CURRENT PERSPECTIVES IN GEOLOGIC DISPOSAL OF RADIOACTIVE WASTE

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Disposing of radioactive waste is a peculiarly difficult problem because of the enormous time involved, because of our inability to predict the state of the world a long time in the future, and because of the emotion generated by an influence as mysterious and potentially lethal as radiation. It is a problem that must be faced squarely, simply because large quantities of waste are already here. One solution to the problem would be to do nothing, which means keeping the waste in their present containers near the earth's surface under careful surveillance for at least a thousand years. Such a solution has little appeal, because of doubts about the adequacy of surveillance through many generations and because of the vulnerability of surface installations to accident or sabotage. Of the many suggestions that have been made for disposing of the wastes more permanently, the one currently in greatest favor is burial of the wastes in rocks deep underground. This proposal has been discussed for more than twenty years, but no high level waste has yet been buried and every suggestion for particular burial sites has been beset by technical and political objections. It is my purpose here to look at the question from a geological point of view, to sort out some of the facts that have been established about deep burial and to highlight the remaining uncertainties.

In most current schemes for waste disposal it is assumed that high-level waste will be converted to a solid form, enclosed in metal canisters, and placed in holes dug in the floor of a mined cavity at a depth of at least a few hundred meters. This means that the waste will be below the water table, and very probably sooner or later at least some water will be in contact with the waste canisters. I personally happen to think that much trouble could be avoided by placing the waste in rock or alluvium of desert areas above the deep regional water table, but for present purposes I will limit myself to the kinds of repository now under active consideration in which water is a major factor to be reckoned with. Contact of water with the waste can be delayed by proper engineering of the repository and suitable choice of metal for the canisters, and reaction of water with the waste can be minimized by incorporating the waste in an inactive solid form. Much study is being devoted to such matters, and very properly so, but my concern here will be rather with geologic aspects of the repository site and the repository medium.

The relative merits of different rocks as possible media for the isolation of high-level waste have been the subject of long and sometimes heated debate. Bedded salt, salt domes, shale, granite, basalt, and tuff all have had staunch advocates. Sometimes it appears to me that too much emphasis has been placed on trying to find a single rock type that would be the best repository medium in all circumstances. Any of the listed rocks, I think, could be a satisfactory material for waste containment in the proper geologic environment, and any of them in other situations could be very poor. Emphasis should be less on the generic properties of different rocks and more on the total geologic characteristics of specific sites. It is the general geologic picture that I want to look at here, rather than details about particular kinds of rock.

Geology, despite all the trumpeting of recent years about the great advances that have come from plate tectonics, is still a very primitive science. When called upon to make predictions about changes in the earth over the times needed for waste isolation, a geologist must necessarily be somewhat evasive. I can maintain, for example, that the chance of this building being destroyed by a major earthquake or a volcanic eruption during the next week is very small, but I could not say on the basis of present geologic knowledge that either of these events is impossible. All a geologist can do is to project his painstaking reconstructions of past events into the future, and to use his knowledge of rocks and rock structures to infer the kinds of geologic activity that are probable in a given area. These are powerful techniques, and predictions based on them can be made with much assurance. But a geologist knows all too well that unexpected events have occurred in the past, and undoubtedly will occur in the future. When he ventures a prediction about the possible loss of long-term integrity of a waste-disposal site, he must speak in terms of probabilities - very low probabilities, to be sure, but always with the reservation that in geology anything is possible.

This ultimate limitation of geologic predictions must be kept in mind in reviewing the various possible occurrences that might jeopardize the isolation of waste in a repository. We can speak only of probabilities, never of absolute assurance Some probabilities are high, some are low - and to reach a reasonable perspective on the geologic suitability of a repository site demands that we order the probabilities roughly according to magnitude.

One dreadful event, for example, that is often suggested as a possible means of breaching a bedrock repository is a direct hit by a large meteorite. Such things have happened in the course of earth history, as is proved by the numerous meteor craters and impact structures that have been discovered in recent years. Yet the probability is vanishingly small. Those who like to quantify probabilities have suggested numbers of the order of 10^{-12} or 10^{-13}, meaning that a meteorite large enough to cause appreciable damage can be expected to strike a particular area of the earth's surface once in a trillion or ten trillion years. Since the earth's entire existence so far is limited to a mere five billion years, this is surely one kind of geologic hazard we can live with.

Other occurrences commonly cited as threats to a subsurface repository are volcanic eruptions in the vicinity, major earthquakes, and deep erosion by water or ice following a change in climate. These events are manifestly possible, and a probability assigned to them would be considerably higher than for a meteor impact. But geologic knowledge is surely sufficient to keep the probability within the range we normally accept as reasonable in ordinary life. No site would be chosen in an area of recent volcanic activity, and immense regions are available where geologists can accurately date the last eruptions at times millions or even billions of years ago. Earthquakes are less predictable, but in large areas of the country neither historical records nor rock structures indicate major seismic activity for long times in the past; moreover, abundant evidence shows that well engineered underground structures are little damaged even by the strongest earthquake vibrations. Amounts of erosion to be expected under present climatic regimes can be accurately predicted, and enough is known about changes in climate over the past million years that possible climatic extremes can be allowed for in the predictions. Regarding possible hazards from volcanic activity, earthquakes, and erosion, geologic and engineering knowledge seems ample to ensure that the probability of damage to a properly selected and well constructed repository is vanishingly small.

The greatest danger of radionuclides escaping to the biosphere lies in possible transport by moving groundwater. Because all disposal schemes currently being considered involve placing the wastes under the regional water table, it seems likely that sooner or later groundwater will gain access to the waste canisters, that the canister metal will slowly corrode, and that ultimately some of the radionuclides will be taken into solution. If the groundwater is moving - and most groundwater is

- the nuclides may then escape into an aquifer, hence into wells or into the water of springs or seepages where the groundwater comes to the surface. This is the contingency requiring the most effort to predict and control in any plan for subsurface waste isolation. It is the geologic aspect where the major uncertainties remain, and where geologists have the greatest difficulty in evaluating probabilities of repository failure.

Many steps can be taken, of course, to make the probability of failure very small. A geologic medium would be chosen with demonstrably low permeability, so that any movement of groundwater would be slow, and a site would be selected to make the path that groundwater must travel to reach the biosphere very long. Walls of the repository can be treated, and openings into it can be sealed, to retard the entrance and escape of water. Metal for the canisters can be chosen to keep the rate of corrosion low, and the solid waste form can be engineered to make it resistant to solution. The rock thru which any dissolved waste must travel can be depended on to retard the motion of most radionuclides by sorption, and the natural sorption can be aided by surrounding the canisters with specially prepared sorbent material tailored to the particular rock environment and the particular kind of waste. With all these precautions, the chance of radionuclides reaching the biosphere in any quantity before radioactive decay has rendered them harmless seems remote.

Nevertheless doubts remain, simply because of the insufficiency of present knowledge. Two of the major uncertainties relate to (1) long-term chemical interactions between groundwater, canister metal, and solid waste, and (2) the rate of groundwater movement thru heterogeneous rock material intersected by cracks and zones of shear. The chemical effects of groundwater must obviously depend on its composition, on the nature of the waste and its enclosing material, and on the temperature reached by the canister and its immediate surroundings as a result of radioactive decay; the possible variables are numerous, and both geological and chemical data are too scanty to permit reliable predictions for particular situations. The movement of groundwater thru homogeneous permeable rocks can be predicted from a well tested body of knowledge, but most rocks are cut by cracks and planes of weakness along which water moves more easily than thru the massive rock material; rate of movement thru such jointed rock is difficult or impossible to calculate, and is especially difficult for rock around a repository that has been disturbed by the process of excavation. Some of the questions raised by these two kinds of uncertainty can be illustrated by reference to a few of the rocks that are regarded as likely candidates for repository media.

Bedded salt has been for many years the rock most widely favored for waste isolation. The only potential repository site in this country on which current intensive study is under way is the WIPP site in the thick salt beds that underlie much of southeastern New Mexico. Salt is attractive because of its near-impermeability, its ease of mining, its high heat conductivity, and its ability to deform plastically so as gradually to fill cracks and other openings. Yet major uncertainty remains, as scientists at the U.S. Geological Survey have recently emphasized, regarding the chemical stability of canisters and solid waste in the presence of water that might collect in a salt repository. The danger here is not groundwater moving long distances thru the salt, but water in tiny inclusions in the salt crystals and possible larger pockets that can be expected to move toward a source of heat, hence to collect around the canisters. The water would necessarily be a concentrated brine, probably of complex composition because of impurities in the salt, and at the high temperatures to be found near a canister would be highly corrosive. How much brine would be likely to collect around a canister, how seriously it might affect the integrity of the repository, and what countermeasures might be feasible, are questions to which we have no satisfactory answers. Presumably they can be answered only when the WIPP site is developed and waste is actually emplaced, on an experimental basis, in contact with salt. In this kind of environment the uncertainty regarding waste-groundwater interaction is extreme, but uncertainty regarding flow of groundwater is less acute because of the demonstrated impermeability of salt and its ability to heal fractures by plastic flow.

Granite is commonly mentioned as an attractive alternative to rock salt for repository development because of its low permeability, its ability to maintain openings indefinitely, and its relative chemical inertness at the temperatures to be expected in a repository. The possibilities of granite have been explored more thoroughly in Sweden than elsewhere, and in most respects the Swedish work has corroborated the desirable attributes of granite. The major uncertainty mentioned in Swedish reports concerns the unexpectedly large amount of water that entered a cavity excavated in granite from cracks in the rock. Almost universally granite bodies are cut by fractures in many directions, some of them partly filled with crushed material and mineral crystals, but all of them permitting more movement of water than the solid rock between. The Swedish work includes field experiments to measure the rate of water movement thru fractured granite from one well to another, and this kind of experiment seems the only reasonable way to learn how much groundwater flow to expect in a particular environment. Waste-groundwater interaction would be a relatively minor problem in a granite repository, because water solutions in granite are generally dilute and of simple composition, but uncertainty regarding rates and direction of water movement thru fractured rock might pose a difficult question.

A third rock generally considered as a potential repository medium is basalt. This rock seems particularly attractive at Hanford in Washington, where the development of a basalt repository would obviate the need to transport the huge quantities of waste now stored in near-surface tanks to a distant site. Compared with rock salt and granite, basalt seems at first glance a poor choice because it occurs in relatively thin flows, much fractured and separated by layers of rubble and sediment that are in part good aquifers for water movement.

Exploration by drilling beneath the Hanford area, however, has shown that some flows at depth are thick enough to contain a repository and that many fractures are tightly filled with secondary minerals. The possibility of finding a suitable repository site is certainly great enough to warrant the current exploration effort. Uncertainty regarding rates of water movement thru fractured rock will be as serious at Hanford as in the Swedish granites, and possible waste-groundwater reactions may be more troublesome because more material would be dissolved from basalt than from granite by hot water in a repository. Uncertainty on both scores will be reduced when experiments can be performed with waste emplaced provisionally in a basalt cavity.

One can argue plausibly that these and other uncertain aspects of waste disposal are relatively unimportant, that enough safeguards are present naturally or can be built into a repository in any of these media to prevent appreciable escape of radionuclides. Suppose, for example, that brine collects quickly and in large quantity around canisters embedded in salt, so that the canister metal is eaten away and the salt structure nearby is weakened: still the great bulk of the salt bed remains impermeable, and any waste that might conceivably escape has a long travel path in very slowly moving groundwater to reach the biosphere. Or suppose that a repository in granite or basalt fills quickly with water and the water moves with unexpected rapidity thru fractures: still the attack on canisters and waste will be slow, the path to the surface will be long, and most radionuclides will be trapped en route by sorption. With deficiencies of present knowledge one cannot guarantee that some radionuclides would not escape from a repository, but the amount would be small, movement would be slow, and dilution with groundwater would be enormous. Even with "worst possible" assumptions, it is hard to see how radioactivity could reach the earth's surface in concentrations as great as those commonly found in springs and seepages of areas with natural uranium deposits.

In this sense I think it is legitimate to claim that radioactive waste can be disposed of safely with present technology. But of course we would like to be still more sure. Faced with a menace as serious and as long lasting as uncontrolled release of radioactive waste would be, we need a redundancy of safeguards to ensure that the waste will remain isolated long enough for decay to render it harmless. To gain this added surety, gaps in present knowledge must be filled. Uncertainties of the sort I have mentioned, plus others related to the effect of heat and radiation on rock properties, must be eliminated as far as possible. To accomplish this will require experiments in the field, with actual waste emplaced in rock and carefully monitored for years. Laboratory experiments can help, but their usefulness is limited because every intended repository site will have peculiarities of its own that cannot easily be duplicated on a small scale. The number of geologic variables is so great that only in nature, in a rock environment subject to the same sort of disturbance that repository construction would cause, can the decisive measurements be made.

The result of such field experiments may be to discredit some sites or some kinds of rock altogether. More likely the result will suggest engineering modifications of a site that can make the waste less vulnerable to groundwater attack. The geologic qualifications of a site can be greatly aided by appropriate engineering - choosing canister material and solid waste form to be compatible with the rock environment, diluting the waste or spacing the canisters to control temperature rise, grouting cracks in the repository wall, adding sorbent material or precipitants to impede motion of any nuclides that might dissolve. The sort of measures that would be desirable can only be known from experiments with actual waste over a period of years.

The long delay in solving the problem of waste disposal has occasioned much public complaint. It is often cited as evidence for the ineptitude, the procrastination, or the secretiveness of government agencies. To some it is proof positive that the development of nuclear energy leads to insoluble problems, hence should be abandoned forthwith. Yet from a long perspective the delay is inevitable, even desirable. Accumulation of radioactive waste in large quantities is something new under the sun, a problem we have never faced before. Disposal of the waste requires answers to new questions, answers that cannot be obtained overnight. The questions are especially difficult because they involve geologic prediction, and the present state of geologic knowledge permits prediction only in terms of probabilities. The major questions about waste disposal are already well in hand: we could now dispose of waste in several kinds of rock with a high probability of isolation from the biosphere for hundreds of thousands of years. But the probability can be made still higher by eliminating additional uncertainties, and the necessary experiments to accomplish this are ample justification for continued delay.

The delay in setting up field experiments, however, is harder to understand. Only one large-scale experiment has been tried in this country, a nineteen-month burial of irradiated fuel assemblies in a salt mine in Kansas in the last decade. The experiment produced much useful information, but was not extensive enough or long continued enough to answer all the possible objections that can be raised to waste isolation in salt. Further experiments with high-level waste are planned at the WIPP site in New Mexico; extensive work in granite is under way in Sweden; and experiments in basalt are planned at Hanford if results from preliminary exploration are favorable. Within a decade or two the necessary data should be available for final evaluation of these sites for repository construction. It is unfortunate that similar experimental work is not going forward at additional sites in these and other rock varieties.

From the perspective of a geologist, then, the current state of the waste-disposal effort seems reasonably satisfactory. Guaranteeing the isolation of radioactive waste for the necessary times is admittedly difficult, but it is no worse than other technical problems that have been solved before. The way to a solution seems clear, and present technical knowledge is adequate for construction of repositories in several kinds of rock that would very probably offer the necessary degree of containment. Since long-time geologic prediction is involved, however, and since some geologic factors remain uncertain, additional experimental work is needed to make the probability of success still higher. No absolute guarantee of containment can ever be given, just because of the nature of geologic processes, but on the basis of field experiments it should be possible to choose or to modify repository sites so that the probability of escape of radionuclides in more than minute amounts is at least as low as the probability of other conceivable catastrophes that cause us no apprehension. Such experiments are planned or under way, and the delay in final waste disposal that the experiments will entail should be welcomed rather than seen as a cause for concern.

there are minerals in the ground of which one ounce is lethal, and we keep things in our houses of which a fraction of an ounce would be fatal if ingested. Mercury which we have in electric switches and in thermometers we put in our mouths is a hundred times more toxic than 500 year old waste, and selenium which is used in our radios and TV sets is five times more toxic still. Even nickel, chromium, and aluminum which everyone uses by the pound is comparably toxic with this waste.

Another interesting perspective is to compare the waste with natural radioactivity. If we would stand on the ground above a 1000 year old repository, there would be as much radioactivity in the ground between us and the repository as there is in the waste buried in the repository.

Moreover, it can be shown that all the radioactivity in the ground, deeper than a few meters, is probably not causing as much as one fatality per year in the U.S. When we store our waste, we increase the radioactivity in the top 2000 ft of U.S. rock and soil by only about one part per million each year, so its effect is to cause less than one millionth of a fatality per year.

When we consider very long time periods, we should take into account the fact that nuclear power burns up uranium, and uranium is the source of a great deal of natural radiation exposure. In fact, radon gas which comes from uranium within the top 10-20 ft of the surface of the ground, is believed to be causing about 5000 fatalities per year in the U.S. Therefore, by consuming uranium, much of which is surface mined, we are saving lives. It turns out that after a thousand years, the consumption of this uranium is saving ten times as many lives as the waste is expected to be ending. Thus, on any long time scale, nuclear power with geologic waste storage is a technique for <u>cleansing</u> the earth of radioactivity. People who live in the far distant future will be exposed to less radiation as a result of our use of nuclear power today.

We often hear that it is immoral for us to enjoy use of the energy now while our progeny will be burdened with the waste. Actually the burden will be trivial once the repository is sealed; watching it would be a part-time job for one person. But far more important is the tremendous burden we place on our progeny by consuming all the Earth's valuable mineral resources. Within a few generations we are using up all the copper, tin, lead, and a long list of valuable elements, and we are burning up coal, oil, and gas, each at a rate of millions of tons per day, depriving our progeny of feedstock for making plastics, organic chemicals, and fertilizers. The only practical way we can compensate them would be to leave them a technology that will allow them to live in reasonable comfort without these resources. The key to such a technology must be cheap and abundant energy, and the only source of this we can now guarantee is nuclear power from fission.