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Strategy for Radioactive Waste Disposal in Crystalline Rocks

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Public acceptance of a waste repository depends on credible predictions of waste movement. Such predictions are difficult because the waste movement (or nonmovement) must be predicted for periods approaching geologic time. For nuclear wastes, predictions for periods of at least 1000 years are required, and, depending on the particular nuclide, perhaps 100,000 years or even longer. Toxic chemical wastes may be even more troublesome; some of them appear to be stable indefinitely, and when disposed of, they may not decay, but remain in the environment to pose a potential threat indefinitely.

Summary. A strategy for waste disposal is proposed in which the repository would be situated in a crystalline rock mass beneath a blanket of sedimentary rocks whose ground-water flow characteristics are well understood. Such an approach exemplifies the concept of multiple barriers to the isolation of radioactive wastes from the biosphere. This strategy has the advantages that (i) ground-water flow within the sedimentary rocks can be investigated and modeled by conventional, well-understood theory and technology; (ii) under favorable circumstances, the flow system operates as an active barrier, so that a long migration path and extremely low flow rate to the biosphere can be assured; and (iii) since, in many locations, ground water is nonpotable, the possibility of future human intrusion can be minimized.

Any prediction method requires an understanding of the processes that are involved and an assessment of the degree of uncertainty associated with the parameters that control each process. For predictions of waste movement, uncertainties in our knowledge of the geologic media are important in both a spatial and time framework, and the uncertainties associated with very long term predictions make the problem of radioactive waste disposal much more difficult. In many engineering problems, the period of observation is often approximately equal to the period of prediction; for example, a 10-year forecast is usually based on at least 10 years of observations of the system behavior. For the long-term predictions of waste movement, a short period of system observation may not be meaningful.

In an earlier statement on waste disposal the concept of multiple barriers was suggested (*1*).

The inability to predict can be offset in part by adoption of a multiple-barrier or "defense-in-depth" philosophy for radionuclide containment. Such a philosophy provides a succession of independent barriers to nuclide migration. The waste form, the host rock, and the ground-water flow path all provide potential barriers.

One example of the multiple-barrier concept of isolating wastes from the biosphere utilizes the ground-water flow characteristics of a geologic environment consisting of crystalline rocks beneath a blanket of sedimentary rocks.

Ground-Water Flow

Crystalline rocks commonly referred to as "granite," which include common rocks such as gneiss and granite, have a number of apparent advantages for the site of a waste repository: (i) they are readily mined; (ii) they are stable at relatively high temperatures; (iii) they have a reasonably high thermal conductivity; (iv) in the absence of fractures they have very low permeability; and (v) they are an abundant rock type within the earth's crust, although in many places on the continents they are covered by a blanket of sedimentary rocks.

One current proposal for locating a repository entails finding a granitic body that extends from great depth to the land surface, where it can be easily explored. The intent is to mine into this body to some depth, perhaps 1 kilometer, where the rock would be relatively unfractured and low in permeability over an area extensive enough to develop a repository. In this design concept, the low permeability of the host rock would retard ground-water movement.

The natural process most likely to move wastes from a repository to the biosphere is transport by ground water. Unfortunately, most explored crystalline rock masses, even those in mines and boreholes at depth, contain fracture systems. In a deep waste-disposal well at the Rocky Mountain Arsenal near Denver, fractures were encountered in the Precambrian crystalline basement at a depth of 3.7 km, and earthquake data suggest that these fractures transmitted fluids to a depth of 7 km at this site (*2*).

Because of the very low intercrystalline permeability, the fracture system in crystalline rock dominates the ground-water flow. Definition of ground-water flow through typical porous media—sand, gravel, sandstone—is well understood. On the other hand, flow through a fractured rock mass is much less predictable because of a poor understanding of fracture aperture, orientation, spacing, and continuity. Neither the theory nor

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the field technology required to measure or model the flow characteristics of a ground-water system in a fractured medium is very advanced (3). The uncertainties in the predictions are thus high in both time and space.

One of the principles that govern the regional ground-water flow is that differences in hydraulic head produced by topography on the boundaries of the flow system are, in most instances, the driving force for the flow. Freeze and Witherspoon (4, 5) demonstrated that the smaller scale topographic effects are damped out with depth and therefore deeper ground-water flow reflects only the major topographic features (Fig. 1).

Although on a local scale ground-water flow may be distorted by the distribution and nature of the fractures, on a large scale the flow within the buried crystalline rocks is controlled by that in the overlying sediments. Figure 2 illustrates the effects of flow in a layered ground-water system (5). The rocks can be thought of as consisting of an aquifer with an overlying confining layer and an underlying crystalline rock mass. The aquifer dominates and controls the flow pattern within the underlying crystalline rock mass.

In Fig. 2 and our other examples, a tenfold contrast in hydraulic conductivity is assumed in order to permit a reasonable graphical representation. Because most natural settings would have contrasts of 100-fold or more, the actual situation would be even more favorable than shown by the figures.

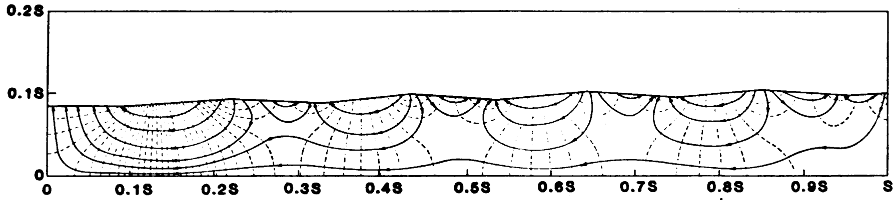

Fig. 1. Flow net showing the effect of water-table configuration on regional ground-water flow through a homogeneous isotropic medium. S is the total horizontal length of the flow system. This flow net demonstrates that the smaller scale topographic effects are damped out with depth. Equipotential lines are dashed; flow lines are solid; the scale is not distorted. [Reprinted from (5)]

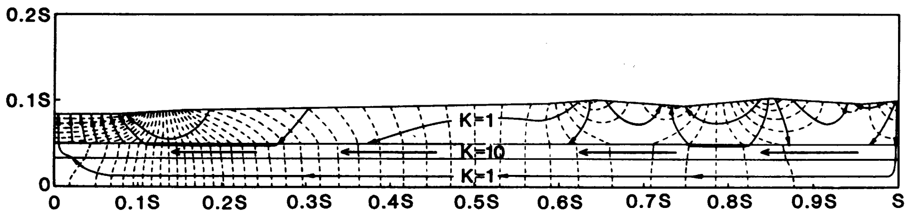

Fig. 2. This flow net illustrates the effect of layering on the ground-water flow system. The values for the hydraulic conductivity (K) are relative. A layer with lower permeability (confining layer, $K = 1$) overlies a layer with higher permeability (aquifer, $K = 10$), which in turn overlies a material with lower permeability ($K = 1$) that might be visualized as crystalline rock. Clearly the potential distribution and therefore flow pattern in the deeper low-permeability rock is controlled by the overlying layered system. Equipotential lines are dashed; flow lines are solid; the scale is not distorted. [Reprinted from (5)]

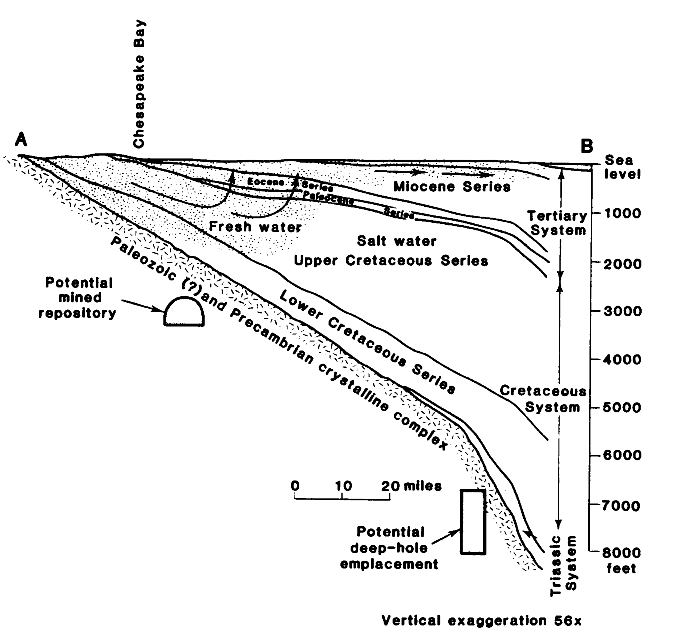

Fig. 3. Geologic cross section of the coastal plain of Maryland illustrating a hypothetical situation in which a crystalline rock waste repository might be built below a blanket of sedimentary rocks. The ground-water flow characteristics within the sedimentary cover can be defined and predicted utilizing well-established techniques as well as theory. [Modified from (7)]

Coastal Site

We propose that a repository be located in crystalline rock overlain by a blanket of sedimentary rocks. In this way it would be possible to retain the major advantages of crystalline rock and at the same time gain confidence in predicting the ground-water movement because of the sedimentary rocks overlying the repository. In such a setting, the ground-water system can be used as an active barrier to waste migration to the biosphere. A hypothetical situation is shown in Fig. 3 for the Atlantic coastal plain; comparable sites exist in many parts of the world. In this situation (considering only geohydrologic conditions), wastes could be emplaced in the crystalline basement below the coastal plain sediments. The maximum depth of fresh ground water within the sediments is 600 meters; over much of the Delaware-Maryland-Virginia peninsula, fresh water does not extend below 150 m.

On the coastal plain of Maryland, which is typical of much of the Atlantic coastal plain, little flow of salt water takes place in the Cretaceous sediments. The head difference at the boundaries of the flow system is too small, less than 60 m, and too distant to provide significant gradients in head within this zone. Flow within the sedimentary section can be investigated and predicted with reasonable confidence by use of well-established techniques and theory.

Figure 4 shows an idealized flow net of a hypothetical coastal setting of the type described above. In this example, no salt-water interface is considered. Again, flow in the crystalline rock mass is controlled by flow in the overlying sedimentary system. Little flow takes place within the crystalline rocks beyond the coastline. Under such circumstances, the waste would be exposed to a well-defined flow system with little flow in the deeper portions of the system beyond the coastline.

Inland Site

In large portions of the continental areas of the world, crystalline basement rocks are covered by a blanket of sedimentary rocks. This makes the proposed strategy possible over wide areas of the globe. Many sedimentary sequences contain salt, shale, and other tight geologic deposits that further isolate the ground-water flow in the deeper sediments and the basement rocks.

Emplacement in the buried basement could be within a mined repository or by means of drill holes. An overlying sedimentary rock, which is more or less plastic, would in time flow back and plug the emplacement hole, thus providing an added benefit in some areas.

A typical cross section of the mid-continental area of the United States is shown in Fig. 5. In this example, the Denver Basin contains a Cretaceous shale sequence approximately 1500 m thick. Hydraulic head in the so-called Cretaceous D and J sands beneath the Cretaceous Pierre Shale over much of the western part of the Denver Basin is approximately 700 m below the land surface. Measurements at a depth of 3.7 km in the Precambrian granite at the Rocky Mountain Arsenal also indicate a head more than 700 m below the land surface, in close agreement with the head in the D and J sands. This head difference indicates a downward flow of ground water from the shallow aquifers near the land surface to the deeper sediments of the basin; the magnitude of the head difference also indicates a high degree of hydraulic isolation of the deeper sediments from the near surface.

Figure 6 is a hypothetical flow net showing idealized flow in a layered sedimentary system such as the Denver Basin. In the Denver Basin, the confining layer, which is Cretaceous shale, overlies a more permeable sequence of Mesozoic and Paleozoic sedimentary rocks. This in turn overlies a less permeable body of rock, the Precambrian crystalline basement. The crystalline rock mass contains a hypothetical zone of higher permeability, which represents a disturbed region caused by the mining of a hypothetical repository. Flow within the Precambrian is again shown to be controlled by the flow system in the overlying sedimentary rocks.

Although the hydrology of the Denver Basin is suited to deep waste disposal, other factors make its suitability questionable. Oil and gas are produced from the deeper sediments of the basin; the state of stress in situ, as determined at the Rocky Mountain Arsenal, indicates that there would be a problem in rock mechanics in emplacing wastes in the Precambrian granite. Despite the difficulties of locating a specific repository, the Denver Basin serves to illustrate the principles under discussion; a thick blanket of low-permeability shale can serve to isolate hydrologically the wastes emplaced in the crystalline basement.

Another example is provided by the Illinois Basin. The deep sedimentary formations of this basin contain concentrated brines containing dissolved solids in excess of 160,000 milligrams per liter. All indications are that the fluid circulation within these formations is extremely slow. The deep sedimentary rocks of the Illinois Basin are devoid of oil and gas. In relation to ground water, this is another example of a crystalline basement overlain by sedimentary formations in

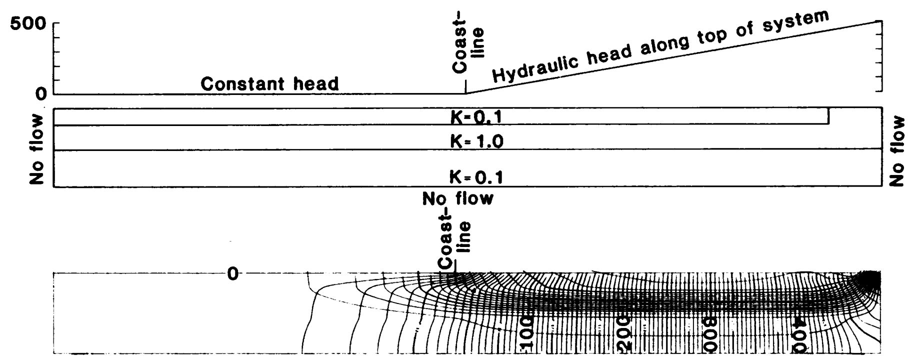

Fig. 4. Idealized flow system in a hypothetical coastal setting. Equipotential lines are numbered; the scale is not distorted. The hydraulic head is arbitrary. The net is distorted slightly by the plotting program.

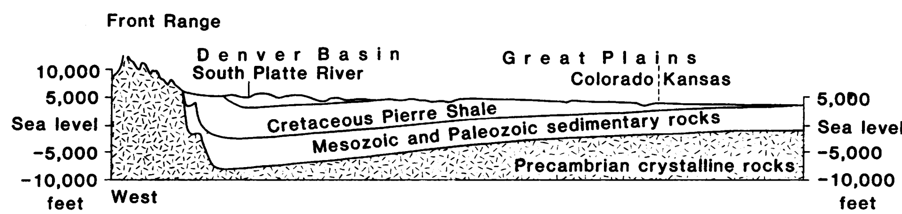

Fig. 5. Cross section from the Rocky Mountains of Colorado to central Kansas showing the relationship of the Precambrian basement to the overlying Paleozoic and Mesozoic sedimentary rocks. The Denver Basin contains a Cretaceous shale sequence approximately 1500 m thick that effectively isolates ground-water flow in the deeper sedimentary rocks within the basin from the surface. In the western portion of the basin, in the vicinity of Denver, there is a downward difference in head in excess of 700 m between the sedimentary rocks above the Pierre Shale and the sedimentary rocks below the Pierre. This downward gradient isolates the deep sedimentary rocks over much of the western part of the basin. [Modified from (8)]

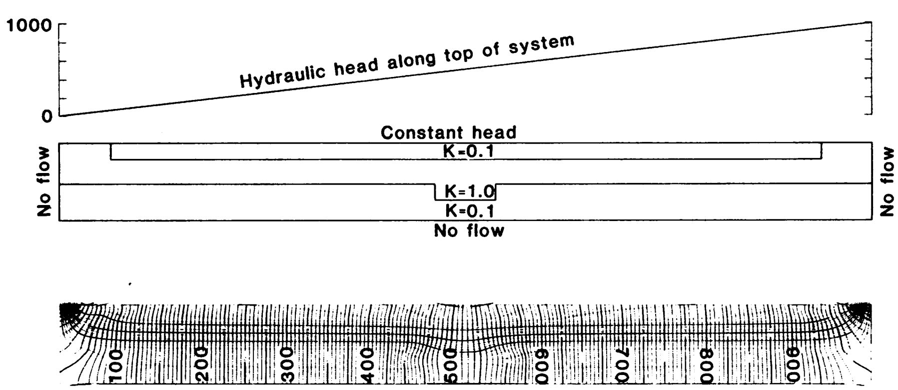

Fig. 6. A hypothetical flow net for a layered system such as the Denver Basin. The Cretaceous shale confining layer ($K = 0.1$) overlies a more permeable layer ($K = 1.0$) representing the Mesozoic and Paleozoic sedimentary rocks. The Precambrian crystalline rocks are represented by the deeper low-permeability layer ($K = 0.1$). A zone of higher permeability in the low layer ($K = 1$) represents a region disturbed by the construction of a hypothetical repository. Equipotential lines are numbered; the scale is not distorted; the hydraulic head is arbitrary. The net is distorted slightly by the plotting program.

which the sedimentary layers would isolate fluids from the surface for long periods.

In our previous examples of a strategy for waste disposal in crystalline rocks, the role of buoyancy-induced flow produced by heat generated in the repository has not been mentioned. This driving mechanism could be significant for inducing flows and transporting nuclear wastes. Recent work (*6*), however, shows that if the waste is allowed to cool for 40 to 60 or 70 years, depending on the waste type, the heat would be reduced to the point where buoyancy-induced flow would not be significant.

Conclusions

The examples presented above illustrate relatively simple alternatives to the current concept of a repository situated in a single geologic medium. With very little change in the present approach, additional natural barriers can be brought into play. There are a number of barriers to migration of the wastes: (i) the waste form and its capsule; (ii) engineered barriers within the repository, such as a low-permeability, highly sorptive backfill; and (iii) the migration path back to the biosphere through the ground-water flow system, which in our examples includes flow through the crystalline rocks as well as overlying sedimentary rocks in which sorption could provide yet an additional barrier.

By selecting an environment in which a crystalline rock mass is beneath a sedimentary rock blanket with suitable hydrologic characteristics, one has the advantage that (i) ground-water flow can be investigated with conventional, well-understood technology; (ii) under favorable circumstances, the flow system can work as an active barrier, so that a long migration and very slow path for the wastes to the biosphere can be assured; and (iii) the wastes can be emplaced in a setting in which the ground water is nonpotable (salty) and not a potentially attractive resource, thus minimizing the possibility of future human intrusion at the site. This is a disposal strategy worthy of careful evaluation.

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Dissections and Reconstructions of Genes and Chromosomes

Paul Berg

The Nobel lecture affords a welcome opportunity to express my gratitude and admiration to the numerous students and colleagues with whom I have worked and shared, alternately, the elation and disappointment of venturing into the unknown. Without their genius, perseverance, and stimulation much of our work would not have flourished. Those who have worked with students and experienced the discomfort of their curiosity, the frustrations of their obstinacy, and the exhilaration of their growth know firsthand the magnitude of their contributions. Each in our common effort left a mark on the other and, I trust, each richer from the experience. I have also been fortunate to have two devoted research assistants, Marianne Dieckmann and June Hoshi, who have labored diligently and effectively, always with understanding and sympathy for my idiosyncracies.

I have also been blessed with an amazing group of colleagues at Stanford University who have created as stimulating and liberating an environment as one could long for. Their many achievements have been inspirational, and without their help—intellectually and materially—my efforts would have been severely handicapped. I am particularly grateful to Arthur Kornberg and Charles Yanofsky, both longtime close personal friends, for their unstinting interest, encouragement, support, and criticism of my work, all of which enabled me to grow and thrive. And finally, there is my wife, Millie, without whom the rare triumphs would have lost their luster. Her strength, assent, and encouragement freed me to immerse myself in research.

Certainly my work could not have taken place without the generous and enlightened support of the U.S. National Institutes of Health, the National Science Foundation, the American Cancer Society, and numerous foundations and individuals who invested their wealth in our research.

Although we are sure not to know everything and rather likely not to know very much, we can know anything that is known to man, and may, with luck and sweat, even find out some things that have not before been known to man.—J. ROBERT OPPENHEIMER

Although the concept that genes transmit and control hereditary characteristics took hold early in this century, ignorance about the chemical nature of genes forestalled most inquiries into how they function. All of this changed as a result of several dramatic developments during the 1940's to 1960's. First, Beadle and Tatum's researches (*1–3*) lent strong support for earlier (*4*) and widespread speculations that genes control the formation of proteins (enzymes); indeed, the dictum, "one gene–one protein," intensified the search for the chemical definition of a gene. The discovery by Avery and his colleagues (*5*) and subsequently by Hershey and Chase (*6*) that genetic information is encoded in the chemical

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This article is the lecture he delivered in Stockholm on 8 December 1980 when he received the Nobel Prize in Chemistry, which he shared with Frederick Sanger and Walter Gilbert. The article is published here with permission from the Nobel Foundation and will also be included in the complete volume of *Les Prix Nobel en 1980* as well as in the series *Nobel Lectures* (in English) published by Elsevier Publishing Company, Amsterdam and New York. The lectures by Dr. Sanger and Dr. Gilbert will be published in a subsequent issue.

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