enough to provide permanent protection to groundwater aquifers.

The site must be reasonably stable and not actively moving along or broken by faults.

Choice of a suitable underground disposal site can be made only after a thorough investigation of available subsurface data, or by drilling and various other processes of subsurface exploration if sufficient data are not available. Preliminary investigations and later subsurface operations will be expensive but they cannot be avoided in locating new sites. Public insistence on an end to pollution must be accompanied by public understanding that a clean environment can be purchased only by higher taxes (if government managed) or by higher prices for consumer goods (if industry managed), plus individual cleanliness.

As waste-management costs rise, it will become more economical to convert wastes into usable products, in effect eliminating rather than managing wastes.

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GEOCHEMICAL EFFECTS AND MOVEMENT OF INJECTED INDUSTRIAL WASTE IN A LIMESTONE AQUIFER

Since 1963 more than 4 billion gal of acidic industrial waste has been injected into a limestone aquifer near Pensacola, Florida. This aquifer is overlain by an extensive clay confining layer, which at the injection site, is approximately 200 ft thick. The waste—an aqueous solution containing organic acids, nitric acid, inorganic salts, and numerous organic compounds—is injected into the aquifer through two wells 1,300 ft apart between depths of approximately 1,400 and 1,700 ft. The present pH of the injected solution is about 2.5; however, before April 1968 the pH was about 5.5.

Approximately 10 months after waste injection began, an increase in calcium-ion concentration and alkalinity was detected in a monitor well open only to the receiving aquifer and located 0.25 mi south of the injection wells. About 5 months after lowering the waste pH, an abrupt increase in calcium-ion concentration followed by an increase in nitrate-ion concentration was observed at this monitor well. Large quantities of nitrogen and methane gas were present in water from the monitor well. This information plus other available data indicate that a major part of the waste is entering the upper 30–50 ft of the aquifer and that waste has moved more than 1 mi from the injection site. Geochemical effects have not been detected in two monitor wells open only to the receiving aquifer and located 1.5 mi south and 1.9 mi north of the injection site nor in a shallow monitor well at the injection site which is open only to the aquifer just above the clay confining layer.

Before the pH of the waste decreased, backflushing tests indicated that denitrification and neutralization of the waste occurred within a very short distance from the injection wells. Denitrification may have accounted for more than half the neutralization, the remainder being caused by solution of calcium carbonate. Denitrification has not been observed since the waste pH was lowered.

Wellhead injection pressures were about 200 psi before the decrease in waste pH but subsequently have decreased slightly to about 175 psi, even though injection rates have increased from about 1,600 to about 2,000 gpm. Wellhead pressures in the monitor wells south and north of the injection site are about 108 psi, which is approximately 90 psi above the preinjection pressure. Calculations indicate that pressure effects in the receiving aquifer may extend more than 30 mi from the injection site. No apparent change in pressure has been detected in the aquifer directly above the clay confining layer.