deep well injection system, this method has generally not been used for disposal of radioactive wastes. It appears that injection into deep permeable formations may be a practical solution for the disposal of large quantities of tritium-bearing wastes from water reactors and nuclear fuel reprocessing plants in the future. Additional research is also required on the potential deep disposal of noble gases such as krypton-85 from reactor and reprocessing plant off-gas streams.

BREDEHOEFT, JOHN D., and GEORGE F. PINDER, U.S. Geol. Survey, Washington, D.C.

Application of Transport Equations to Flowing Groundwater Systems

To manage a subsurface waste-disposal system effectively it is necessary to predict the response of groundwater systems to various hydrologic stresses. To predict a complex system response generally requires simulation of the field problem through the use of a deterministic model. In the most general case, the complete physical-chemical description of moving groundwater must include chemical reactions in a multicomponent fluid, and requires the simultaneous solution of the differential equations that describe the transport of mass, momentum, and energy in porous media.

The difficulties encountered in solving this set of equations for real problems have forced hydrologists and reservoir engineers to consider simplified subsets of the general problem. The equation of motion for single-component groundwater flow, which describes the rate of propagation of a pressure change in an aquifer, has been solved for many different initial and boundary conditions. To describe the transport of miscible fluids of different density, such as salt water and fresh water, the mass transport equation and the equation of motion have been coupled and solved numerically. Numerical solutions have also been obtained for the heat transport equation and the equation of motion, particularly for convection problems.

A case history of groundwater contamination at Brunswick, Georgia, illustrates the use of the transport equations in predicting the future movement and control of contaminants.

The challenging problem for the future is the simultaneous treatment of mass, momentum, and energy in porous flow and simulation of the complete groundwater system.

COHEN, J. J., A. E. LEWIS, and R. L. BRAUN, Lawrence Radiation Laboratory, Univ. of California, Livermore, Calif.

Disposal of Nuclear Waste by *In Situ* Incorporation in Deep Molten Silicate Rock

Utilizing heat generated by decay, radioactive waste can be solidified and encapsulated *in situ* in deep silicate rock. This method involves the following steps:

1. High-level liquid wastes are injected into chimneys formed in silicate rock by deep underground nuclear explosions. Heat generated by the radioactive decay of these wastes raises the chimney temperature to the boiling point.
2. Once boiling conditions are attained, low- and intermediate-level wastes, plus additional water, are added for disposal and/or temperature regulation. The resulting steam is condensed, processed, and recirculated either as process water to the plant, or as cooling water to the chimney.
3. After waste addition is terminated, the chimney is allowed to boil dry thereby solidifying the waste.
4. Subsequently, heat generated by the radioactive waste melts the surrounding rock.
5. Finally, as the rate of heat output diminishes due to radioactive decay, the molten rock refreezes, permanently trapping the radioactivity in an insoluble rock matrix deep underground.

With nuclear fuel reprocessing and waste management integrated at one common facility, the need for transportation of wastes is eliminated. Consideration must be given to ground motion at detonation time, heat flow, geology, and hydrology during operation.

The explosive yield required is small enough (∼5 kt) that damage from ground motion would be limited to a small area. A site 5 mi or more from small towns and at least 10–15 mi from major population centers should be selected. A chimney or chimneys could be produced most simply prior to construction of a plant.

Cooling water is required at an increasing rate during the period of waste introduction. For a 5-ton/day processing plant the cooling water recirculation rate approaches 1.8 cu m/min at the end of 25 years. The power output of the chimney at this time is about 67 megawatts. If waste introduction is terminated at 25 years, the melt radius grows to a maximum of about 96 m in about 90 years. The molten rock begins to freeze at 90 years and the radius decreases slowly until all of the rock is frozen.

The chimney itself should be placed in low permeability rock. A layer 100 m or more thick is required to contain the chimney and associated fractures. Thus a negligible amount of water will enter the chimney prior to and during the early part of the first phase and no radioactivity will migrate away from the chimney.

Care must be taken to avoid the introduction of radioactivity into rock zones containing mobile water. The system (chimney and holes) would be operated at a pressure less than that in any water-bearing zones except perhaps those close to the surface. A site should be selected with no important aquifers within several hundred feet of the surface and, preferably, none at all.

The requirement for the melting phase is a silicate rock of sufficient dimensions to contain the molten rock at its maximum dimensions. There should be a negligible amount of carbonate rock in order to avoid the generation of CO_2. Once the rock starts to melt, the radioactive materials are dissolved and soon are surrounded by molten rock with little or no radioactivity in the peripheral melt zone.

Economic analyses indicate the costs for waste management (for high-, intermediate-, and low-level liquids) would be equivalent to ∼0.008 mills/KWH.

Environmental advantages of this method would include:

1. Elimination of several waste processing and transportation operations thereby greatly reducing risk of accident.
2. Prompt disposal of wastes eliminating concerns involving long-term storage.
3. Binding of wastes in an inaccessible rock matrix deep underground, giving assurance of its permanent elimination from man's environment.
4. Provision for a safe method of disposal of low- and intermediate- as well as high-level wastes.

DONALDSON, ERLE C., U.S. Dept. Interior, Bureau of Mines, Bartlesville, Okla.

Injection Wells and Operations Today

Bureau of Mines engineers have investigated the applicability 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.

EHRLICH, GARRY G., U.S. Geol. Survey, Menlo Park, Calif.

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.

FERRIS, J. G., U.S. Geol. Survey, Washington, D.C.

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.