

Options for Nuclear Waste Disposal

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At present the growth of commercial nuclear power has slowed in the U.S. for a variety of reasons, not the least of which is the opposition of the anti-nuclear movement. A principle worry of that movement and of many other concerned citizens is the possible hazard to future generations from the radioactive wastes resulting from the operation of nuclear power plants. Studies for isolating high-level waste have been in progress in the U.S. since 1957 when the National Academy of Sciences first recommended deep geological disposal. The possibility of long-term storage and isolation of nuclear wastes in underground repositories for perhaps hundreds of thousands of years, (or until the amount of radioactivity has decayed to a safe level) has been considered for a number of different geologic media. For example, repositories mined in such formations as tuff (a volcanic ash rock widespread in the southwestern U.S.), granite, basalt, or salt have been considered. Chemists and geochemists currently are playing a major role in the research on such systems.

The Nuclear Waste Policy Act (NWPA) passed by Congress in 1983 was a major milestone which established a national policy for safely storing, transporting and disposing of spent nuclear fuel and high-level radioactive waste. This legislation established the Office of Civilian Radioactive Waste Management (OCRWM) within the Department of Energy (DOE) to implement the policy and to develop, manage, and operate a safe waste management system to protect public health and the environment. It also called for the President to recommend the first site to Congress by March 31, 1987, and for the first repository to be in operation by 1998. Reviews of potential sites by the DOE, the National Academy of Sciences, and the U.S. Geological Survey lead to the identification of nine potentially acceptable sites. As required by the NWPA, guidelines for evaluating the suitability of potential sites for nuclear waste repositories were issued. The guidelines were developed to be compatible the requirements of the Nuclear Regulatory Agency (NRC) and the environmental standards established by the Environmental Protection Agency (EPA). In addition, the guidelines were subjected to extensive Federal, State, and public review. By 1986, the number of potential sites was reduced to five and the Secretary of Energy recommended that only three sites be characterized. Then in 1987, Congress enacted the Nuclear Waste Policy Amendments Act directing the DOE to characterize the suitability of only one site for a national repository. Yucca Mountain, located at the Nevada Test Site, was selected since this area was already used for nuclear operations and the land had

been previously committed to long-term institutional control. Characterization of all other sites was terminated at that time.

Whether or not a repository is constructed in the next 10 to 20 years at Yucca Mountain, there will be an increasing need for more chemists with specializations in nuclear and radiochemistry and geochemistry to help design and access the effectiveness of long-term storage as well as to develop even better methods for isolating nuclear wastes.

Origins of the Nuclear Wastes

Nuclear waste is the by-product that results from using radioactive material. Easily, the largest amounts of nuclear waste (radioactive materials) are produced by nuclear power plants. In a reactor, as the fuel is consumed, other radioactive materials are produced. By far, the largest quantities of nuclear waste are produced when the uranium fuel captures a neutron and then breaks apart or fissions into two fragments. These fragments are radioactive and commonly referred to as fission products. However sometimes when a neutron is captured by the nuclear fuel, fission does not occur and products, elements heavier than the fuel, are formed. These radioactive elements are collectively called the transuranium elements (e.g. isotopes of the elements neptunium, plutonium, americium, and curium.) In addition, some of the neutrons produced in the fission process are captured by other components of the reactor besides the fuel. For example, some of the neutrons are captured by the structural materials in the reactor such as the reactor walls or the cladding surrounding the fuel elements. The radioactive species produced in this way are called activation products.

Spent fuel is the fuel that has been used in a nuclear reactor to the point that it no longer contributes efficiently to the nuclear chain reaction and thus, to the production of electrical power. When the spent fuel is removed from the reactor, it is highly radioactive since it contains fission products, transuranium elements, and activation products, all of which are radioactive. During radioactive decay, the atoms that are radioactive emit radiation in the form of energetic waves (gamma radiation) or fast moving particles (alpha or beta particles). The decay process results in large amounts of heat being generated in the spent fuel. For this reason, at the reactor site, spent fuel is initially stored under water to thermally cool. During this cooling period, the spent fuel also becomes less radioactive due to the natural process of radioactive decay. After three months of storage, the amount of radioactivity in the spent fuel decreases to approximately 50 percent of its

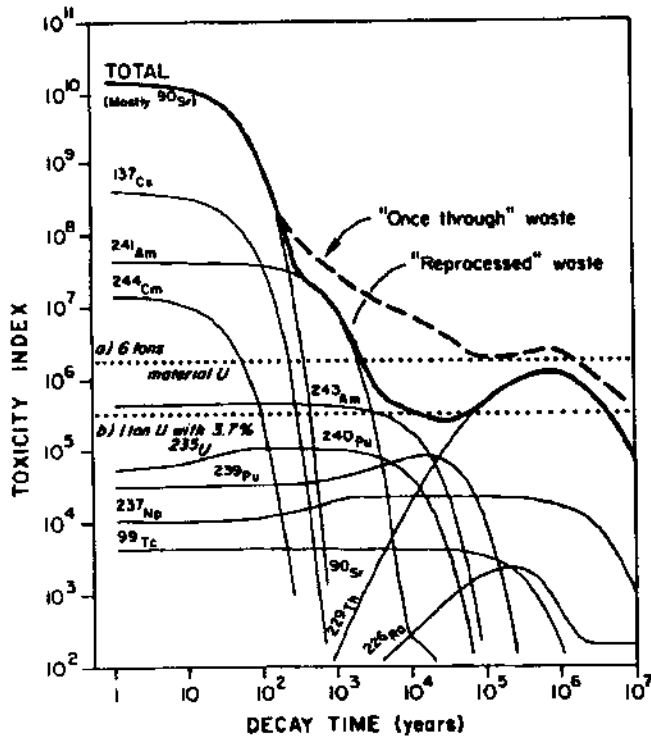


Figure 1. Toxicity Index (a measure of the health hazard) of high-level nuclear waste containing all the fission products as well as Np, Am, and Cm and 0.1% U and 0.5% Pu (or their original levels) as a function of time after reprocessing. A storage time of 10 years precedes reprocessing. (From ref. 1.)

original value; in one year, to about 80 percent; and in ten years, to about 90 percent. Of the radioactive species contained in the spent fuel, only a few live long enough to require isolation from the accessible environment for hundred of thousands of years. Figure 1 shows the trend in the "Toxicity Index" (a relative measure of the health hazard) of the major radionuclides as a function of time. ^{90}Sr and ^{137}Cs compose the major danger in the first 300 years and after that, the transuranium nuclides and their decay products, such as ^{239}Pu and ^{226}Ra , become the hazardous species. After about a million years, the toxicity index falls below that of the natural uranium in the earth. The problem then is how to devise a way of isolating the nuclear waste in a manner which pose an acceptable level of social risk for the environment today and in the future. The development and assessment of safe systems for radioactive waste isolation will require detailed chemical and geochemical research.

Different National Disposal Plans

Many nations have research and development programs (2-6) for the disposal of nuclear wastes. These vary widely in scope but do have many common features. The primary focus is on disposal of the unreprocessed spent fuel elements or processed high-level radioactive waste immobilized in some insoluble matrix. These waste forms are to be encased in corrosion-

resistant containers and placed in underground repositories. Disposal sites in different types of geologic media are being studied in the various national programs; in a few, the feasibility of disposal at the bottom of the sea is also being evaluated. Disposal of high-level waste in ice or in outer space is not being investigated currently.

Sweden and Switzerland are planning on disposal deep in granite rocks. France is studying salt and clay beds as well as granite. Canada has a 20-year research and development program to study the use of plutonic igneous rock. The nations of the European community have joint research coordinated with their individual national programs. For example, salt is being studied by the Federal Republic of Germany and the Netherlands, argillaceous formations mainly by Belgium and Italy, and crystalline rocks (granite) by France and the United Kingdom.

Some of the regions in the U.S. that have been previously considered by the DOE as possible repository sites are shown in Figure 2. Initially the emphasis was on salt deposits, and possible sites in the Paradox and Permian Basins and the Gulf Coast were examined. Before its termination in 1987, the Basalt Waste Isolation Project (BWIP) at DOE's Hanford Site near Richland Washington was concerned with studies of basalt in the Pasco Basin and Columbia Plateau. The Yucca Mountain Project, formerly called the Nevada Nuclear Waste Storage Investigation (NNWSI), is now exploring tuffaceous media* at the NTS for a geologic repository. *(Tuff is a volcanic material that exhibits a wide range of physical and chemical properties. Tuff may be deposited either directly by explosive volcanic eruptions or may be reworked and redeposited by surface processes.)

Yucca Mountain is the preferred site in the U.S. for a number of reasons:

1) In southern Nevada, ground water does not discharge into rivers that flow to major bodies of surface water.

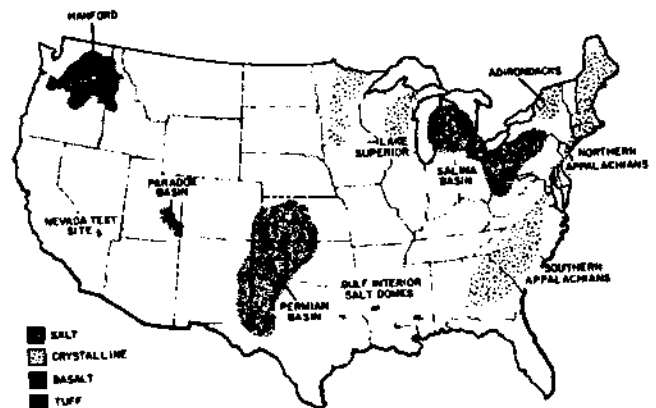


Figure 2. Regions studied or now being considered for terminal storage of radioactive waste. (From ref. 5.)

2) Many of the rocks at the NTS have geologic properties that tend to retard the migration of radionuclides and thus favor long-term storage and containment of nuclear wastes.

3) The paths of ground water flow between the potential location for a repository and the points of ground water discharge are long.

4) Because the region is arid, the rate at which ground water is recharged is very low and therefore the amount of moving ground water is also very low, especially for the unsaturated rocks.

In 1988 a site characterization plan (SCP) for Yucca Mountain was written to detail the studies needed to access the local conditions pertinent to a geologic repository. (7) The plan includes drilling many exploratory holes in and around the Yucca Mountain area to learn more about the hydrology and to remove drill core for detailed studies of the stratigraphy and the geochemical and mechanical properties of the tuff. The site characterization also includes plans for the construction of two exploratory shafts to depths of more than 1000 feet to provide access for *in situ* testing and analysis of the potential repository area. Studies of the surface geology as well as studies of both the unsaturated and saturated zones in the region will be carried out. Since characterization of the site also depends on the design of the engineered elements of the repository system — repository and waste package — the design of the repository and the form of the waste package are concurrently being considered to ensure that the proper data are collected during the site characterization of Yucca Mountain.

Multiple-Barrier Concept

The concept of isolation in deep geologic repositories has been expanded to encompass a multiple-barrier system in which engineered barriers may, if necessary, provide further protection beyond that provided by the geology, hydrology, and geochemistry of the repository site itself. These multiple barriers will be designed to ensure containment of the radionuclides in the repository site and further reduce the risk of migration into the biosphere. A systems analysis approach can then be utilized in which the following barriers are all considered:

- 1) A waste form of high stability;
- 2) Encapsulation or containment of the waste form in a canister and packing materials of high corrosion resistance and durability;
- 3) An engineered or artificial overpack or backfill around the canister that has high sorptive properties for the radionuclides that might be released by dissolution of the canister and waste form;
- 4) The geologic medium itself including its geochemical and hydrologic properties;
- 5) The distance to population centers and water supplies may also be considered as a final barrier.

Thus the suitability of various sites can be evaluated and several may be found to be equally acceptable. Although the relative merits of a given barrier might be different for each site, deficiencies in a particular natural barrier might be remedied by a specifically designed artificial barrier. In addition, a disposal scheme that might overly stress a given medium can often be adjusted. For example, spent fuel elements can be allowed to cool in temporary storage for longer periods or they may be less densely placed in the repository so that temperatures will be of the order of 100°C. Figure 3 shows schematically the components of the barriers and some of the different materials being considered for each.

The waste form may consist of the unreprocessed used or "spent" fuel element itself. Or in the case of defense-related wastes, the high-level radioactivity from reprocessing will probably be reduced to oxide compounds that will then be fixed in a solid waste form such as borosilicate glass, a ceramic, or a synthetic

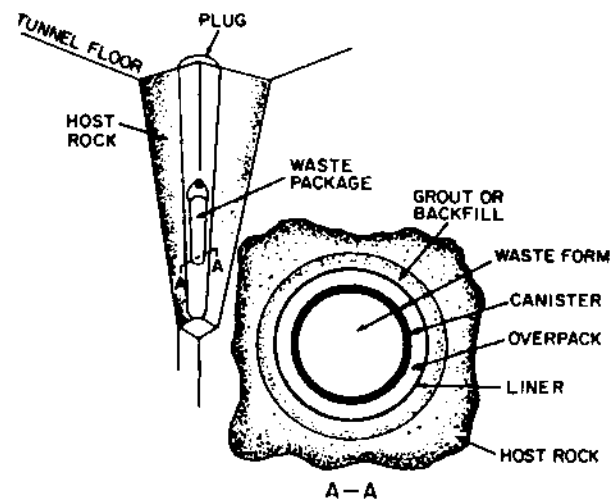


Figure 3. Schematic of multiple-barrier concept for nuclear waste isolation. The waste form, the canister and overpack, and the emplacement scheme are the first engineered barriers to radionuclide migration from the repository. (From ref. 5.)

"rock". (Currently, commercial nuclear waste is not being reprocessed in the U.S.) This material must have a low solubility, be relatively chemically inert to the environment of the storage site, be stable to heat and radiation, and have good heat conduction and mechanical and structural stability. The waste form might then be placed in a metal jacket or canister designed to last a few hundred to a few thousand years, and it is hoped much longer, after which groundwater might contact the waste form and possibly start a slow leaching and dissolution process.

Studies in which water flowed past glass cylinders containing radioactive nuclides have indicated that the rate of leaching of the radioactivity into the water is quite slow and that it would take thousands and possi-

bly hundreds of thousands of years for the glass block to dissolve completely. Therefore, the ^{90}Sr and ^{137}Cs , with half-lives of about 30 years, would decay before the glass block dissolved. The additional geochemical and geohydrologic barriers beyond the solid waste form must be relied upon to retain the longer-lived actinide elements and their decay products but need not be designed to hold the Sr and Cs.

As an additional artificial barrier, it is proposed that the canister be surrounded with an overpack of clay or some other material with good ion-exchange or sorptive properties. This material would retain the various radioactive cations as they are leached from the glass by the groundwater in the same way that ion-exchanger water softeners remove Mg^{2+} and Ca^{2+} from hard water. The backfill or overpack could act not only as a chemical barrier to the migration of radionuclides into the groundwater but also could serve to conduct heat from the canister, and to hinder the flow of water around the canister, thereby slowing its rate of dissolution. It could also function as an elastic support for the canister to prevent cracking of the waste form in case of rock movements in rigid formations such as granite. It has been further suggested that certain chemicals be added to this material to cause enhanced chemical retention. For example, the presence of $\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$ would provide Fe(II) to destroy any oxidizing agents in the water and produce reducing conditions to retard the corrosion of the metal canister. Backfilling the canisters with inert gas to provide a non-oxidizing environment is also being considered as a method to retard corrosion.

If the waste package and overpack materials are eventually breached, then the geologic medium surrounding the repository becomes the final barrier between the stored radioactivity and the environment accessible to people. Thus its hydrologic and geochemical properties are of utmost importance in selection of a repository site.

The current plans for a U.S. repository require that the wastes be retrievable for 50 years after the start of emplacement. Since the emplacement is scheduled to last for about 26 years, there would be a 24 year period during which the performance of the repository could be evaluated. If the performance meets expectations, the repository would be prepared for permanent closure. This includes backfilling the underground areas and decontaminating and decommissioning surface facilities. When the area was returned to its natural state to the extent practicable, permanent site markers would be erected to warn future generations of the presence of the repository.

Chemical and Geochemical Questions

It is not possible in this article to consider fully all the studies required before a detailed model can be developed for the probable chemical history of a nuclear

waste disposal site over hundreds of thousands of years. However, even a brief consideration can serve to illustrate the importance of the role of chemists and geochemists in studies on nuclear waste disposal.

At the depths (300-1000 m) planned (8) for most proposed repositories, the estimated temperatures may vary (depending on the precooling time of the nuclear waste, etc.) from 60 to 300°C while the water pressure would range from 100 kPa (1 atm) to 10 MPa. Rock pressures would be 2 to 3 times greater than the water pressure. Such pressures and temperatures represent conditions in which chemical behavior is largely unstudied. Geochemically, under such conditions, mineral-water reactions are slow, and most systems are metastable as kinetics dominate equilibrium factors. Common processes include precipitation of amorphous solids, recrystallization of metastable minerals and of carbonaceous materials into graphite, dehydration of some clays and zeolites, changes in ground water conditions, etc. Not only are laboratory studies needed under these temperature-pressure conditions, but they must be conducted in a manner that, if possible, allows confidence in extrapolation of the data from a few years of laboratory observations to the 10^4 to 10^6 years required for the repository to function safely.

Consider a glass cylinder containing radioactive wastes and enclosed in a metal jacket. This canister is surrounded by an overpack layer, perhaps of an ion-exchanging clay, enclosed in a liner, and placed in an underground cavity (Fig. 3). The package might be cemented to the surrounding rock or covered with a backfill of crushed rock. Assume that tuff or granite is the host rock and that underground water has breached the liner and flows slowly through the clay and around the canister. What are some of the chemical and geochemical reactions that can influence the retention or passage of radionuclides from the glass to the surface of the ground around the burial site? Obviously, these reactions will be due to attack of the groundwater first

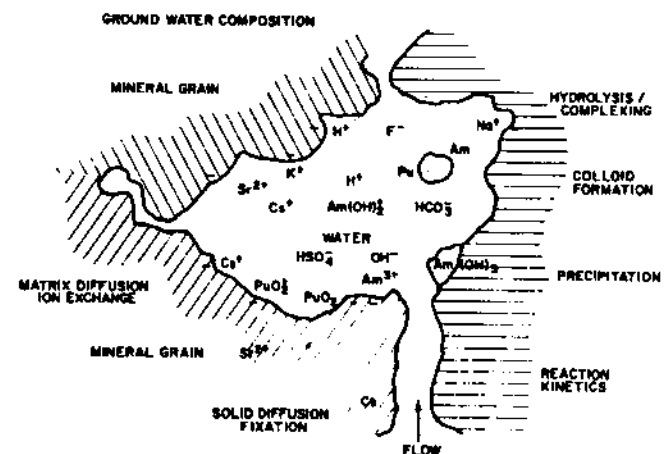


Figure 4. Schematic representation of some species and processes which may be important as groundwater flows through the repository rock and reacts with stored radionuclides.

on the metal canister, then, when this is corroded sufficiently to expose the glass, on the glass itself. As the glass dissolves, the water must flow through the clay barrier, then through the pores and cracks of the rock until it reaches the surface (see Figure 4). So we must have some knowledge of the ability of the groundwater to dissolve the metal and the glass and to retain the radionuclides in solution.

Table 1. Composition of Groundwater from Deep in Crystalline Rock (9)†

Species	Probable Range (mg/L)
Ca ²⁺	25-50
Mg ²⁺	5-20
Na ⁺	10-100
K ⁺	1-5
Fe ²⁺	0.5-15
Fe _{total}	1-20
Mn ²⁺	0.1-0.5
HCO ₃ ⁻	60-400
CO ₂	0-25
Cl ⁻	5-50
SO ₄ ²⁻	1-15
PO ₄ ³⁻	0.01-0.1
F ⁻	0.5-2
SiO ₂	5-30
HS ⁻	<0.1-1
O ₂	<0.01-0.07

† pH = 7.2 to 8.5

Table 2. Composition of Groundwater from Tuff in the Vicinity of Yucca Mountain, NTS (10)‡

Species	Probable Range (mg/L)
Ca	1-20
Mg	0.05-2
Na	45-95
K	1-5
Li	0.05-0.4
Fe	0.01-0.05
Mn	0.01-0.03
Al	0.004-0.03
Si	20-30
HCO ₃ ⁻	120-170
Cl ⁻	5.5-7.7
SO ₄ ²⁻	18-28
NO ₃ ⁻	0.6-10
F ⁻	1.0-4.5
O ₂	1.8-6.4

‡ pH = 6.9 to 7.7

The groundwater could contain HCO₃⁻, NO₃⁻, F⁻, SO₄²⁻, Cl⁻, PO₄³⁻, K⁺, Na⁺, Ca²⁺, Fe²⁺, Mg²⁺, colloidal SiO₂, and possible polymeric organic compounds such as humates and fulvates. The exact species and their concentrations will vary with the host rock type and the depth because the interaction between the water and the minerals in the rock determines the solution composition. Representative compositions of groundwater from tuff and deep crystalline rock are given in Tables 1 and 2. The water is neutral to somewhat basic and, in the case of granite, is reducing as indicated by the presence of Fe²⁺. (This is in contrast to the tuff water, which may be oxidizing, and to surface water, which is oxidizing due to dissolved oxygen.) The reducing property of the groundwater could decrease the corrosion rate of the metal jacket and an asset for a burial site might be the presence of Fe²⁺ in the groundwater. Lead, iron, copper, titanium, and Al₂O₃ jackets have been proposed, but iron would probably corrode too fast (hundreds of years) even in reducing groundwater. Further research is needed on corrosion rates in order to choose the best material for the canister jacket.

Once the jacket is breached, the groundwater can begin to attack the waste form. This would probably be a borosilicate glass containing about 9% by weight of fission products plus actinides. The amorphous character of glass is an advantage in that it prevents glass from "storing" energy. The lattice forces in a crystal are so strong that a rather large amount of energy can be added as increased vibrational energy without causing disruption of the lattice. Such "stored" energy, however, can be released rapidly with a catastrophic disintegration of the crystal. Since radioactive decay could be a source of energy, even insoluble crystalline materials containing radioactive wastes could disintegrate after a period of storage due to this effect, whereas noncrystalline glass cannot retain such energy and has no such problem. On the other hand, glass is thermodynamically unstable to crystallization. However, since such crystallization occurs in an aqueous medium only above 300-400°C, it is of no real concern because in the geologic sites under consideration for waste disposal the temperature surrounding the glass canister would not exceed 60-300°C. The rate and mechanisms of dissolution of the glass as a function of water flow, silica concentration, temperature, etc. is an area that is being, and must continue to be, studied intensively to evaluate the release rate of the radioactivity from the glass, the chemical form of the dissolution products, and what the best waste form may be. Studies (11) of ancient glasses have shown that even after 3,000 years the original surfaces are often still intact. This may bode well for the disposal of nuclear waste especially considering that the much more limited surface area of waste glass cylinders should drastically reduce

vulnerability to such surface weathering. Ceramics and "synrock" are also being investigated for use as waste forms. "Synrock" is the name given to synthetic minerals similar to those found in nature which have survived for eons and should be particularly resistant to reaction and dissolution in the natural environment.

As the groundwater leaves the canister and flows through the clay, cationic species of ^{90}Sr , ^{239}Pu , ^{235}U , ^{237}Np , etc., can be retained by ion exchange with Na^+ in the clay. However, the extent of this ion exchange depends on temperature, the concentration and speciation of dissolution products, and the degree of hydrolysis, complexation, sorption on colloids, etc., of the released radioactivities. Similarly, the rate of migration of the radioactivity through the geologic medium will be dependent on these same factors. A whole area of solution chemistry in neutral and basic waters must be studied to measure the hydrolytic behavior as well as the degree of complexation by anionic species such as CO_3^{2-} , HCO_3^- , F^- , Cl^- , and SO_4^{2-} present in the groundwaters. Even more difficult are the investigations of binding of these species by organic polyelectrolytes such as humic acid and adsorption by colloids such as hydrous silica and by the solid surfaces of the minerals of the rock formation and possible consequences of biological activity, either natural or introduced by man. Research on these problems not only will be useful for modeling waste disposal but also could add significantly to our understanding of geochemical and marine behavior and of the properties of neutral and basic solutions.

Should the waste products escape the backfill barrier, the rate of migration in the groundwater through the natural geologic environment becomes of concern. Again, questions of complexation, hydrolysis, redox behavior, colloid formation, and precipitation in the neutral or basic water, as well as of ion exchange and adsorption by interaction with the rock surfaces, must be considered. Tuffs from the Nevada Test Site contain natural zeolites and clays such as mordenite, smectite, clinoptilolite, and heulandite which are known for their high sorptive capability. Their sorptive properties are particularly high for strontium, cesium, and barium, which are thought to sorb mainly by ion-exchange reactions. These natural minerals have sorptive properties comparable to those of materials being considered for use as "artificial" or engineered barriers to be emplaced around radioactivity stored in less sorptive media. Methods and models for predicting sorptive properties for geologic media containing a variety of sorbing minerals are now being developed. A knowledge of the rate of water movement and proximity or possible connections to water supplies are also important.

Extrapolations in Time and Size: Correlation of Laboratory with Field Studies

Questions are often raised about the validity of the extrapolation of laboratory measurements to actual repository conditions, i.e., scaling in both size and time—micro to macro sizes, and times of weeks or even years in the laboratory to hundreds or thousands of years or more for an actual repository. Attempts are being made to develop and validate models that can utilize data from the laboratory and intermediate-size experiments and apply them to other repository sites so that extensive field experiments will not have to be conducted for every potential site.

Figure 5 illustrates the idea of progressing from very small-scale laboratory studies to intermediate-size studies to field studies. One of the smallest-scale techniques is microauto-radiography (MAR), which shows (12) the actual components in a rock sample that grab and hold a radioactive nuclide such as plutonium. In this technique a solution of the radioactivity is allowed to contact a thin section of the rock. The solution is removed, and a photographic emulsion is placed on the rock. The film is developed and the alpha radiation from the plutonium shows up as black tracks (Fig. 6). Examination with a microscope allows the petrographer to correlate the position of these tracks with the particular mineral component that is doing the sorbing and to identify the component.

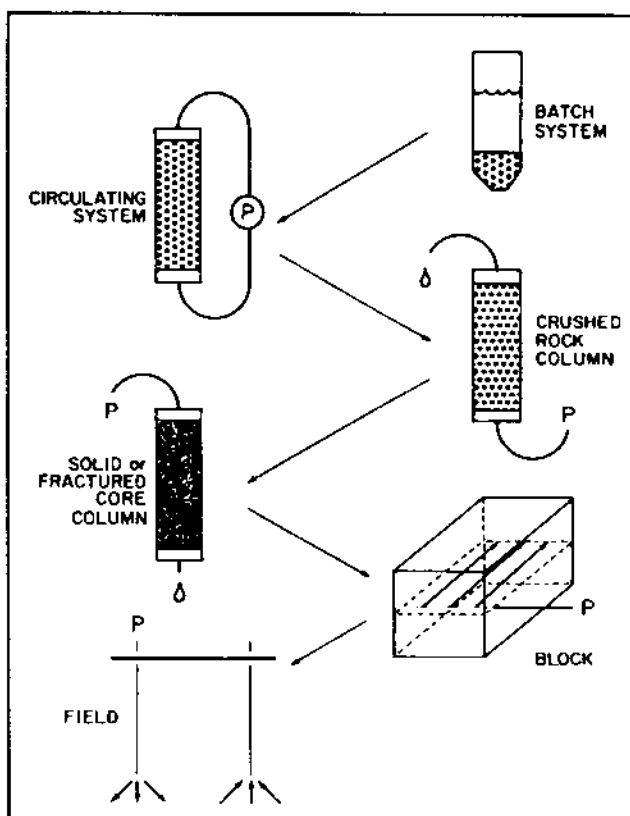


Figure 5. Batch-to-field concept for experimental studies.

A step up in size is a batch technique in which crushed rock is simply shaken with a solution of the radionuclide in question to see what fraction attaches to the solid. Other similar studies include columns of crushed rock through which the solution is passed. In order to avoid altering the rock, solid rock cores can also be used and water is pumped through sections of the core at different pressures. The flow patterns can be examined later by slicing the rock and taking autoradiographs to determine where the radionuclides went. Intermediate-scale field experiments are planned in which stable or short-lived isotopes are injected into fractures in the strata to be studied. Detailed post-flow analyses of the nuclide distributions will be performed in order to answer the question, "Based on physical and chemical properties of a rock and solution measured in the laboratory, can accurate predictive models of radionuclide migration through that rock in the field be formulated?"



Figure 6. Microautoradiograph showing sorption of plutonium-239 on a thin section of tuff. The alpha radiation emitted by the plutonium shows up as the black tracks. (From ref. 11.)

Finally, we come to scaling in time as well as size, which is an even more difficult problem. For example, the weathering of fissure surfaces is a time-dependent process that must be understood in order to extrapolate the results of laboratory experiments to long periods of time. However, we can derive much valuable information from a fascinating natural phenomenon that was discovered in 1972 by scientists of the French Atomic Energy Commission. They discovered natural

fission reactors at the Oklo Mine in the Gabon Republic on the west equatorial coast of Africa. Subsequent studies have shown that these *natural* reactors operated (13) nearly two billion years ago, although the first man-made fission reactor was not operated until 1942! The discovery of the Oklo reactors came about because very careful analyses revealed that samples of the ore, which was being shipped to France for use in their gaseous diffusion separation plant for enrichment of ^{235}U , were actually slightly depleted in ^{235}U ! In fact some samples contained only about half as much as they should have.

The hypothesis that the ^{235}U might have been depleted because it was the fuel in a natural fission reactor was confirmed by measurements of stable isotopic ratios for several elements that matched their known yields from nuclear fission of uranium and that were different from the abundances in normal natural materials. From detailed analyses of these samples it was further deduced that ^{239}Pu had also been formed in nature (long before man learned to produce it) by neutron capture in ^{238}U , just as we make it in reactors today; some of the ^{239}Pu fissioned, and the remainder decayed back to ^{235}U . Nearly half of the original U fuel burned by fission was replaced in this manner! It is particularly noteworthy as we debate present-day issues of nuclear waste management (14) that this natural reactor operated at a low power of 10 to 100 kw over several hundred thousand years, generated about 15,000 megawatt-years of energy, two and a half tons of plutonium, and six tons of fission products. None of the regions of the reactor were enriched in ^{235}U , the decay product of ^{239}Pu , thus indicating that the plutonium had not migrated away from its original production site during the lifetime of the plutonium! In addition, analyses have shown (Fig. 7) that many other nuclides such as thorium, zirconium, niobium, technetium, and rare earths also remained in place even though water was present from time to time. This is obviously relevant to the problem of the long-term storage of nuclear waste.

The immobility of the uraninite ore itself is also noteworthy, and it has been suggested that it might be a good waste storage form in geologic media where conditions are similar to those at Oklo. Fractional loss rates were less than one billionth per year for the least volatile elements and one millionth per year for the more-volatile elements. Lead, one of the nonradioactive daughters of uranium decay, has migrated away from the reactor sites, and it can be used to trace the paths of the water flow and to see which, if any, other nuclides might also have been transported from the reactor sites. Studies of migration of decay products from other natural uranium ore bodies can also be helpful in determining leach and migration rates in the natural environment over long periods of time. We can take

advantage of information obtained by studying these natural analog systems and apply it to the problem of achieving safe, long-term storage of radioactive or other toxic wastes.

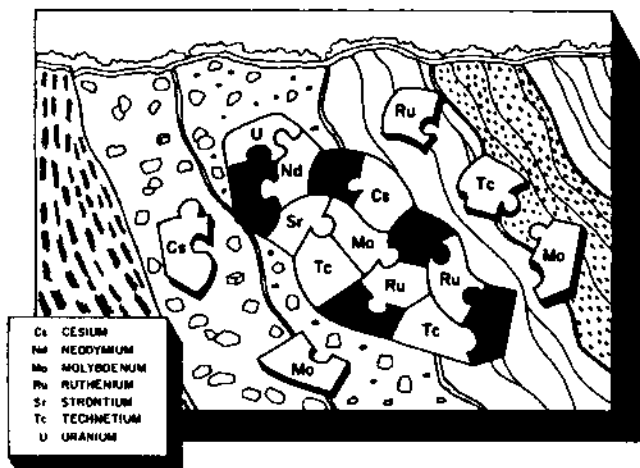


Figure 7. Oklo is a uranium mine in Gabon, Africa that contains the only known remnants of natural nuclear reactors which operated nearly two billion years ago. Studying the Oklo site is somewhat like trying to put a puzzle together with some of the pieces missing. However, by chemically analyzing the surrounding rock, researchers can identify the missing pieces – namely, the fission products that have been transported from their original location. (From ref. 11.)

The majority of the text of this paper was taken verbatim from the American Chemical Society's Journal of Chemical Education article, Vol. 63, page 1059-1064, entitled "Chemistry Related to Isolation of High-Level Nuclear Waste" by Darleane C. Hoffman, University of California, Berkeley, CA 94720, and Gregory R. Choppin, Florida State University, Tallahassee, FL 32306. The author gratefully acknowledges permission of the original authors and the Journal of Chemical Education for the use of this article for this symposium in the 11th Biennial Conference on Chemical Education.

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