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-