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UCRL-52522

GEOLOGIC FACTORS IN NUCLEAR WASTE DISPOSAL

DONALD TOWSE

July 1978

This work was supported by the U.S. Nuclear Regulatory Commission under Interagency Agreement DOE 40-550-75 with the U.S. Department of Energy.

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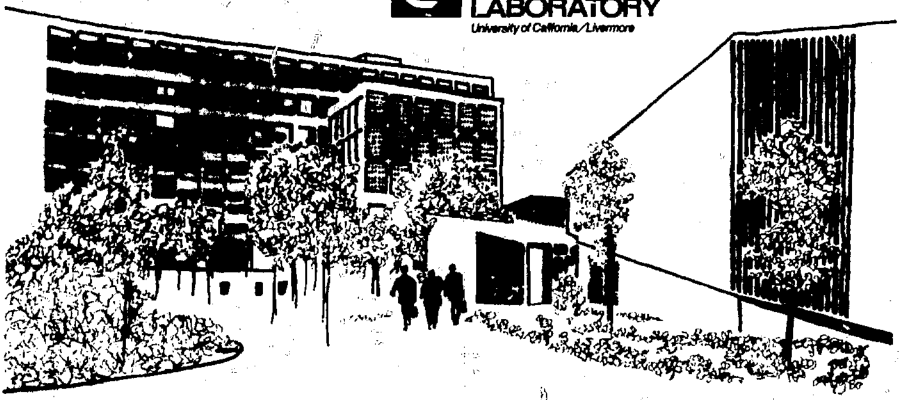

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FOREWORD

The work described in this report was performed by LLL under contract to the Nuclear Regulatory Commission, Office of Nuclear Material Safety & Safeguards under Interagency Agreement DOF 40-550-75 with the U.S. Department of Energy.

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ABSTRACT

The study of geosciences and their relation to nuclear waste disposal and management entails analyzing the hydrology, chemistry, and geometry of the nuclear waste migration process. Hydrologic effects are determined by analyzing the porosity and permeability (natural and induced) of rock as well as pressures and gradients, dispersion, and aquifer length of the system. Chemistry parameters include radionuclide retardation factors and waste dissolution rate. Geometric parameters (i.e., parameters with dimension) evaluated include repository layer thickness, fracture zone area, tunnel length, and aquifer length. The above parameters act as natural barriers or controls to nuclear waste migration, and are evaluated in three potential geologic media: salt, shale, and crystalline rock deposits. Parametric values are assigned that correspond to many existing situations. These values, in addition to other important inputs, are lumped as a hydrology input into a computer simulation program used to model and calculate nuclear waste migration from the repository to the biosphere, and potential individual and population dose and radiation effects. These results are preliminary and show trends only; they do not represent an actual risk analysis.

INTRODUCTION AND SCOPE

The purpose of the Lawrence Livermore Laboratory (LLL) waste management effort is to: (1) determine the important geologic factors involved in nuclear waste migration, (2) quanitify the factors, and (3) develop a technical base for site suitability criteria.

Geosciences are part of a larger, more detailed system study of the waste management process. This report discusses how problems associated with nuclear waste disposal can be examined by analyzing the relevant geologic factors in relation to the back end of the nuclear fuel cycle. Because actual _in situ_ field experiments are difficult and time consuming, at best, and for the long term, impossible, a computer simulation program was developed to determine the major factors of the waste migration process. Studies included risk calculations on different media, geometries, and histories; sensitivity analyses of the important parameters; and uncertainty analyses.

BACKGROUND

To date we have analyzed the deep geologic disposal of the high-level waste product from a nuclear fission cycle, and are beginning the analysis of site design problems and of spent reactor fuel as a waste product.* As shown in Fig. 1, options available for the disposal of nuclear wastes include: (1) disposing directly of spent fuel, or (2) reprocessing spent fuel to recover the plutonium or the uranium. If the spent fuel is reprocessed, the plutonium may be stored or it may be used as part of the mixed oxide (MOX) fuel cycle, or the uranium may be used as a fuel and the plutonium may be stored or wasted.

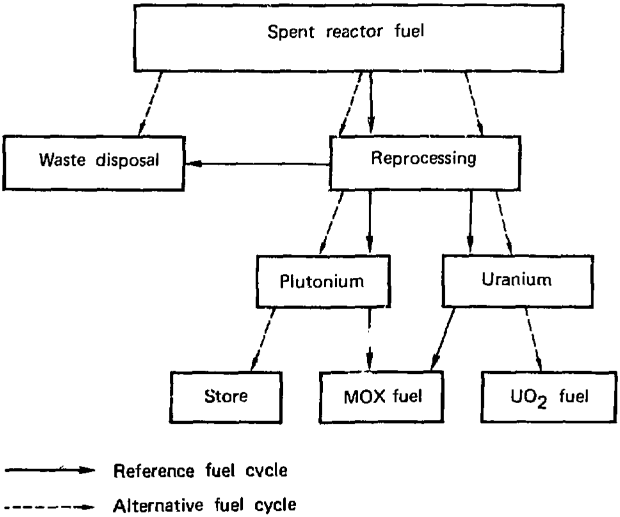

FIG. 1. Options available for nuclear waste disposal.

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*Reference 1 contains an extended treatment of the analyses and the models used.

Nuclear waste disposal presents unusual problems in hydrogeology and rock mechanics:

- Radionuclides decay with time.
- Radionuclides are retarded through the geosphere. Iodine and technetium are not retarded; they move directly with the flowing water. Fission products are retarded by a factor of 10^3 or 10^4. Some transuranic elements are greatly retarded. Figure 2 illustrates the potential hazard of waste materials after removal from the reactor.
- Heat and radiation are produced by the spent fuels. The heat, which amounts to at least 3.5 kW per unit of high-level waste, and the radiation may change the physical performance of the rock in a repository.
- Water velocity is slow.
- Time periods are considered in terms of tens or hundreds of thousands of years, which is greater than the usual time periods considered for engineered features.

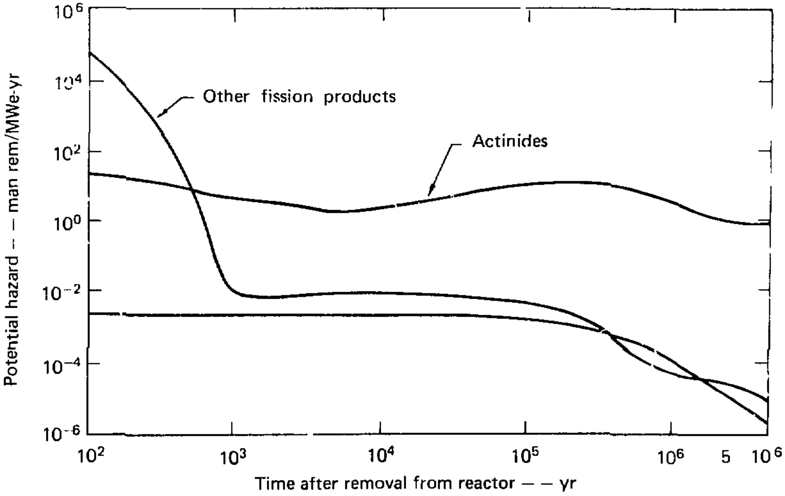

FIG. 2. Potential hazard of nuclear wastes after removal from the reactor.(1)

To decrease individual and population radiation exposure, radionuclide retention time must be increased to allow radioactive decay of the hazardous nuclides. Individual exposure can be decreased through dispersion of the contaminant, and could be achieved by increasing the geographic distances between the repository and the biosphere, by decreasing the velocity rate of flow, by increasing retardation factors, or by lowering the solubility rate through critical selectivity of waste forms. The radionuclide retardation system is illustrated in Fig. 3.

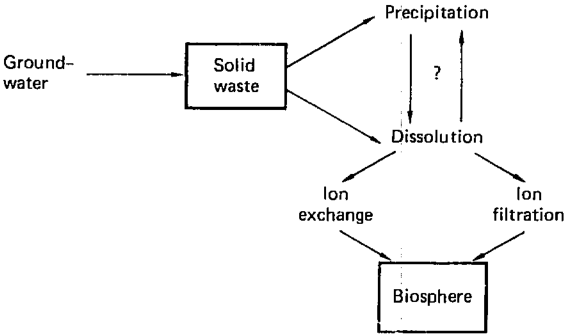

FIG. 3. Radionuclide retardation system.

ANALYSIS OF GEOSCIENCES

As seen in Fig. 4, the geosciences related to nuclear waste migration include: (1) geochemistry--the effect of chemistry on the waste and the interaction of the waste, the water, and the rock; *(2) hydrogeology--controls* of rate and volume of water flow; (3) rock mechanics--the effect of heat, radiation, and stress on the rock; (4) climatology--as it bears on the hydrogeology environment; and (5) seismology--the effect of earthquakes on underground structures, a small but important part of the geological sciences.

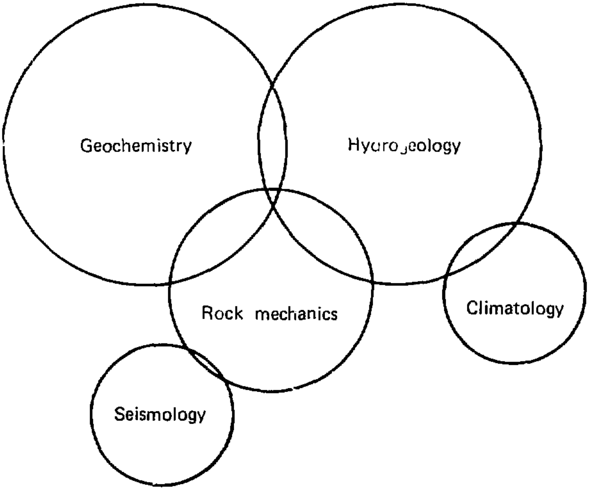

FIG. 4. Geoscience areas affecting radionuclide migration.

Parameters of hydrology, chemistry, and geometry that affect nuclear waste containment consideration are listed and discussed below. These parameters act as natural barriers or controls to waste transport from the repository to the biosphere.

- Hydrology
    - Rock properties
        - Porosity
        - Permeability (natural and induced)
    - System properties
        - Pressures and gradients
        - Dispersion
        - Aquifer length
- Chemistry
    - Radionuclide retardation
    - Waste dissolution rate
- Geometry
    - Layer thickness
    - Fracture zone area
    - Tunnel length
    - Aquifer length

BARRIERS AND CONTROLS

Hydrology can be analyzed by considering porosity and permeability of the natural rock. Porosity and permeability control the velocity of water flow in the rock. In addition, the system properties, i.e., pressures, pressure gradients, dispersion, and distance to the biosphere, control the time and, therefore, the nuclide concentrations within the system.

The chemistry of the radionuclide migration system includes the retardation of radionuclides, whether by absorption or complexing or other processes that control the retardation. The solubility or rate of dissolution of the waste affects the introduction of the waste products into the water system.

Geometric parameters have dimension, i.e., the length of flow paths and area of flow paths, which in turn control time and volume of water flow toward the biosphere. These also include thickness of rock layers; areas of fracture zones, whether singular and in faults or in general throughout the rock mass; length of tunnels, drill holes, and other man-made features and their associated induced permeability; and length of an aquifer or other path between the repository area and the earth's surface.

POTENTIAL GEOLOGIC MEDIA

Salt, shale, and crystalline rock types are being considered as deep geologic waste disposal media in the United States and abroad, as shown in Figs. 5 through 7.(2) These media vary in quality and physical characteristics.

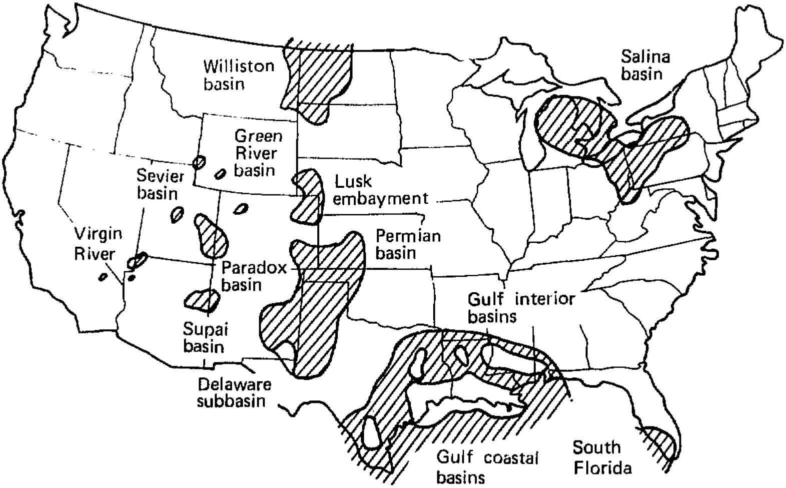

FIG. 5. Major salt areas in the United States

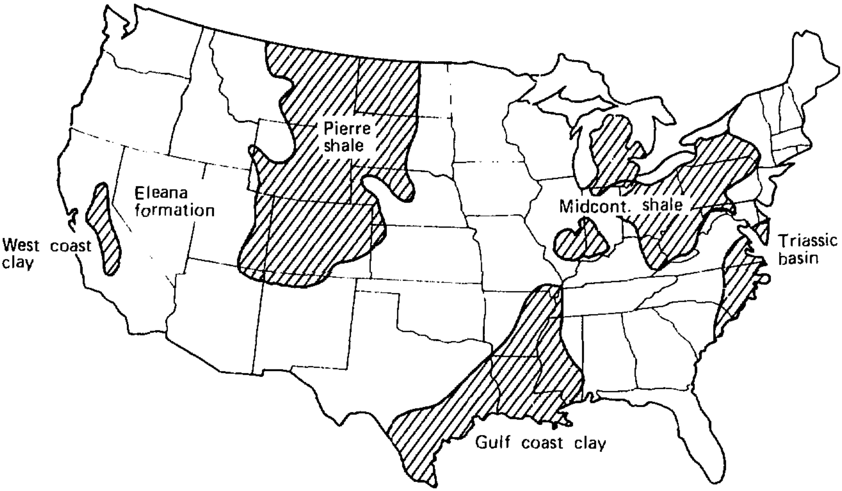

FIG. 6. Major shale areas in the United States

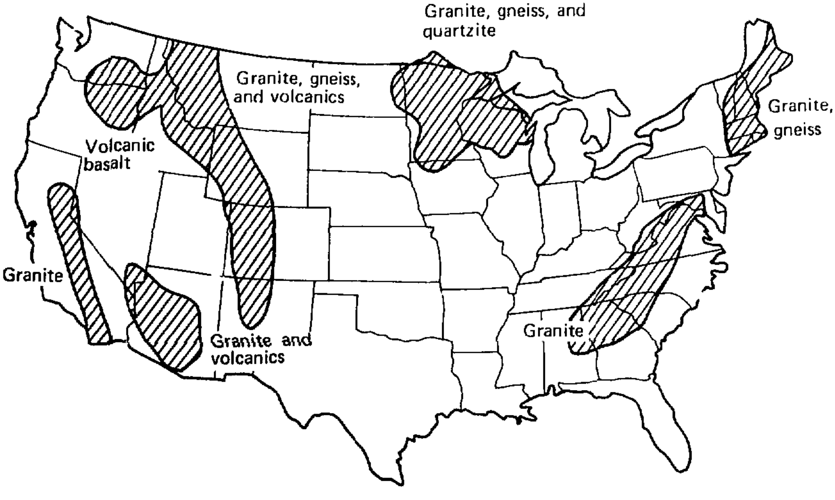

FIG. 7. Crystalline rock areas in the United States

Salt has been considered as a deep geologic waste disposal medium for many years.(3) It has low permeability, high heat conduction, and openings can be engineered easily at nominal depths. Because salt is plastic and tends to deform easily, plastic deformation closes the mine openings and may heal the fractures and other openings that might produce leaks to the biosphere. However, radionuclide retardation is low in chloride brine solutions. The high solubility of salt allows it in time to dissolve and to form an opening that might result in vertical breccia pipe development or other subsidence features. Also, the movement and migration of liquid inclusions within the salt could cause corrosion, dissolution, and other undesirable processes in and near waste canisters. In addition, most salt basins contain other valuable resources that may tend to promote future exploration and possible penetration of the repository, or may prevent these resources from being used in the future.

Currently in West Germany,(4) low-level and medium-level nuclear waste is being stored in salt. In the United States, large salt deposits are commmon in many of the intracratonic basins throughout the continent. The Permian basin of the southwestern United States is the site of an experimental program by the Department of Energy (DOE) near Carlsbad, New Mexico. Because potable water is an important resource in most West and Southwest areas and will continue to be in the future, sites with important groundwater resources should be analyzed carefully with a view toward preservation and conservation. If, however, the water is highly saline or unusable, the aquifers in the region may provide a suitable site for the dispersion, dissolution, and eventual containment of nuclear waste.

Shale is considered as a desirable disposal medium because it demonstrates low permeability and, with many types, a high retardation factor. There is some plasticity in shale that might promote healing of fractures, and economical mining is possible. Several disadvantages include possible fracture permeability and low strength in many places. Response of shale to the thermal energy from the nuclear waste and its reaction with the water and the shale minerals is a possible source of mechanical failure. Shale areas, much like salt areas, contain large mineral fuel resources and other hard minerals. Future exploration or mining activities should be studied before considering shale basins as possible nuclear disposal sites.

Large shale areas exist in the United States, notably the Triassic basins near the east coast, the Illinois and Michigan basins, and the Pierre shale of the western plains states. The small Eleana shale area at the Nevada Test Site currently is being analyzed by DOE contractors.

Crystalline rocks vary in grain size, foliation, and geometry. The igneous metamorphic and volcanic rocks are harder than sedimentary rocks; have a higher strength; and, thus, are more difficult to mine than sedimentary rocks. Their high strengths, however, allow deeper mining and stronger underground openings. Insufficient information exists regarding deep water circulation in crystalline rock, although investigations have been made in Canada and Sweden. The low permeability of most crystalline rock is an advantage; however, they are subject to fracture permeability and singular features such as fracture zones and fault zones. The volcanic rocks may be interlaid with other types of volcanic debris with high permeability. The retardation in many of the volcanic rocks appears promising, but little is known about the actual in situ processes in these harder rocks, particularly at depth. The mineral resources in crystalline rocks include many metals and nonmetals, but are more dispersed and occur over smaller individual areas than do the fuel minerals and other nonmetallics in sedimentary basins.

The crystalline rocks, granite, quartzite, and volcanic rocks in the United States comprise large areas, which include the shield areas in New England, Wisconsin, and northern Michigan, and the granite metamorphic rocks in the Piedmont area in the Southeast. The Rocky Mountain ranges and the Sierra Nevada are largely granite or volcanic areas. The Snake River plain and the Columbia River basin in the Northwest contain bedded volcanics. Currently, investigations are being performed at the Hanford Reservation in Washington to test the bedded volcanics as a possible nuclear waste disposal medium.

MODELING AND SIMULATION

To measure or model individual or population dose effects, we must assume migration of the nuclear waste. This is a conservative approach, and is not necessarily applicable to any real waste repository. It allows us to measure the sensitivity of the system to different geologic and geometric factors. We assume: (1) the repository will be resaturated by inflow into the facility; (2) the surrounding rock has some finite permeability, however low; (3) a pressure system promoting flow to the biosphere; and (4) a waste that is soluble to some degree. To accomplish this, we have used geologic parameter values similar to many existing situations, and by exercising the model, we calculate nuclide concentrations at several points along the paths to the biosphere and doses to the individual and population. These results are preliminary and show trends only; they do not represent an actual risk analysis.(1)

Model input includes parameter values that describe the geologic-hydrologic system, i.e., the chemical, hydrologic, and geometric properties shown in Fig. 8, lumped as a hydrology input. The other important input is the radiological source term, the composition, solubility, and the radiolytic decay history of the waste form. This is calculated by use of the Oak Ridge ORIGEN(5) code (as shown in Fig. 8). The transport model, which models transport to the geologic system, waste dispersal, and radionuclide retardation, provides concentrations at several points in the system. From these, the dose model, which models the biologic and surface water system, can provide the dose and radiation effects on humans.

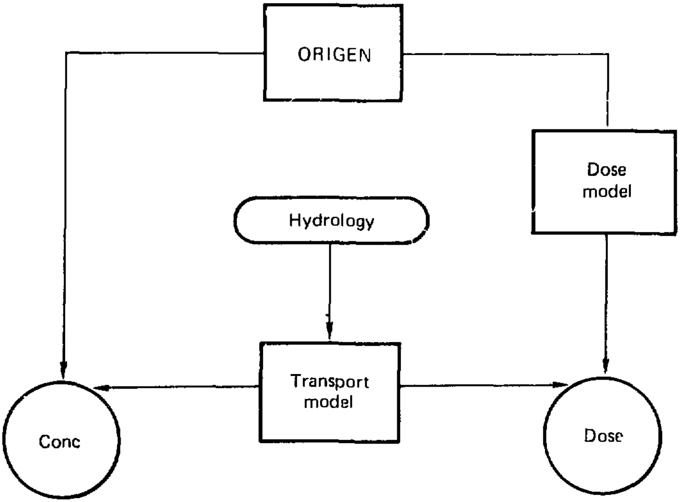

FIG. 8. Mathematical models used to provide dose and radioactivity effects information.

Figure 9 illustrates the physical model, which is one of many configurations that could be used. In this model, the repository is sited in a thick salt or shale bed and is connected to the surface via a tunnel and shaft. Above and below the repository are barrier beds, less thick; above and below the barrier beds are the two aquifers. The bottom aquifer has a pressure such that flow is induced through the repository layer, through the upper barrier layer, and into the near-surface aquifer. In turn, the near-surface aquifer has a gradient such that the flow is induced to the biosphere, represented by a river.

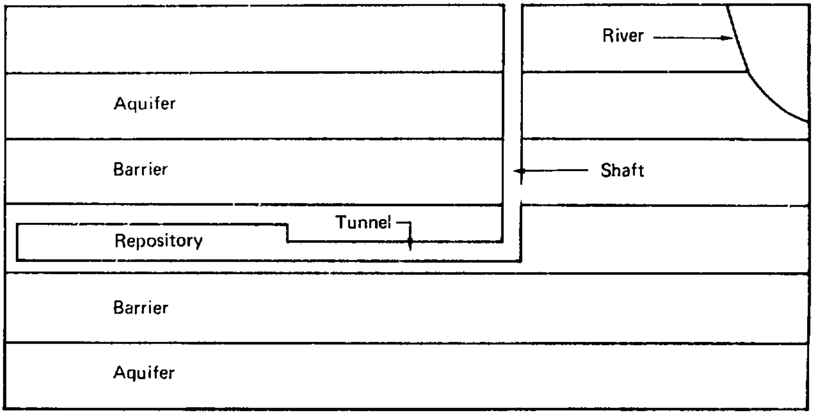

FIG. 9. Representative model configuration for repository in salt or shale deposits.

Figure 10 illustrates a surface water system based on an actual river basin. Contributing sources to individual and population dose include: aquatic foods; direct contact with water; drinking water supply; and secondary sources where contaminated water may be absorbed by plants that are consumed directly by man, or by plants used for animal feed, which, in turn, are consumed by man. This example represents one measure of the relative effect of the radionuclides in the biosphere.

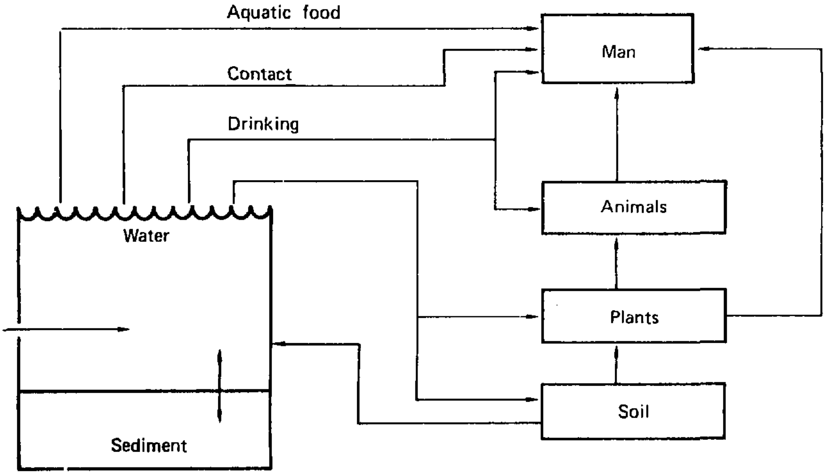

FIG. 10. Representation of surface water system.

FLOW REGIMES

Figure 11 shows the essential features of the flow path model. Flow paths are selected and modeled as one-dimensional flow pathways with Darcy flow. In the basic unflawed case, with a repository in either shale or salt, one pathway of modeled flow is through the undisturbed rock from the lower aquifer, through the barrier bed, through the repository layer, and to the upper aquifer where the flow is then directed toward the river. Another set of important possible flow paths is along the fractures induced by mining of the repository rooms, tunnels, and shaft. There will be several shafts in most designs, two or three for men or materials or waste, and several for ventilation. When the permeability and porosity values of the rocks are reasonable and when there are important differences in permeabililty between the flow paths and the separate layers, this one-dimensional system appears to be adequate for the purposes of our sensitivity analysis. Examples of results through this unflawed repository case will be presented later.

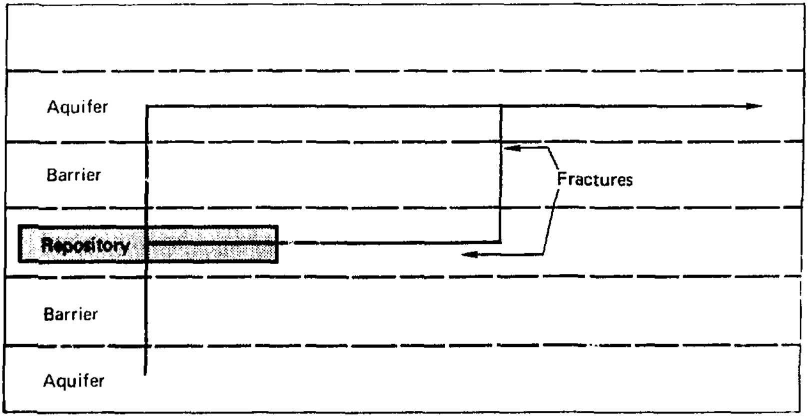

FIG. 11. Model of unflawed flow pathway in salt or shale deposit.

Similarly, as shown in Fig. 12, flow paths along man-made features can be simulated. For example, a drill hole entering the repository is an additional flow pathway, and if the backfill or the grouting around the tunnels and the shaft deteriorate, other flow paths may be formed. These are simulated in our model by additional pathways.

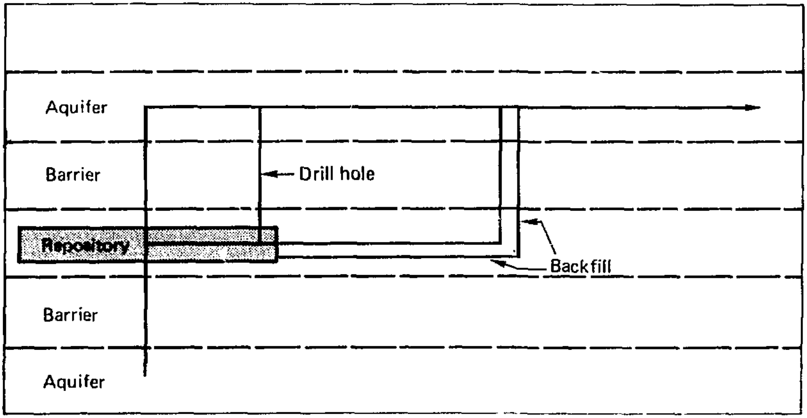

FIG. 12. Model for flow pathways with man-made features in salt or shale

Natural features such as a fault through the repository or a breccia pipe collapse above the repository, as shown in Fig. 13, can be simulated in this manner. Simulations of natural and man-made features provide a measure of sensitivity of the system to these types of flaws. The effect of changes from the fluvial cycle can be similarly simulated by changing the artesian pressures and the pressure gradients in the model.

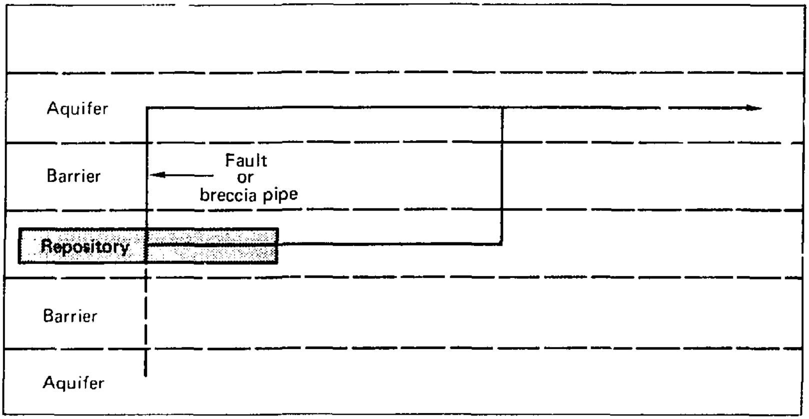

FIG. 13. Model for flow pathways with natural features in salt or shale deposit.

EXAMPLE CALCULATIONS

A few examples of simple calculations and results are discussed below for relative comparison to illustrate the sensitivity of some of the important groups of parameters and the use of the simulation model. The simulation results show the effect on dose resulting from chemical and hydrologic parameter changes. The doses given are relative, and do not simulate an actual site.

Results plotted in Fig. 14 represent the base case for a repository in shale, which separates two aquifers and has no flaws except a small induced permeability around the man-made openings in the facility. The plot shows dose as a function of time calculated in terms of the individual 50-yr whole-body dose in rem/MWe-yr. The repository is expected to hold about 6,000,000 MWe-yr of radioactive waste. These illustrative results show minimal individual dose. Concentrations and population doses are other measures of risk that often produce different conclusions. In this unflawed base case, almost 10,000 yr could elapse before the first nuclides migrate to the surface water system at a distance of 16 km (10 mi) from the repository. Over this long stretch of aquifer and through the slow movement of the waste water upward through the repository area, radioactive decay occurs, thus lowering the exposure risk factor. All three control systems influence these events: the chemical, with a high retardation factor; the hydrologic, with tight impermeable rocks and a slow water flow; and the geometric, with a long distance from the repository to the biosphere.

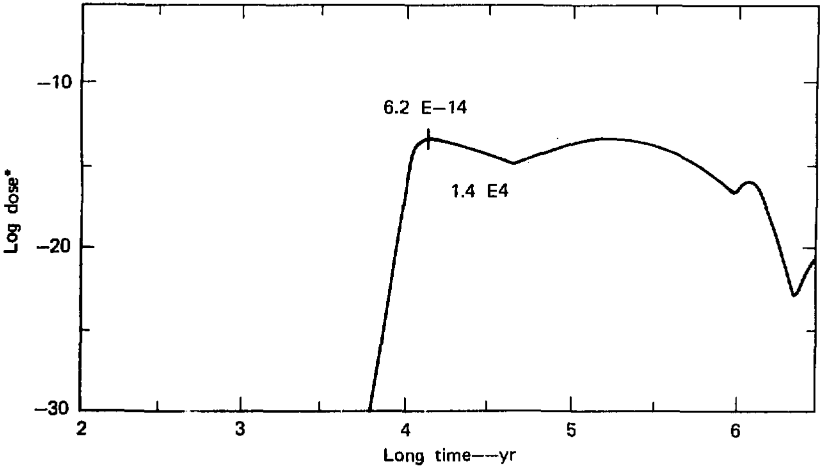

FIG. 14. Representative base case for a repository in shale deposit.

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*Illustrative relative dose (see text).

Results plotted in Fig. 15 illustrate conditions the same as for the base case except for the chemical retardation, the value of which has decreased 100 times. Such a change in retardation might be the result of unfavorable rock chemistry or of competing ions in a brine-filled aquifer system. Note that the first arrival of waste material is at nearly the same time as in the base case because of the unchanged hydrologic factors, but that the dose to the individual is higher throughout the time; the maximum dose at 1200 yr is 100 times greater than the base case.

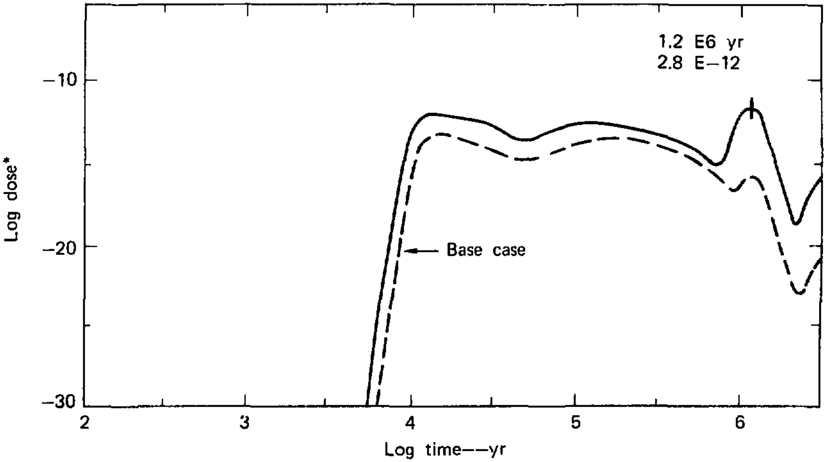

FIG. 15. Representative chemical retardation change from base case conditions.

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*Illustrative relative dose (see text).

Figure 16 illustrates the effect of increased permeabilities in the fractures around the repository and in the aquifer that carries waste to the biosphere. In this case, the hydrologic controls have been lost while the geochemical controls remain, resulting in a rapid flow over a short time through the escape route to the biosphere. The same result could be had from a shorter distance, i.e., a loss of some of the geometric controls, or by increased pressure differentials that would increase the flow velocity. Note, by increasing the permeability 100 times, the maximum dose is increased by approximately the same amount. In this case, there is an early release of radionuclides, and, therefore, some of the shorter-lived fission products are coming to the biosphere here, as well as some of the longer more mobile ones such as iodine and technetium. Integrated over time, the total dose is significantly greater than in the base case.

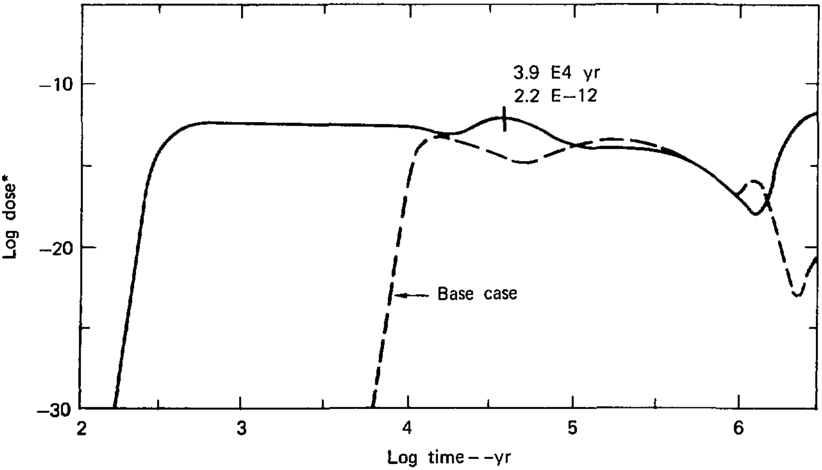

FIG. 16. Representative increased fracture and aquifer permeabilities effects.

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*Illustrative relative dose (see text).

In Fig. 17, hydrologic and chemical controls have been lost. This is simulated by increasing the permeability values (as in Fig. 16) and by decreasing the retardation factors (as shown in Fig. 15). In this case, we have an early release of waste material and a significantly greater individual dose. Note that at 41,000 yr, the maximum dose is 10,000 times greater than it was in the base case of the unflawed shale repository. Then, with earlier release resulting from reduced hydrologic controls, the integrated effect over time is greater.

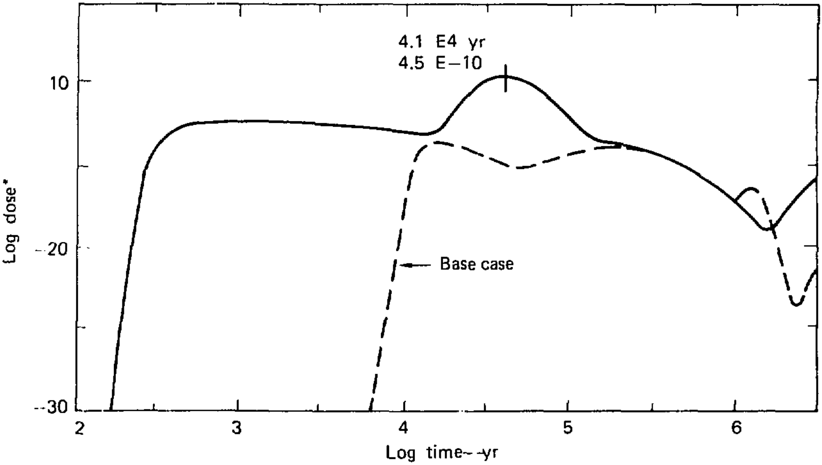

FIG. 17. Representative increased permeabilities and decreased retardation effects.

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[*] Illustrative relative dose (see text).

CONCLUSION

By constructing a simple flexible model that simulates release of waste to the biosphere and the resulting effects on man, we have been able to analyze the three control groups that form barriers to radionuclide migration and the important related parameters, as well as analyze how the operation of the system relates to long-term radiological risk.

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