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 About 10 million b/d of oil-field brines are being injected into formations from which no fluids are withdrawn.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.