are common in those areas, such as along the Gulf Coast, where only lightly consolidated or unconsolidated sands are the disposal zones. These wells employ gravel-packed screen sections and are generally similar to large-capacity water wells in design. Other openhole completions are made in those areas where the disposal zones are in competent rocks, such as limestone, dolomite, and sandstone, and do not require casing. In places where the disposal liquid may attack the cementation of a sandstone or adversely affect a limestone or dolomite, casing is required for the full depth of the hole. Casing may be either of plastic materials or some of the more costly metals, such as stainless steel, Hastelloy, Carpenter 20, or zirconium.

Tubing and packer requirements vary depending on the nature of the waste stream. Lined tubing is required in almost all wells to avoid excess corrosion. Tubing lining may be either sprayed-on plastic or thin-gage metallic alloys swedged to the base metal. Packers must be made of the same materials as the tubing to insure longevity. Some wells employ hydraulic seals rather than packers. This is a good installation if injection is always under pressure.

Detailed designs of each type of injection well are shown, and in every case, safety of the installation is a paramount consideration.

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WATER-MINERAL REACTIONS

Reinjection of formation waters creates few chemical problems if no large change in temperature has occurred, no gas or vapor has separated, access of air has been prevented, and the fluids have had an opportunity to react with the minerals to the point of compatibility. Injection of incompatible fluids may cause chemical problems. There is a need for prediction of fluid-mineral reactions.

Most geochemists who have worked on mineral-fluid reactions have had inadequate data and have been reduced to assuming reaction states. The state most geochemists have assumed is one of equilibrium because it is uniquely defined and readily calculable. In an effort to test the applicability of an equilibrium model under real geologic conditions, real systems have been studied. Systems are chosen where reactions are known to occur and where the reactant minerals and fluids and product minerals and fluids can be identified and analyzed. Very seldom have stable equilibrium (minimum Gibbs free energy) conditions been found, although in some instances metastable equilibrium conditions have been found. The assumption of a stable equilibrium state is a very poor choice of model, especially at temperatures of 100°C and below.

The general lack of attainment of equilibrium in no way impairs prediction of reactions, however. Admittedly there is no *a priori* thermodynamic method of predicting what phase will react, nor can the necessary departures from equilibrium be predicted before a reaction will occur at a significant rate, because thermodynamic arguments are time-independent. However, in geologic systems now accessible, enough reactions are occurring that, by observation, an empirical knowledge will provide a base for predicting reactions.

The equations used for describing reaction states are

$$\Delta G_R = RT \ \ln(Q/K)$$

and

$$\Delta G_R = nF \ (Eh_{eq} - Eh_m)$$

where

ΔG_R is the Gibbs free energy of the reaction
R is the gas constant
T is the temperature in degrees Kelvin
Q is the reaction quotient
K is the equilibrium constant
n is the number of electrons in redox reactions
F is the volt-gram equivalent
Eh_{eq} is the Eh that would be measured if the reaction were at equilibrium
Eh_m is the measured Eh.

ΔG_R is the exact statement of the departure from equilibrium for the reaction of interest.

Reactions should be studied in both reaction directions. Most reactions are asymmetric in that the ΔG_R's required to dissolve most phases are of different values than the ΔG_R's necessary to form the mineral from solution. The reactions should all be treated as congruent reactions. All the species in solution generated by complete solution of the solid must be considered. Using incongruent reactions introduces the unwarranted assumption of equilibrium.

Some generalizations about the result can be made. Small, highly charged cations yield hydrous metastable phases ($Fe(OH)_3$, amorphous silica) or a stable phase ($Mg(OH)_2$) at very slight supersaturations. Subsequent dehydration is very sluggish. Simple anhydrous carbonates require greater departures from equilibrium for precipitation to occur, but dissolve fairly readily. Simple anhydrous silicates dissolve with modest unsaturation but the hydrous crystalline silicates require large supersaturations for precipitation. Sulfide minerals, although they may dissolve with oxidation of the sulfur to SO_4^{-2}, do not form except with enormous supersaturations. The problem is probably with the bisulfide ion. Siderite requires much less departure from equilibrium than pyrite for precipitation, yet both have Fe^{+2} as the cation.

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DEEP DISPOSAL SYSTEMS FOR RADIOACTIVE WASTES

As of July 1, 1971, approximately 100 million kilowatts of nuclear power-plant capacity was in operation or under construction and/or contract. During the 1960s, an extensive research, development, and demonstration program was carried out on the treatment and disposal of all types of gaseous, liquid, and solid radioactive wastes. Geochemical research coupled with extensive field exploration and demonstration studies have been carried out on several deep disposal systems for radioactive wastes including the application of hydrofracturing techniques in bedded shale for low-heat producing wastes and the use of bedded salt and crystalline bedrock for highly radioactive wastes.

The Atomic Energy Commission has adopted a regulatory policy which requires that all high-level liquid wastes from licensed irradiated fuel reprocessing plants must be solidified and shipped to a national respository on land owned and controlled by the Federal Government. A tentative selection of a site near Lyons, Kansas, has been made for an initial salt-mine respository for the demonstration of long-term storage for both solid high-level and long-lived *alpha*-contaminated wastes.

Because of a general requirement for adequate monitoring to assure the safe and effective operation of a 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.

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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.

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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.

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INJECTION WELLS AND OPERATIONS TODAY

Bureau of Mines engineers have investigated the ap-