jection except for increased concentrations of silica, aluminum, and certain trace elements indicating slow dissolution of alumino-silicate minerals by the organic acids in the waste. Native aquifer water was mostly displaced by the injected waste, and carbonate minerals within the Upper Cretaceous sands and gravels were dissolved and decomposed by the organic acid waste constituents.

Since June 1972, trace quantities of waste were detected in an observation well 1,500 ft (457 m) north of the original injection wells, and a weekly sampling program was instituted to monitor the geochemical transformations during passage of the waste front. After the appearance of methane gas, the dissolved organic carbon concentration of the waste varied inversely with methane gas evolution, indicating reductive conversion of the waste to methane. Increased concentrations of ferrous iron, hydrogen sulfide gas, and sulfide precipitates were additional indicators of geochemical and microbiologic reductive processes.

The waste front was found to be broad and diffuse to the extent that the waste would disappear during certain periods of sampling. Measurements made up to February 1973 indicated that the waste concentration was not sufficiently high to affect pH, alkalinity, specific conductance, and most of the standard inorganic water-quality parameters.

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HAZARDS OF WASTE DISPOSAL IN GROUNDWATER BASINS

As problems of waste disposal become more critical, and environmental constraints more demanding, serious consideration is being given to isolated zones in groundwater basins as burial grounds for hazardous wastes. Proponents have suggested various geologic environments—thick impermeable clay or shale layers, heavily pumped subsidence basins, deep saline water bodies, *etc.*—as being safe disposal sites. However, several hydrogeologic constraints must be understood fully before a prospective site can be considered "isolated."

Unconsolidated deposits, even at great depth, are highly sensitive to changes in applied stress. Interstitial fluids may be squeezed from even relatively impermeable beds by modest stress changes. Compaction of the deposits below 2,500 ft has been induced in the San Joaquin Valley by groundwater pumping. As much as 30 ft of vertical shortening in 3,000 ft of water-bearing deposits has been measured. At Alpaugh, more than 4 ft of surface subsidence, principally due to the compaction of fine-grained beds at depth, has resulted from 250 ft of artesian head decline. Interstitial arsenic, presumably "locked" in clay interbeds for thousands of years of interaquifer circulation, now is being squeezed into the aquifers.

Hydraulic stresses in a developing groundwater basin may affect beds considerably below the deepest pumping wells. Theoretically, seepage stresses, and thereby groundwater movement, ultimately would affect all beds down to basement or some underlying truly impermeable layer. Slow drainage continues from each interbed as long as excess pore pressures exist in that interbed. Injection of wastes into clay or shale interbeds would cause a sharp increase in pore pressures in these interbeds.

Subsidence areas are usually poor candidates for waste-disposal sites. Generally, they have demonstrated their close communication with the groundwater system, their direct response to pressure changes, and their high compressibility. Heavily depleted artesian aquifers are not empty reservoirs ready for refilling. Rather, the groundwater systems are "full" and adjusting to the various stresses imposed on the basin. Compaction recorders show that pore pressures throughout the vertical section respond rapidly to pumping stresses.

Horizontal and vertical ground movement, caused by horizontal and vertical groundwater flow, can be a serious threat to surface or buried structures. Subsidence affects probably 7,000 sq mi in California alone in amounts to 28 ft in a few places, and has caused the failure of thousands of deep and shallow water and oil wells. Horizontal shear stresses and surface tension cracks are a continued threat in a developing groundwater basin.

Saline-water bodies in a basin are not necessarily permanently out of touch with the circulation system of the basin. Hydrologic stresses may force some of this saline water into the circulating groundwater system. Evidence suggests that upward seepage stresses may extend below the freshwater-saline water interface; also, in some areas, saline water may be moving upward into the freshwater zones.

Few regions of a groundwater basin are isolated from the circulating flow system. Although injecting liquid wastes deep underground is sometimes expedient, the effects are complex and never ending. Long-lived radioactive wastes require isolation from the hydrosphere for periods of time ranging from 1,000 to several hundreds of thousands of years, but much waste material, to be "safe," must be contained *forever*. And who can anticipate future natural and man-made stresses on the system?

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SITE INVESTIGATIONS FOR BEDDED-SALT PILOT PLANT IN PERMIAN BASIN

High-level radioactive waste contains long-lived nuclides that require complete confinement for long periods of geologic time. Rock salt long has been acclaimed as the preferred geologic medium for the ultimate disposal of these wastes, inasmuch as its unique self-healing properties make it impervious to the intraformational circulation of groundwaters. Data have been compiled on the nature and extent of all major salt deposits in the conterminous United States; however, specific site studies have been confined to the Permian basin, to central Kansas, and to a large tract of federally owned land in southeastern New Mexico. A series of coreholes has been drilled to provide the critical data for selecting appropriate disposal levels and assessing the hydraulic characteristics of the overlying and underlying formations. Selective parts of the cores have been analyzed to determine the quantities and characteristics of various minerals in the evaporite section and, in particular, of any hydrated minerals and rocks that could dehydrate upon heating because of radioactive decay of the wastes. Measurements of the physical properties of these rocks also have been made to calculate their deformational behavior.

Because of the need for long-term waste confinement, several unique studies have been initiated. The long geologic history of relative quiescence, coupled with data on historic earthquakes, strongly suggests that the Permian basin will continue to be tectonically stable for the next few hundreds of thousands of years, or for the effective lifetime of the wastes. In addition, studies of subsurface salt dissolution show that the rate of basinward migration of the relatively shallow edges of the salt during Quaternary time has averaged only a few miles per million years. Also, in central Kansas present rates of denudation have been found to average less than 1 ft per 1,000 years while stream incisions in the same area during Quaternary time have not exceeded several hundred feet. Finally, investigations have revealed that the buried wastes would not be affected adversely by the advance of a new continental ice sheet.

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GEOHYDROLOGY OF BURIED TRIASSIC BASIN AT SAVANNAH RIVER PLANT

At the Savannah River plant near Aiken, South Carolina, as at other locations where there are chemical-separation plants for the processing of nuclear fuels, the high-level radioactive wastes are stored in concrete-and-steel tanks buried just beneath the surface of the ground. This waste is of such activity and longevity that it cannot be dispersed into the environment, but it must be contained for periods of time extending at least into hundreds and perhaps thousands of years. One concept for the terminal containment of this waste is to store it in excavated chambers within the bedrock, which is covered by about 1,000 ft of coastal plain sediments at the plant site. As part of the safety evaluation of this concept, the geology and hydrology of both the coastal plain sediments and the bedrock have been studied. Intensive investigation of bedrock waste storage now has been postponed indefinitely while other concepts of waste storage and management are being investigated.

A buried Triassic basin that might have potential for waste storage was discovered beneath the southern third of the plant site. Investigation into the characteristics of this basin was started in 1971. This was not an engineering on design study but was aimed at understanding the geohydrology of the Triassic basin to determine its compatibility with the safe storage of waste.

Seismic surveys, gravity and magnetic surveys, and the drilling of several exploratory wells indicate that the Triassic basin is about 30 mi long, 6 or more mi wide, and perhaps 5,300 ft thick. One well penetrated the Triassic border, a second was in the center of the basin, and a third investigated an intrabasin fault. The rock is predominantly mudstone of very low permeability, with a few lenses of poorly sorted gritty sand. The water yield of all the exploratory wells is extremely low, and water-transmitting fractures are virtually nonexistent.

In 2 wells within the basin, heads above land surface have been measured that cannot be explained by connection with a recharge area. Ten possible explanations have been evaluated: aquifer head, fossil head, tectonic compression, rapid loading and compaction of sediments, water derived from igneous intrusions, infiltration of gas, precipitation of minerals, phase changes, temperature increase, and osmotic membrane phenomena. Systematic evaluation, particularly of the time for dissipation of the elevated head to the head of its surroundings, eliminates most of these explanations. Those that remain as possible explanations are: tectonic compression, temperature increase, and osmotic membrane phenomena. It is not known at present whether the high head is general over the entire basin or only in segments of it.

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DESIGN, DRILLING, COMPLETION, OPERATION, AND COST OF UNDERGROUND WASTE-DISPOSAL WELLS IN GULF COAST REGION OF TEXAS AND LOUISIANA

The first factor in considering the feasibility of underground waste disposal is the quality of the waste stream. A practicable method or methods of removing suspended solids must be planned. Equally important is that the effluent be chemically stable, after filtration, under elevated temperature conditions of the injection zone. Compatibility of the waste with the indigenous brine is necessary to avoid plugging. The disposal well is the final filter in the waste-disposal system; it is the nature of filters to become plugged, and a filter several thousand feet underground is difficult to clean and the cleaning process is usually expensive.

Once the suitability of the waste stream for underground waste disposal has been determined, the reservoir must be selected. Existing knowledge of the subsurface gained from oil and gas exploration will provide enough data to plan the well depth at which several probable reservoirs will have been penetrated. Sand parameters measured in the disposal well will permit selection of the most suitable reservoir. The geologic subsurface study will provide information as to the areal extent and thickness of probable reservoirs.

Well design must meet state requirements for protecting surface freshwater sands and confining the waste to the selected reservoir. Drilling and well-completion techniques, including casing and cement selection to meet corrosion protection needs, should all be planned so as to offer maximum protection against failure of any part of the waste system.

The quantity and quality of the waste stream, the type and size of drilling equipment, and the type of contract used are the principal factors affecting the cost of a disposal well. Area experience with drilling conditions and potential problems, together with a good equipment and material-inspection program, will produce surprising cost reducing results.

Operating an underground disposal well properly is just as important to success as good well design and good reservoir selection. Operating personnel should receive careful training in how to handle new waste sources and maintain good instrumentation and records. A dependable underground disposal system should include a standby or alternate well.

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POTENTIAL IMPACT OF COMMERCIAL LOW-LEVEL RADIOACTIVE-WASTE DISPOSAL PRACTICES ON HYDROGEOLOGIC ENVIRONMENT

The present practices, trends, and conditions in the shallow land burial of "low-level" radioactive wastes have a potential impact on the hydrogeologic environment and on environmental safety. New data are available from recently conducted inventories and surveys of operating conditions at the 6 commercial radioactive waste burial facilities in the United States.

"Low-level" radioactive wastes (as defined by the AEC) are being buried under widely differing conditions caused by local variations in geology, hydrology, weather, and operating procedures. The wastes themselves vary greatly in character from relatively harmless (due to decay or dilute concentration) to extremely hazardous (due to chemical or radioactive toxicity). Other new data include: (1) the potential environmental impact which present trends in "low-level" waste character and quantities pose to the hydrogeo-