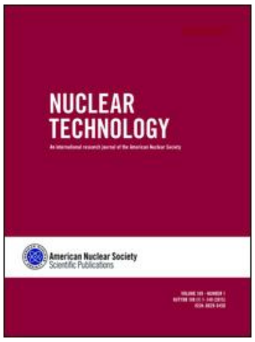

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GEOHYDROLOGIC CONSIDERATIONS IN THE MANAGEMENT OF RADIOACTIVE WASTE

RADIOACTIVE WASTE

KEYWORDS: *geology, liquid wastes, radioactive waste management, hydrology, radioactive waste disposal, underground disposal, solid wastes*

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Nongaseous radioactive wastes occur as liquids containing high-level concentrations of radionuclides, liquids containing low concentrations of radionuclides, and solids contaminated by radioactivity. Whether released by accident or design into the earth or onto the earth's surface, only water is capable of transporting significant quantities of radionuclides away from burial sites. Geohydrologic information that must be determined to predict the velocity and direction of waste movement from a site include climate, hydrology, detailed subsurface geology, permeability, porosity, sorptive potential, seismic potential, and geologic history of the area.

Since the late 1960's mathematical models have been used to make predictions of waste transport in some hydrologic systems. Intensive field investigations at each site are needed before these models can be used.

INTRODUCTION

Radioactive wastes are generated at several different times or stages in the uranium fuel cycle. The more important sources of waste result from activities involving mining, milling, refining, and fabrication of the fuel, the reprocessing of spent fuel elements for the recovery and reuse of the unused uranium and/or plutonium, and to a lesser extent nuclear research and development. Wastes so generated range from low-level waste which can be discharged to the environment, pursuant to U.S. Atomic Energy Commission's (USAEC) *Manual*,[1] to high-level wastes which are to be converted to suitable physical and chemical forms and confined in a manner which shall provide high assurance of isolation from man's environment with a minimal reliance on perpetual maintenance and surveillance by man, under conditions of credible geologic, seismic, and other naturally occurring events.[2]

Nongaseous wastes occur as liquids containing small amounts of low-level radioisotopes, liquids containing high-level activity, solidified products of high-level liquids, and the low-level solid contaminated wastes disposed of routinely in burial grounds located in selected areas on large isolated sites controlled by the USAEC or its licensees. These solid low-level wastes consist of paper, clothing, wood, metal, and other materials which have become contaminated and, as such, have no useful or economic value. Such wastes are usually buried in shallow (6- or 7-m-deep) trenches and covered with sufficient soil to achieve shielding.

Low-level liquid wastes are either ponded at the earth's surface or discharged into cribs or dry wells several meters deep but bottomed tens of meters above the water table. Low-level liquids with concentrations below the maximum permissible as defined by the USAEC[1] have also been discharged directly to streams; this process will no longer be used in commercial fuel processing plants. Monitoring of some of low-level waste disposal operations indicates that burying of solid waste and discharging of liquid waste to the ground have not resulted in the migration of biologically significant amounts of radiation beyond the controlled areas. However, it should be recognized that not all burial sites are monitored and that these burial and discharge practices have been used only during the past 30 years; whereas the longevity of the toxicity of these wastes is measured in terms of hundreds of years and in the instances of some alpha emitting wastes, such as ^{239}Pu, the waste products must be considered hazardous for hundreds of thousands of years. USAEC policy now requires that solid wastes with transuranic (alpha) nuclide activity above 10 nCi/g must be stored so that these wastes can be readily retrieved intact after a period of 20 years.[3]

The primary purpose for burying solid waste or the ponding and/or discharging of low-level liquid waste on or into the surficial deposits of the earth is to immobilize or lock up radioactivity in the earth's materials. The intent is good and, where it can be accomplished for the toxic life of the material, it may be a reasonable answer to one of the controversial problems in the development of nuclear energy. However, some of the geohydrologic processes which apparently are useful in the solution of the waste problems can and often do raise other problems which must be resolved before it can be said that the wastes have been disposed of permanently and safely.

Once waste material is buried or released beneath the soil, only water is capable of transporting it in significant quantities away from a burial site on or beneath the surface of the ground. For this reason, to evaluate the suitability of the site for disposal it is necessary to determine the amount, direction, and rate of water movement through a disposal site. Of equal importance are the direction and rate of movement of water after it leaves the immediate disposal site.

The principal mechanism preventing or modifying water-borne movement of radionuclides buried in the ground is sorption on mineral particles comprising the soil and bedrock. To measure the sorption process of a burial site it is necessary to obtain detailed information on (a) the mineralogy (by size fraction including colloidal material) of all stratigraphic zones traversed by the waste solute, including those zones in the unsaturated zone; (b) the chemistry of the aquifer water and water in the confining beds; (c) the chemistry of the leachate from the waste fields; and (d) the distribution coefficient (K) by laboratory experiments, for the critical nuclides in representative samples of each permeable zone along paths of waste movement away from the burial site.

Toxic radionuclides in buried low-level waste can be moved from the burial site and released to the atmosphere, the hydrosphere, or the biosphere by three different naturally occurring mechanisms:

1. The radionuclides can be desorbed by percolating ground waters and moved by gravity downward to the water table where they can then move laterally to points of discharge such as at wells, springs, or as groundwater increments to bodies of surface water.

2. After being desorbed, the nuclides can be transported upward to the soil zone by capillary flow and from there be concentrated in the plant life or as salts on the land surface by evapotranspiration processes.

3. Waste materials and nuclides disposed or stored in surficial materials can also be exposed at the land surface by the normal erosional processes of water and wind erosion due to extreme flooding, or erosion following disruption of the landscape by earthquakes or landslides.

The suitability of an area for disposing of low-level waste in the surficial deposits, therefore, depends on the potential of such an area for preventing the occurrence of these three release mechanisms. Criteria for the evaluation of a site's potential for preventing the work of one or more of the release mechanisms have been discussed by many geohydrologists including Lieberman and Simpson,[4] Peckham and Belter,[5] Richardson,[6,7] Mawson and Russell,[8] Cherry et al.,[9] and more recently Papadopulos and Winograd.[10]

The approach used by Cherry et al.[9] of classifying burial sites for low-level waste as (a) intermediate term sites, suitable for wastes that decay to a safe level within several decades and for which protection is mainly provided by the engineered structure in which the waste is buried, and as (b) long-term sites for wastes with a longer life, which depend mainly on geohydrologic conditions for protection, appears to be a rational approach to the site evaluation problem. Criteria used by Cherry for intermediate-term burial sites include

1. burial site devoid of surface water except snowmelt and rainfall

2. burial trenches sufficiently above fractured bedrock to prevent migration of radionuclides through the bedrock

3. predicted rate of waste solvents movement provides decades of delay time before radionuclides can reach undesirable areas

4. water table, naturally or artificially, below bottom of burial trenches

5. site hydrologically suitable to monitoring and to waste containment by groundwater flow manipulation by pumping.

Cherry's criteria for so-called long-term burial sites can be expressed as

1. burial site devoid of surface water and stable geomorphically

2. groundwater flow paths that do not lead to undesirable areas
3. predicted residence time of radionuclides in the order of hundreds of years (hydrologic system must be simple enough to make possible reliable residual-time predictions)
4. the highest water table several meters below burial zone.

Papadopulos and Winograd[10] have used the hydrologic criteria presented by Cherry et al.[9] to formulate guidelines in defining the types of basic data that are needed to study and monitor the efficiency of the geohydrologic environment of a selected site for burial of low-level waste.

The basic data needed for site evaluation include the following:

1. depth to water table
2. location and distance to points of water use
3. minimum of 2 years precipitation and land pan evaporation records
4. water-table contour map for different seasons of the year
5. magnitude of annual water-table fluctuations
6. detailed stratigraphic and structural data to base of shallowest confining aquifer
7. base-flow data on nearby perennial streams
8. chemistry of water in aquifer, confining beds and of leachate from burial trenches
9. laboratory measurements of porosity, permeability, mineralogy, and ion exchange capacities of each lithology in saturated and unsaturated zones
10. a record of at least 2 years of moisture content and *in situ* soil moisture-tension in the upper 10 to 15 m of unsaturated zone at burial site
11. three-dimensional distribution of heat to base of shallowest confining aquifer
12. field test determination of storage coefficient and transmissivity
13. definition of recharge and discharge areas
14. field measurements of dispersion coefficient
15. laboratory and field determination of the distribution coefficient
16. rates of denudation and slope retreat.

DISPOSAL OF LOW-LEVEL RADIOACTIVE SOLID WASTE

Prior to the selection of a site for the burial of low-level solid radioactive waste, the candidate sites need to be evaluated to determine if their geohydrologic parameters are suitable for monitoring future movement of the waste. Unless the waste can be monitored for substantial periods following its emplacement, there is no way to confirm the safety of the site. All the disposal sites that are in use today need to be monitored to demonstrate their safety. Gross geohydrologic parameters that need to be considered in the preliminary evaluation of site safety include the following

Precipitation

The major source of groundwater and surfacewater potentially capable of transporting activity from a burial site to a point of release to the environment is precipitation. Hence, the greater the precipitation the greater the possibility of activity migrating away from the site.

Topography

The topography of a site including the location of streams and other bodies of surfacewater is an important consideration in determining site suitability for use as a burial ground. A relatively flat level surface is desirable, as this permits maximum utilization of land and simplifies burial operations. However, in the humid parts of the country, areas with flat level surfaces are usually characterized by shallow water tables, and the land area may be subject to flooding.

Geology

The characteristics of the overburden ideally should permit easy excavation of burial trenches with conventional earth moving equipment. The texture of the overburden should be such as to permit the trenches to stand open without support. Ideally, the depth of the overburden should be thick enough to provide several meters of earth materials between the bottom of the burial trench and the top of the underlying bedrock. Bedrock characteristics are also important with unconsolidated rock being preferred to consolidated rock for reasons to be discussed later.

Permeability and Porosity

The overburden material needs to be sufficiently porous and permeable to permit water that may collect in the burial trench to drain readily and not to pond or accumulate in the bottom of the excavation. With reference to bedrock, some consolidated rocks such as shale, limestone, and crystalline rocks are inferior to unconsolidated rocks for safety of burial grounds. The joints, bedding planes, fractures, and other openings that commonly occur in consolidated rocks permit, under certain conditions, waste solute velocities which are much greater than the velocities usually occurring in granular materials and therefore do not afford as much retention time in the movement of waste material. More importantly, granular materials such as sand, silt, or sandstone afford a much greater surface area per unit of volume for sorption and thereby aid in the retention of waste. In addition, the presence of significant fracture permeability greatly complicates predictions of waste transport.

Sorptive Properties

The ability of earth materials to sorb, or otherwise immobilize or slow down the movement of water-borne radioactive waste, is the principal reason some environments are acceptable for the disposal of low-level radioactive waste. Therefore, it is essential that the mineralogy of the soil and rocks of a proposed burial site be thoroughly investigated. The chemistry of the natural groundwater also needs to be known to predict sorption properties of the soil or rock with respect to specific dissolved nuclides. Although some general work has been done on this subject, the work is not believed to have progressed sufficiently to safely generalize on soil and water types. Laboratory studies of undisturbed rock samples collected from each site must be considered along with field measures of sorption distribution coefficient.

Groundwater

Groundwater generally may be divided into two principal zones, the upper near-surface zone of active flow, which extends from the level of the water table to the first impermeable material of general extent reached by the groundwater in its downward percolation, and a deeper zone of relatively stagnant flow. Frequently, the deeper zones lie below both the base level of the larger surface streams and the first impermeable stratum. There may be two or more deeper zones. In the deeper zones, the direction and characteristics of flow may be independent of local topography and be controlled by regional topography and hydrogeologic conditions. In burial ground operations in humid areas primary concern is with the upper near-surface zone of active flow. In arid regions, however, it is possible for leached radionuclides from burial grounds to reach the deeper zone of flow and become a part of the regional groundwater flow system.

In humid areas the near-surface zone of groundwater flow that is of concern is generally confined to the drainage basin in which the burial ground may be located. The source of water in this zone is the precipitation within the drainage basin, and the direction of flow conforms primarily to the configuration of the land surface; that is, in the near-surface zone, groundwater flow follows the general direction of surface drainage.

Water moving through the near-surface zone is discharged at the surface to the nearest stream down-gradient from the area of recharge. Thus, the distance traveled underground is controlled by the density of surface streams and the topography. The rate of groundwater flow, or velocity, in this near-surface zone is controlled by the hydraulic gradient and the permeability and porosity of the soil and rocks. In humid regions with high drainage density, water reaching the water table may be discharged on the surface after traveling at most a few hundred meters underground.

The depth to the water table below the land surface varies greatly in different localities. In arid regions, its depth may be measured in hundreds of meters. In humid regions, it is usually but a few meters or at most tens of meters below the surface. Low permeability materials and high rainfall tend to make groundwater stand high beneath topographic highs and to form water tables with steep hydraulic gradients. Conversely, coarse materials and low rainfall favor formation of low water table and low gradients. The depth to the water table is of critical concern in shallow land disposal. Circulating groundwater is the only natural vehicle capable of transporting significant quantities of activity from point of burial to point of discharge at the surface. For this reason the bottom of the trenches in which radioactive waste is buried needs to be above the water table at all times.

Reactions between water-borne radionuclides and minerals in soil and rock are influenced profoundly by the chemical characteristics of water. For this reason, a knowledge of the chemical character of water in the burial zone of groundwater flow and their effects on possible reactions between the more critical nuclides and local earth materials is required.

Surface Water

The density of the surface stream network is controlled principally by the amount and seasonal distribution of precipitation and by rock type. The stream density is important in that it controls the distance that groundwater, in the upper zone of active circulation, can move from point of recharge in interstream areas to points of discharge along stream courses.

Streamflow, like precipitation that generates it, varies with time and space. The waste disposal or storage manager needs to be concerned with the magnitude of flow and its variations in time in streams that drain burial sites. The flow variations control the amount of dilution of radionuclides that might enter the stream. In view of the wide seasonal variation in streamflow, dilution calculations based on average flow are not meaningful. A more conservative figure of discharge is the discharge that is exceeded 90% of time or some other realistic low-flow figure.

Information on chemical and physical quality of the water in streams draining disposal areas is needed to evaluate possible reaction between the more hazardous nuclides and mineral and organic material suspended in the water and on the streambed.

Water Use

The possibility of contaminating areally significant bodies of groundwater by disposal operations needs to be considered. In humid areas the short horizontal distances usually involved between recharge and discharge points plus the rural location of disposal sites suggest that at a maximum only a few domestic groundwater supplies would be jeopardized. However, the possible contamination of surface waters downstream from disposal operations cannot be dismissed. In arid regions or in areas where the disposal operation may be located on a recharge area for deeper aquifers, a whole aquifer system could be in jeopardy.

DISPOSAL OF HIGH-LEVEL RADIOACTIVE WASTE

High-level waste is described by Pittman[2] as being of any one of three types: (a) high-level liquid waste, (b) the products from solidification of high-level liquid waste, or (c) irradiated fuel elements, if discarded without processing.

When considering where and how these wastes will be managed or disposed of, each of the geohydrologic parameters previously discussed for shallow land burial needs to be evaluated for any selected geologic environment plus the effects of geologic processes which are operative through geologic time. Admittedly, surface hydrology has a different priority of importance when considering the isolation of waste products in geologic structures several hundreds of meters below the land surface, but still it is an important consideration in the overall analysis.

Isolation of Wastes

Probably the single most important hydrologic consideration in high-level waste management is the isolation of the waste products from circulating groundwater. If the waste can be so isolated it can be considered to be immobile. If it is not immobile then all considerations which apply to shallow burial of low-level waste need to be examined—where and how fast it will move within the toxic life of the waste.

Providing complete assurance of immobility for hundreds of thousands of years does not appear possible to many geohydrologists. However, if we accept the uniformitarian principle, the view that existing natural processes acting in the same manner and under essentially the same intensity as at present are sufficient to account for geologic changes in the past, it is not unrealistic to evaluate which geologic environments appear to have the best potential for isolating high-level waste products.

In applying the uniformitarian principle to specific geohydrologic environments, one cannot help but be impressed by the bedded salt deposits in various parts of the United States. For example, the bedded salts of the Permian Basin, a geological structural basin underlying parts of Kansas, Oklahoma, Texas, and New Mexico, have been isolated from circulating groundwater for some 230 million years or since they were first deposited. Therefore, if the principle of uniformitarianism is applicable at least in gross terms, then one can presume that the deposits will remain isolated from circulating groundwater for a long time in the future.

Another geologic environment that has been suggested by some geohydrologists to have a potential for containment of waste for a long period of time is found in the geologically stable platform areas of the North American Continent—the Canadian Shield. The shield area extends southward from central Canada into Minnesota and the northern part of Michigan. In this area, despite the fact that there is abundant water on and near the land surface, some of the deeper mines are reported to be dry. This area is several hundred million years older than the salt deposits, so again applying the uniformitarian principle, we can presume the area will remain dry for a long time.

Structural Stability

The structural stability of an area is probably the second major consideration in evaluating its safety for high-level waste disposal. That is to say, if it were decided that a given geological environment would naturally protect waste from circulating groundwater, then the next consideration is what would or could change this natural protection. The largest single force that could change this protection would be crustal movements resulting in faulting and changes in sea-level elevation. Despite the fact that seismologists have made tremendous strides in their earthquake prediction investigations, they still have some way to go. They do, however, point out that there are areas that are prone to seismic disturbance and areas that are relatively stable. Therefore, we apply the uniformitarian principle to predict which areas are most likely to remain stable in the future.

Interference with Resource Exploitation

Another consideration of a geologic nature is the resource potential of the area where the waste is to be isolated. This problem can be evaluated in light of present day technology, and economic judgments can be made as to whether a resource potential is more valuable than a waste disposal site; so it does not seem to be quite as nebulous as the problem of stability and hydrologic isolation.

It is obvious that along these lines of reasoning man can narrow the potential high-level waste disposal sites to a few areas that appear to have potential, but from there where do we go? In the past, man has reacted to problems after they have developed. It is also possible to react to problems that can develop in the future. We can never identify all the geohydrologic parameters prior to taking a positive step forward in high-level waste management practices, but we can use the best data available prior to making decisions that may seriously affect mankind. We do have expertise and techniques that can be used to collect and interpret basic geohydrological data prior to final decisions in waste management. These techniques are not cheap, and there are no safe short cuts to obtaining the data, but the cost of data collection at this stage is minimal in total amount as compared to the consequences of a mistake made in absence of adequate data.

CONCLUSIONS

The management and disposal of radioactive waste necessitates consideration of geologic and hydrologic processes that can reasonably be expected to supervene during the toxic life of the waste. Each proposed waste site should be studied to assure that the waste products, geologic environment, and hydrologic conditions all blend together to facilitate maximum use of geochemical and hydrologic conditions to isolate the waste from the biosphere. The geohydrologic environment differs at each site so that it is not possible to transfer basic data from site to site. Society cannot tolerate mistakes in radioactive waste management endeavors created by insufficient use of data readily available with today's technology.

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