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Radioactive Waste Disposal: Nature's Way vs. Government's Way

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Executive Summary

The problem of the disposal of radioactive waste from reactors is one of the chief obstacles to increased reliance on nuclear power. In this paper, Dr. Bernard L. Cohen, a physicist at the University of Pittsburgh, examines the problem and compares two strategies for disposing of "radwaste" from spent fuel.

The current government solution to radwaste disposal is to place it in high-tech underground storage chambers designed to prevent or greatly delay contact with groundwater, which is the main source of leakage outside the containment site. Aside from the cost and scientific uncertainties involved, this strategy is encumbered by political resistance in host communities. Dr. Cohen proposes using "Nature's solution" to contain spent fuel by burying it without elaborate artificial encapsulation, just as naturally-occurring radioactive materials are found in the ground. Using standard risk-assessment methodologies, he concludes that burying reprocessed radwaste simply and securely deep underground would cause much less than one death per year in the U.S., less than 0.01% of the number now caused by wastes from coal-burning electricity generation.

In November 2007, nine governors of midwestern states agreed on a plan to fight global warming.[1] It did *not* include generating more electricity from nuclear energy, which now provides 20% of our electricity without emitting greenhouse gases. According to the Governor of South Dakota, it was not included because "it's useless without a national plan to deal with radioactive waste." He was referring to the problem of disposing of the highly radioactive waste (radwaste) in the spent fuel after it is removed from nuclear reactors. Our purpose here is to put this problem in proper perspective and clear up some of the gross misunderstandings about it.

The generally recognized solution for disposing of this radwaste is to bury it deep underground, typically about 600 meters below the surface.* How safe would that be? It is universally agreed that the principal danger is that this buried radwaste will be dissolved by groundwater, transported in this solution as it works its way toward the surface, and eventually ingested by people with potable water, that used for drinking and preparing food – 40% of our potable water is derived from groundwater. Once inside the body, where it may remain for many years, the radioactive materials continually expose body organs to radiation which can cause cancer.

The generally accepted details of estimating the radiation dose to various body organs from ingesting a given quantity of each radioactive species are worked out and published [1] by the International Commission on Radiological Protection (ICRP). The calculations involve the probability for the material to pass through the intestine walls into the blood stream, the probability for it to deposit from the blood into each

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[1] *Governors Sign Energy Security and Climate Stewardship Platform and Greenhouse Gas Accord http://www.midwesterngovernors.org/govenergynov.htm*

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body organ, and the duration of its residence in that organ, to derive the total radiation energy deposited in the organ which determines the dose it receives. The cancer risk from a given radiation dose is estimated in publications [2,3] by the National Academy of Sciences Committee on Biological Effects of Ionizing Radiation (BEIR) and the United Nations Scientific Committee on Effects of Atomic Radiation (UNSCEAR). These cancer risks are based on a linear-no threshold (LNT) relationship between risk and dose, assuming, for example, that the risk from 1 unit of dose is 0.001 times the risk from 1000 units of dose. The cancer risk from such high doses as the latter is well known from studies of groups who experienced large exposures, such as the Japanese A-bomb survivors, patients treated with radiation therapy, workers occupationally exposed, victims of accidents, etc. There is extensive evidence [4] that the LNT assumption grossly over-estimates the risks from the low doses that can be caused by escape of buried radwaste, but LNT is widely used and we use it here. Thus, the risk estimates we derive may well be too high.

Using BEIR and UNSCEAR with LNT, it is straightforward to estimate the number of fatal cancers that would be caused if all of the buried radwaste were converted into digestible form and fed to people.[5] We define this as the number of cancer doses (CD) in that radwaste. (This assumes that there are enough people involved so that none of the toxicity is wasted by feeding more than a fraction of one CD to any one individual.) The number of CD in the spent fuel vs. time following removal from the reactor is plotted in Fig. 1. An alternative procedure is to chemically reprocess the spent fuel to remove the uranium and plutonium, which are useful for fueling future reactors – we assume the 99.5% removal by current technology (PUREX) used since the 1940s. Most European nations and Japan do reprocessing now, but it is not the present U.S. policy. The equivalent of Fig. 1 for the radwaste left after reprocessing is shown in Fig. 2.

Figure 1

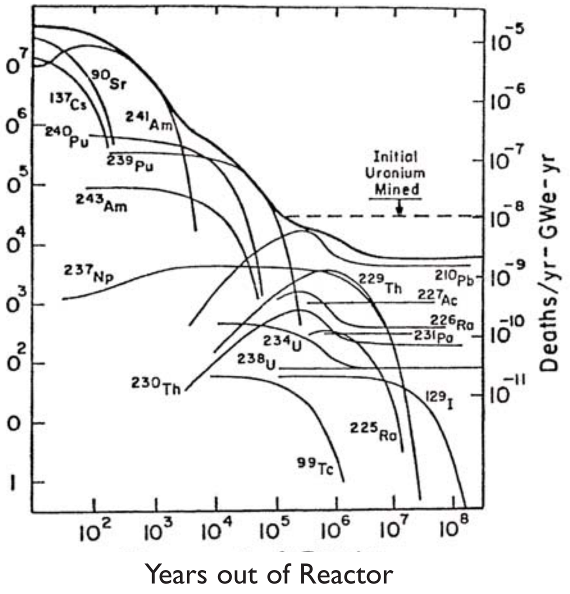

Figure 1: Number of cancer deaths (CD) expected if the spent fuel produced from generating one Gigawatt of electric power for one year (one GWe-yr) were converted into digestible form and fed to enough people such that none of the toxicity is wasted by feeding more than one CD to any one person. Abscissa is time after the spent fuel is removed from the reactor. Individual curves show contributions of individual radioactive nuclides, and the thicker curve at the top is their sum. Scale on right side gives deaths per year assuming that the transfer probability for an atom of buried waste from its original burial status into a human stomach is 4 x 10^{-13} per year. The dashed line shows the number of cancer deaths expected due to radiation if the 160 tonnes of uranium (plus decay daughters) that was originally mined to fuel the reactor were fed to people.

The number of CD in the ground from buried radwaste will depend on how much nuclear power we generate continually into the indefinite future. The results we give here are based on assuming 100 GW (Gigawatts = one million Kilowatts) of nuclear-derived electric power (we currently use 88 GW), but they are readily translated into alternative assumptions by simple proportionality. This 100 GW assumption multiplies the effects of Fig. 1 and 2 by 100. The other important variable in determining the number of CDs in the radwaste is the time (T) before we convert from permanently burying spent fuel to chemically reprocessing it. As newly mined uranium becomes scarcer and hence more expensive, this will very

Figure 2

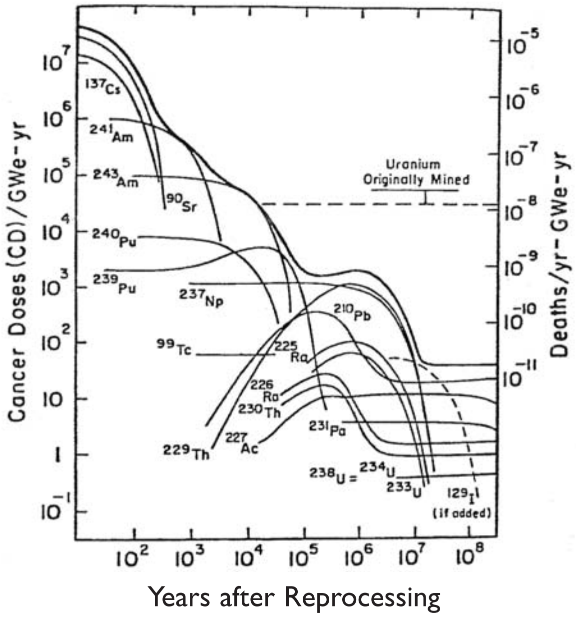

Figure 2: Same as Fig. 1 for the residual waste after chemically reprocessing this fuel.

probably be necessary within the next 100 years, and will surely be required within the next 300 years.

Calculations based on the above considerations [6] show that the total accumulated number of CDs in U.S. buried radwaste reaches a first peak at the time T: for T = 100 years, it is 1.9 x 10^{12}, and for T = 300 years it is 3.1 x 10^{12}. After time T, the number of CDs decreases slowly over the next several thousand years as the large contributions from the spent fuel era decay away faster than the new contributions from the reprocessing era increase. For T = 100 years there would be 1.6 x 10^{12} CD after 1000 years and 1.3 x 10^{12} CD after 2000 years; for T = 300 years there would be 2.2 x 10^{12} CD after 1000 years and 1.5 x 10^{12} CD after 2000 years. In either case, it would slowly increase to 2.0 x 10^{12} CD after 20,000 years. To simplify the following discussion, we assume there will always be about 2 x 10^{12} CD (2 trillion CD) of radioactive waste from nuclear power plants buried 600 meters below various locations throughout the U.S. (contiguous 48 states) over the next many thousands of years.

How many cancers will this cause and how acceptable is the situation from the standpoint of public health? This depends on how the waste is buried, and there are two approaches to that operation – we call these "Nature's way" and "Government's way."

Nature's Way

The "Nature's way" option is based on how nature "manages" radioactive materials in rocks. It would consist of simply burying the waste in the natural habitat of rocks, deep underground. If the waste has been reprocessed, the buried material, in accordance with current technology, would be a glass. Many natural rocks are glasses, so it seems reasonable to assume that nature will treat it as it treats other rocks containing radioactive materials. There is substantial evidence supporting this assumption, but if it is not accepted, technology is available for converting the radwaste into a form mimicking average rock.

If the waste is permanently buried as spent fuel without reprocessing, there may be some question as to whether it would be as secure from being dissolved as ordinary rock. There is some evidence on this from natural uranium deposits. For example, the Cigar Lake deposit in Northern Saskatchewan (which contains 11% of the world's known uranium reserves) consists of uranium dioxide, the same material we would bury as spent reactor fuel, 430 meters below the surface. It has been there for 1.3 billion years, but no uranium can be detected in the ground above the deposit. There is similar evidence from other natural uranium deposits in Canada and Australia.

Perhaps it is fair to say that the security of buried spent fuel is a research problem for geochemists. If it is decided that its security is much less than for average rock, we could reprocess all fuel before burial, or retrieve buried spent fuel for reprocessing when such a decision is made. For further discussion, we assume that the buried radwaste will behave as ordinary average rock.

Let's see how nature "manages" its radioactive materials buried in the ground. Rocks contain uranium and thorium, radioactive elements that decay into other radioactive elements such as radium, polonium, and some isotopes of lead and bismuth. The quantities of these naturally occurring materials in the top 600 meters of U.S. rock – that is, closer to the surface (and hence more potentially dangerous) than the buried radwaste – comes to 30×10^{12} CD, 15 times the number of CD in the radwaste below it [6].

In the normal course of events, some of this uranium, thorium, radium, etc. is dissolved out by groundwater and eventually ingested by people with potable water, exposing their body organs to radiation. From measurements on human corpses, we know how much of these naturally radioactive materials is in our bodies, from which it is straightforward to calculate the radiation dose to which they expose us. From that dose, using BEIR and UNSCEAR publications with LNT, we can estimate the number of cancer deaths per year caused by this radiation. Chemical analyses of foods and water supplies tells us what fraction of these materials in our bodies is derived from potable water rather than from food; this varies from 2% for thorium to 50% for uranium. (Materials in food were picked up by plant roots in the top few meters of soil that is normally watered by rain or river water irrigation soaking down from above, so groundwater contributions are of minimal importance.) The conclusion is that ingestion of these naturally radioactive materials with potable water derived from groundwater causes about 29 cancer deaths per year in the U.S.[6].

As these 29 deaths are caused by the 30 trillion CD in the ground (we ignore the small contributions from below 600 meters), this is about one death per year per trillion CD. Applying this to the 2 trillion CD in the buried radwaste from nuclear power plants gives us an estimate of about 2 deaths per year expected from the latter. However there are several reasons why this is a substantial over-estimate:

1. The nuclear power radwastes will be buried at 600 meters depth, whereas the natural radioactivity we are considering is at depths between there and the surface. The average groundwater flow per meter of depth through this region is 6 times larger than at 600 meters, so we should divide the above result by 6.
2. There is a substantial time delay in travel from deep underground to near the surface for materials dissolved in ground water; typical ground water flow rates are less than one foot per day and typical travel distances to reach near the surface are 20 to 100 miles, leading to travel times of many hundreds of years. Materials dissolved in groundwater are filtered out via ion-exchange and other such processes by the rock through which the water passes, extending their travel times to many thousands or millions of years. As is evident from Fig. 1 and 2, such time delays allow large fractions of the radioactivity in the radwaste to decay away. This decrease in radioactivity with travel time does not apply to the naturally occurring uranium and thorium because of their long half lives, and it does not apply to their decay products as these are replenished as rapidly as they decay away.
3. The medical cure rate for cancer is improving at a rate of about one percent per year, so the great majority of the cancers predicted in our calculation, occurring thousands of years in the future, will probably be easily cured.
4. Our calculation is based on *average* conditions in the ground throughout the U.S., whereas radwaste repositories will be built at sites carefully selected by the best experts in geology and hydrology. This should provide more security than average sites.
5. It would be very easy to detect any substantial amount of escaping radioactivity

from these sites if it should occur, so measures could be taken to greatly reduce human exposures.

Our final conclusion is, then, that if we took advantage of Nature's way, burying the radwaste in the deep underground natural habitat of rocks, the accumulated waste from producing nuclear electricity continually and indefinitely in the U.S. would cause much less than one death per year in the U.S., only a tiny fraction of the number now caused by the wastes from coal-burning electricity generation.

There are other completely independent ways [5, 7, 8, 9] of arriving at this conclusion, based on assuming that radwaste behaves like average ordinary rock. For example, from the rate at which rivers carry dissolved and suspended material into oceans, it is straightforward to calculate that the surface of the ground under U.S. is eroding away at an average rate of 4.5 x 10^{-5} meters of depth per year (1 meter per 22,000 years). About 28% of this is in solution (the rest is suspended particles); hydrologists estimate that 15% of the water flow in rivers is derived from ground water (the rest is from surface run-off), and ground water contains about twice the solute concentration of river water. Applying these corrections leads to the conclusion that groundwater dissolves and removes a total of (4.5 x 10^{-5} x 0.28 x 0.15 x 2 =) 3.8 x 10^{-6} meters per year of depth.

Consider the fraction of this total that is derived from between 599 and 600 meters below the surface. It is obviously much less than 1/600, and an elaborate calculation [7] indicates that it is about 1/4000. Thus (3.8 x 10^{-6} x 1/4000 =) 1 x 10^{-9} meters of depth per year are dissolved out of that one meter of depth. Therefore the average probability per year for an atom of rock at 600 meter depth to be dissolved out and carried away is 1 x 10^{-9}. This means that an average rock at that depth can be expected to survive for about a billion (10^9) years.

There is an interesting confirmation of this durability from the OKLO reactor, a rich uranium deposit under ground in Gabon (Africa) which operated as a natural reactor two billion years ago, producing about 8 tons of radioactive waste including 1.8 tons of plutonium. These materials and those into which they eventually decayed were continually exposed to ground water, but they have essentially remained in place; for example, the plutonium and its decay products have moved less than 10 feet in these two billion years.

Once dissolved in ground water, the most important pathway for an atom into human stomachs is via drawing potable water from wells. The total water flow in U.S. shallow aquifers is 2.8 x 10^{14} liters per year, and the total well water ingested in U.S. is 7.4 x 10^{10} liters per year, so the probability for a molecule of water from groundwater entering a human stomach is the ratio of these, 2.6 x 10^{-4}; we assume this also applies to material dissolved in the water, not taking into account its possible removal in water purification systems. Thus, the probability for an atom of rock at 600 meter depth to be dissolved out and eventually enter a human stomach is (1 x 10^{-9} x 2.6 x 10^{-4} =) 2.6 x 10^{-13} per year.

There are parallel pathways to be considered: ground water eventually flows into rivers or lakes which are utilized as sources for potable water, fish from these rivers are used for human food, and ground water and river water are used for irrigating food crops. Adding contributions from these [8, 9] brings the total transfer probability from rock to human stomachs to 4 x 10^{-13} per year.

The number of deaths each year following burial is then obtained by multiplying the ordinates in Fig. 1 and 2 by 4 x 10^{-13} which is conveniently done by the scale shift shown on the right side of those figures. The total number of deaths is then obtained by adding up the number of deaths each year over time. This summation is complicated by recognizing that erosion at 1 meter of depth per 22,000 years will gradually bring the material to the surface after (600 x 22,000 =) 13 million years, at which time it will most probably be released into rivers, to be ingested with the probability for ingestion of river water, 1 x 10^{-4}. The final result is that the radwaste generated in one year from 100 GW of nuclear power will eventually cause 2 deaths without reprocessing and 0.6 deaths with reprocessing, so that if this rate of nuclear power generation is continued, there would be less than 2 deaths per year in U.S. indefinitely into the future from buried radwaste.

This result is in substantial agreement with our above estimate from an entirely independent approach. Most of the effects listed in connection with that estimate as reducing the toll also apply here – the time delay allowing much of the radioactivity to decay away en route to the surface, the improving cancer cure rate, the expertise of geologists and hydrologists utilized in site selection, and the detection of escaping radioactivity. It thus seems safe to confirm our previous conclusion that there would be less than one death per year in U.S. from buried radwaste.

All of the estimates described above (and some others) have been published in widely read scientific journals, and none of them has been challenged, or even criticized in the scientific literature. It thus seems clear that if we were to utilize Nature's way of managing radwaste, converting it into rocks and burying them deep underground, we could expect something less than one cancer death per year in U.S. to result. This surely compares very favorably with the many thousands of deaths per year we now accept from the wastes, principally air pollution, of generating the same amount of electricity by burning fossil fuels. Following Nature's way would be a simple and very acceptable solution to the issue of radwaste disposal.

Government's way

For the problem of radwaste burial, the U.S. government approaches safety issues mainly through three agencies. The Environmental Protection Agency (EPA) sets up dose limits to people from potential radioactivity releases, the Nuclear Regulatory Commission (NRC) sets up licensing procedures for technical evaluation of performance, and the Department of Energy (DOE) designs repositories to comply with the EPA dose limits and applies to NRC for a license to build and operate them. All of this is subject to substantial interactions with the public, including government financing for activities of opposition organizations and their legal appeals to Federal courts. The entire process involves roles for the President, the Secretary of Energy, the government of the host state, and final approval by Congress. Obviously, these procedures involve extensive political activity.

The principal licensing requirement set up by this system is that DOE must demonstrate with high confidence that at no time in the next million years will any single individual member of the public be exposed to stipulated radiation doses in any one year. For the first 10,000 years the stipulated dose is 15 millirem, which would give him a risk of cancer death (assuming there is no progress in curing cancer from now until that time) equal to 2% of the average American's present risk of being killed in an accident in any one year. There is no stipulation on how many other people are exposed to that or lower doses, or over what time period these exposures occur, so there is no consideration given to the total number of cancers caused. Isn't that what we should be concerned about? With this licensing requirement, nuclear bomb testing in the atmosphere over a remote unpopulated area could be licensed since no one person living at locations remote from test sites has received more than about 5 millirem in any one year, but that practice was abandoned in 1962 because it was estimated (using LNT) to be killing thousands of people throughout the world every year – a risk to individuals of one chance in a million has that effect when applied to billions of people.

This licensing process precludes any direct use of Nature's way. The calculations described above for Nature's way utilize data averaged over the entire U.S. Its result, less than one death per year, is equivalent to the total eventual consequences of siting a large number of repositories at random locations throughout the U.S. But it does not predict the effects on a single individual person of a repository at a specific site at some particular future time.

If the radwaste were simply buried deep underground, mimicking Nature's way, licensing would require knowledge of and future predictions for all aspects of groundwater behavior at that site, such as the effects of possible earthquakes and volcanic action in the vicinity, different future climates (10,000 years ago the Arizona desert was a rain forest and the Sahara desert was well watered), geological land uplifting which can drastically alter river and groundwater flow patterns, intrusion by humans and lower life forms, etc. Note that these are automatically taken into account in Nature's way because all of them are occurring in some U.S. locales now and hence contribute with their proper weightings to the averages used in the calculations.

Aside from problems in predicting the future, we do not well understand the present details of Nature's way. A government-sponsored National Academy of Sciences study of the interaction of radwaste-rock with groundwater [10] was shown to be wildly erroneous [11]. There was nothing in the treatment that would not apply to ordinary rock, and when so applied it predicts that the continents would be dissolved away in a few thousand years, and that certain chemical elements (cesium, thorium, selenium, tin, and others) would have long since been dissolved out of the ground, contrary to the fact that their concentrations have not even been depleted. There is little understanding of the occurrence and effects of cracks in the rocks, of effects of the granular nature of rock, and other matters.

The DOE solution to this problem is not to depend on Nature's way, but rather to install the radwaste in a large underground man-made storage chamber in which everything is designed so as to prevent contact with groundwater [12]. It includes parts made of special (and very expensive) corrosion-resistant metal alloys and devices for conducting away the heat from the radioactivity. The design includes provisions for preventing and/or mitigating effects of water dripping into this chamber, of falling rock, and of other possible intrusions. In summary, Government's way is to depend heavily on technology to prevent, or at least greatly delay, encounters with groundwater, in contrast to Nature's way in which radwaste rock is ordinarily fully exposed to groundwater from the time of burial.* There is a problem here: if and when encounters with groundwater do occur in the Government's way, they take place under rather different circumstances than contact with groundwater in Nature's way. It is therefore assumed that the interaction is what is measured in engineering tests involving a stream of water running over the radwaste, which gives dissolution rates of about 10^{-3} per year, in sharp contrast to the 10^{-9} per year found above for rock in the natural deep underground environment. To fully compensate for this enormous discrepancy, the design should presumably guarantee there is less than one chance in a million for water to reach the wasteSince this can hardly be done convincingly, the DOE analysis depends on some of the other factors we have mentioned but which we hardly used in evaluating Nature's way, like the long travel times for groundwater to approach the surface and the filtering properties of the rock. Here again large errors are possible if, for example, there are cracks in the rock.

In order to satisfy the licensing requirement utilizing the Government's way, it is necessary that everything be calculated for the specific site. Such calculations require that assumptions be made about processes that are not well understood and about the probabilities for various possible future disrupting circumstances. Judgments on these assumptions are somewhat personal and are susceptible to a wide range of uncertainty, and hence they are readily vulnerable to reasonable criticisms. These judgments have been debated, negotiated, and agreed upon by DOE-sponsored scientific experts involved in reaching a consensus [12], but opponents have had little difficulty in finding not irrational objections with major consequences for these judgments.

To make matters much worse, the political debate heavily involves non-experts who have little interest in the thousands of pages of documented scientific input leading to these judgments. Many of them are committed to opposing any such consensus, motivated by politically useful slogans such as “we don’t want our area to be the nation’s garbage dump.” Politics in Nevada, where the first repository is being planned at Yucca Mountain, seems to require that any candidate for political office adopt that position. That includes Senator Harry Reid who is the majority leader in the U.S. Senate and who has vowed to do anything in his very considerable power to obstruct the process. All of the candidates who were vying for the 2008 Democratic presidential nomination seem to agree with his position.

Needless to say, this licensing procedure requires a lot of time and a lot of money. About 20 years and at least 8 billion dollars has already been spent on the licensing of the proposed Nevada repository, and the end is hardly in sight. The opponents, including Senator Reid, argue that there is no urgency to making a final decision as the waste is now being safely stored at the various nuclear plants where it is generated.

However the lack of a decision is impeding the construction of new nuclear power plants. Some states such as California legally prohibit such new construction until the radwaste problem is “solved,” and some utility executives refuse to consider undertaking such construction fearing the political impacts of that “unsolved problem.” Since nuclear power is the principal means we have for generating electricity without contributing to global warming, the current situation is a real obstacle to our future energy security.

Looking to the future, the difficulties escalate. If we are to continue our use of nuclear power, many repositories will eventually be required. If each of these involves the time and cost and political energy of the Yucca Mountain site, it is difficult to see how they can be built.

My solution to the dilemma

In my view, this very serious dilemma is caused by following the Government’s way rather than Nature’s way of managing radioactive waste. This problem can only be remedied by changing the legally required procedures. I have proposed [13] that it is reasonable to assume that utilizing all the expert knowledge of geologists and hydrologists would select repository sites at least as secure as random selections. Licensing would then consist simply of showing that waste burial in a randomly selected site would be adequately safe. This is basically what has been shown above in our discussion of Nature’s way. If additional security is required, a ground water monitoring system of wells could be included at trivial cost around each repository.

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*The treatments in this paper do not apply directly to the Yucca Mountain repository in Nevada, where the burial is to be 300 meters below the surface (reducing its security) but 300 meters above the water table, which greatly improves its security. Our discussion is based on assuming that the waste will be buried in the water table, where the rock is saturated with water.

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