NATURAL RESOURCES JOURNAL

Volume 21
Issue 4 *Symposium on the Management of Nuclear Wastes*

Fall 1981

High Level Radioactive Waste

Bernard L. Cohen

HIGH LEVEL RADIOACTIVE WASTE

BERNARD L. COHEN*

When fuels are burned to produce energy, they don't just disappear. Rather, they are converted into wastes. This is true for any fuel, but we will limit our discussion to the two principal fuels now available for generating electricity; coal and uranium. A comparison of the wastes produced in one year by a large[1] coal burning plant with wastes produced by a uranium burning plant of comparable capacity in one year yields an interesting perspective.

From the coal burning plant, the principal waste product is carbon dioxide, produced at a rate of 500 pounds each second. This waste is not ordinarily categorized as a dangerous gas. Nevertheless, there are now serious concerns that carbon dioxide may cause important changes in the world's climate, which would in turn have profound ecological effects.

The most important toxic gases produced by a coal burning plant are the sulfur oxides, emitted at a rate of about 10 pounds per second. The sulfur oxides from a single plant are estimated to cause about 25 fatalities and 60,000 cases of respiratory disease each year. Further, they cause about $25 million in property damage annually. Another type of toxic gas, the nitrogen oxides, are best known as the principal pollutant from automobiles. Most of the air pollution control devices on cars, and the use of lead-free gasoline are intended to decrease the emission of nitrogen oxides. A coal burning plant produces as much nitrogen oxide as 200,000 automobiles.

Smoke and dust consisting of tiny solid particles comprise another important pollutant from coal burning. There is a widespread misbelief that this problem has been largely eliminated by smoke control equipment. This equipment eliminates the larger visible particles, but it does little to protect us against the very tiny particles. The minute particles pose serious health problems because they can be inhaled deep into the lungs. The potential health damage resulting from solid particles therefore can be as serious as the health damage from sulfur oxides.

Coal burning produces a variety of cancer causing chemicals, in-

---

*Professor of Physics, The University of Pittsburgh.

1. SENATE COMMITTEE ON PUBLIC WORKS, AIR QUALITY AND STATIONARY SOURCE EMISSION CONTROL (1975).

cluding benzpyrene. This compound is believed to be the principal cancer causing agent in cigarette smoke. Coal burning also releases small amounts of many highly toxic metals into the environment, such as mercury, cadmium and selenium. Also among these metals are uranium and thorium. Thus, coal burning exposes the public to radioactive gases.

Finally, coal burning releases ash into the environment at a rate of 1,000 pounds per minute. Disposal of this bulky, solid material frequently presents difficult environmental problems.

In summary, the environmental effects of wastes from coal burning plants remain largely unquantified. These wastes, however, are causing at least 25 fatalities per year. Pollution control equipment can curtail deaths attributable to coal waste, but it is highly doubtful that the toll can be reduced to less than five fatalities per year.

These effects compare unfavorably with the effects of radioactive wastes from a nuclear plant generating the same amount of electricity. A tiny fraction of nuclear wastes are released into the air and water near the power plant. Less harmful radioactivity is released in this way from the nuclear plant than from the coal burning plant, and radioactivity releases are among the least serious of the coal plant's problems. Estimates show that radioactive emissions from a nuclear plant may cause about one fatality every 50 years.[2]

The vast bulk of the radioactivity produced in a nuclear power plant, however, becomes high level waste, which is the principal focus of attention. The question of waste disposal has been a topic of great concern and speculation. There is a simple answer to the questions posed by disposal: the waste will be converted into a rock-like material and placed where the rocks are, deep underground. The safety of this method has been questioned. A simple answer is that if the buried waste behaves as rocks behave, it is extremely safe by any reasonable standard. Among scientists, it is widely believed that this standard can be realized.

But our purpose is to examine high level waste problems in some detail. One interesting aspect of the problem is the quantities involved. The waste generated by one large nuclear power plant in one year amounts to about two to three cubic yards. Such an amount would fit under a typical dining room table. This quantity is five million times smaller by weight and billions of times smaller by volume than the wastes from the coal burning plant. The electricity generated

---

2. *American Physical Society Study Group on the Nuclear Fuel Cycle*, 50 REV. of MOD. PHYSICS (1978); U.S. NUCLEAR REGULATORY COMMISSION, DOC. NUREG-0002 (1976); U.N. SCIENTIFIC COMMITTEE ON EFFECTS OF ATOMIC RADIATION, SOURCES AND EFFECTS OF IONIZING RADIATION (1977).

by one of these plants in a year sells for more than $200 million. Hence, if we divert only 1% of the electricity's sales price to waste disposal, we can spend $2 million to bury an amount of rock-like waste material that would fit under a dining room table. Clearly, we can afford to use some very elaborate protective measures.

Another characteristic distinguishes nuclear wastes. Their potential as a health hazard arises not from their chemical properties, but from the radiation they emit. There appears to be a widespread misapprehension that this characteristic introduces a considerable degree of uncertainty into the evaluation of the potential health hazards associated with nuclear wastes. The truth is quite the opposite. The effects of radiation on the human body are far better understood than the effects of chemicals such as air pollutants, food additives, effluents from industrial plants, and pesticides. Radiation is easy to measure accurately with inexpensive but highly sensitive instruments. Moreover, a large body of information has been compiled over the years from human exposure to radiation, including the atomic-bomb attacks on Japan, medical treatment with X-rays and radium, industrial exposure to radium, and inhalation of radon gas by miners. The available data has been analyzed by national and international groups, including the National Academy of Sciences Committee on the Biological Effects of Ionizing Radiation,[3] the International Commission on Radiological Protection,[4] and the United Nations Scientific Committee on the Effects of Atomic Radiation.[5] The result is a reliable set of estimates of at least the maximum effects of various levels of radiation on the human body.

The radioactive substances in the waste products of a nuclear reactor and their formation warrant close examination. In a light-water reactor (the type of nuclear plant now in general service for generating electricity in this country) the fuel consists initially of a mixture of two isotopes of uranium: the rare, readily fissionable isotope uranium 235 ("enriched" to about 3 percent) and the abundant, ordinarily nonfissionable isotope uranium 238 ("enriched" to 96.7 percent). The fuel mixture is fabricated in the form of ceramic pellets of uranium dioxide (UO_2) which are sealed inside containers made of stainless steel or a zirconium alloy. In the course of the reactor's operation, neutrons produced initially by the fission of some of the

3. U.S. NATIONAL ACADEMY OF SCIENCES, COMMITTEE ON BIOLOGICAL EFFECTS OF IONIZING RADIATION, THE EFFECTS ON POPULATIONS OF EXPOSURE TO LOW LEVELS OF IONIZING RADIATION (Washington, D.C. 1980).

4. INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, PUBLICATION NO. 26: Recommendation of ICRP Pergamon Press, New York, 1977.

5. U.N. SCIENTIFIC COMMITTEE, *supra* note 2.

uranium-235 nuclei strike other uranium nuclei, either splitting them in two (and thereby continuing the chain reaction) or being absorbed (and thereby increasing the atomic weight of the struck nucleus by one unit). These two types of reactions result in a variety of radioactive nuclei.

After the spent fuel is removed from the reactor, it is stored for several months to allow the isotopes with a short radioactive half-life to decay. This temporary storage is particularly important with respect to an isotope such as iodine 131, one of the most dangerous fission products, which has a half-life of only eight days. The spent fuel is then sent to a chemical reprocessing plant, where the fuel pins are cut into short lengths, dissolved in acid and put through chemical separation processes to remove the uranium and plutonium. These substances would then be available to make new fuel. Everything remaining except for gases, which would be discharged separately, and the pieces of the metal fuel pins that do not dissolve in the acid is referred to as "high level" waste. The fission products generate the vast preponderance of the radioactivity associated with nuclear waste. Other high level wastes would in this case include the isotopes of neptunium, americium and curium, together with the small amounts of uranium and plutonium that would not be removed in reprocessing, owing to inefficiencies in the chemical separations.

Deep burial affords the simplest safe method of high level waste disposal. The detailed burial procedures are not yet definite. Present indications are that the wastes will be incorporated into a glass which will be fabricated in the form of cylinders perhaps about 300 centimeters long and 30 centimeters in diameter. Each glass cylinder will in turn be sealed inside a thick stainless steel casing. These waste canisters will then be shipped to a federally operated repository for burial. One year's wastes from a single 1,000 megawatt nuclear power plant will convert into 10 such canisters. The canisters might be buried about 10 meters apart. Hence, each canister might occupy an area of 100 square meters. An all nuclear U.S. electric power system might require roughly 400-1,000 megawatt plants, capable of generating 400,000 megawatts at full capacity (our present average electric-power usage is about 230,000 megawatts). Accordingly, the total high-level wastes generated annually by an all-nuclear U.S. electric-power system should occupy an area of less than half a square kilometer.

The main reason for spreading the canisters over such a large area is to dissipate the heat generated by their radioactivity. The problem of dealing with this heat can be substantially alleviated by waiting for 10 years after the reprocessing operation. Such a delay diminishes

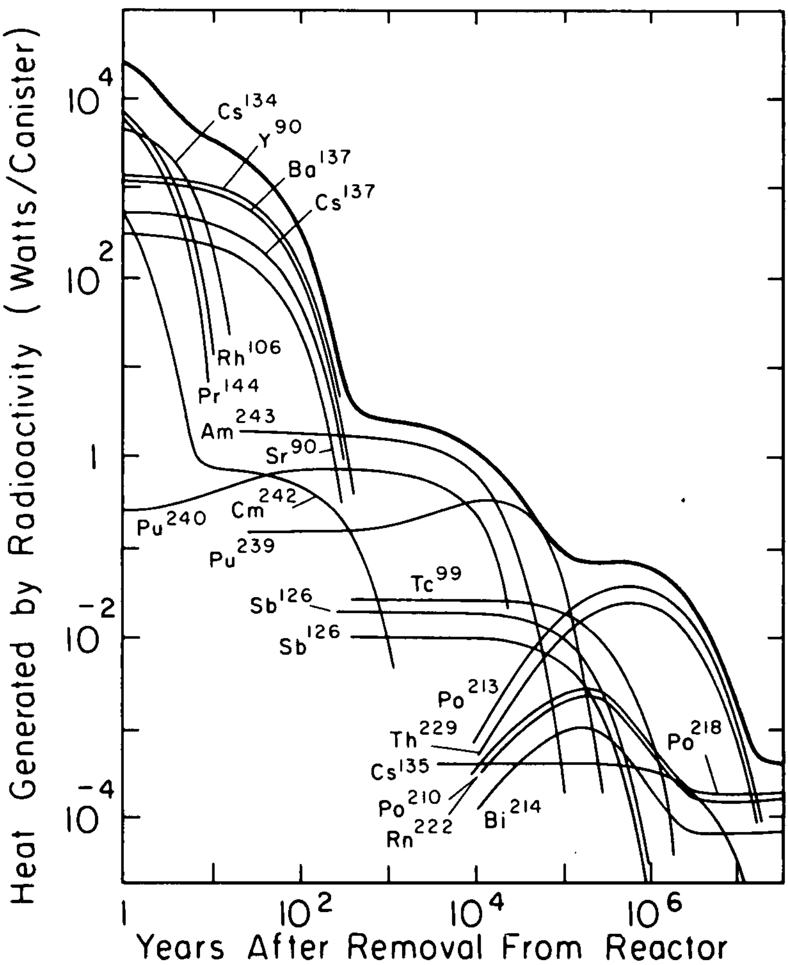

FIGURE 1

Heat generated by radioactivity in the waste as a function of time. Thin lines show the contributions from various radioactive isotopes as labeled, and the thick line shows the total from all. The former can be ignored if not understood. Note that the total heat generation is reduced by a factor of 8 (from 2.5 x 10^4 to 3.4 x 10^3) if burial is at 10 years rather than at 1 year.

the level of heat generated by each canister to about 3.4 kilowatts.[6] The advantage of delayed burial is seen in Figure 1, which shows the

6. Recent attention has been focused on the possibility of reducing this heat to about one Kilowatt, by putting less waste in each canister and increasing the number of canisters proportionately.

temperature at the canister surface for various delay times before burial.

Public concern prompts consideration of health hazards in the waste. For such purposes, exposure to radiation is expressed in *rem;* exposures are readily calculated and measured in that unit, and effects of radiation are expressed in terms of effects per rem of exposure. The principal effect worthy of consideration here is cancer induction. For whole body radiation such as would be delivered by a source of gamma rays outside the body, the risk of incurring a radiation induced fatal cancer is approximately 1.8 chances in 10,000 per rem of radiation exposure.

Gamma rays emitted from radioactive waste pose one potential hazard. The energy emitted in the form of gamma rays from the waste produced by one year of all nuclear electricity in the U.S. (as defined above) is shown in Figure 2. This is a potentially very dangerous quantity. The scale on the right side of Figure 2 shows the number of cancer deaths that would result if this material were spread randomly over the ground in the U.S. For example, the dashed lines in Figure 2 show that if this distribution of nuclear waste took place 10 years after the fuel was consumed, over 100,000 deaths/year would result. Clearly, such a method is not a viable option for disposal. But if the material is buried deep underground and remains there, the risk from gamma rays is completely negligible; not a single gamma ray would ever reach the surface.

More important than the hazard of external exposure to gamma rays is the potential hazard of the radioactive material if it enters the human body. There are two major entry routes; ingestion with food or drink, and inhalation. Figure 3 shows the ingestion hazard that would result if all energy needs were met by nuclear power for one year. In this graph, the value of 10^6 at 10^4 years shown by the dashed lines, for example, indicates that if all the wastes, after aging for 10,000 years, were to be converted into digestible form and fed to people, one could expect a million fatal cancers to ensue. This "worst case" scenario rests on the assumption that many millions of people are involved. But in view of the linear relation between dose and effect generally assumed for calculating such radiation risks, the number of people involved is irrelevant. The derivation of such a graph is rather complex. It involves for each radioactive species the probability of transfer across the intestinal wall into the bloodstream, the probability of transfer from the blood into each body organ, the time the radioactive substance spends in each organ, the energy of the radiation emitted by the substance and the fraction of the energy absorbed by the organ, the mass of the organ, the relative biological

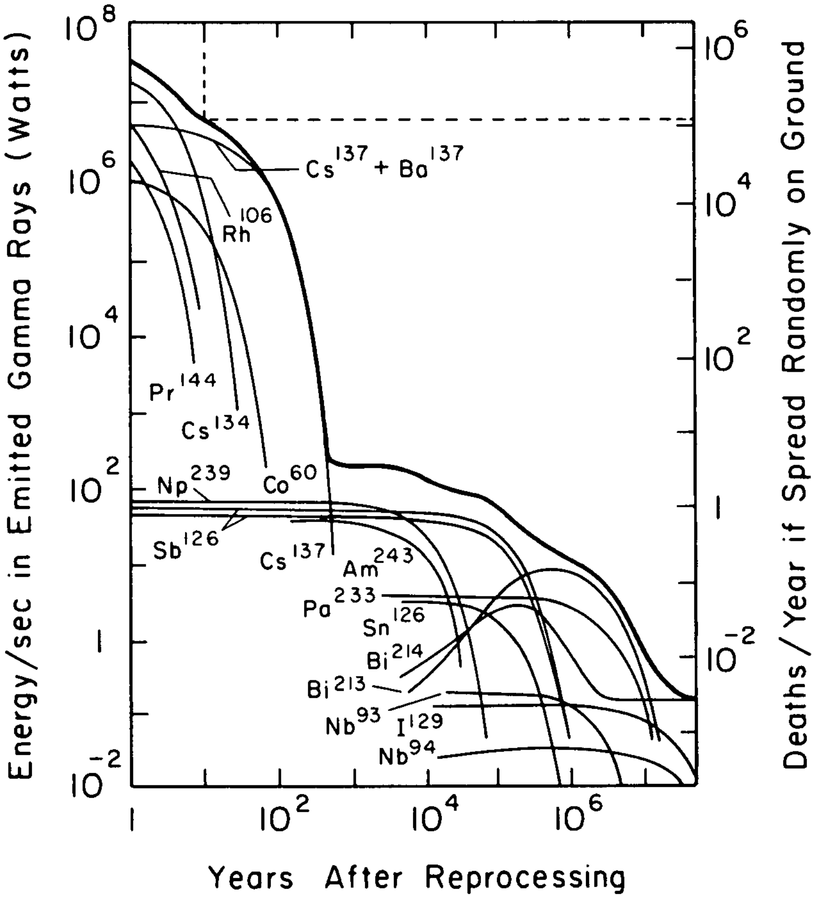

FIGURE 2

Energy per second emitted in the form of gamma rays from the waste generated by one year of all U.S. power nuclear as a function of time; this is proportional to the danger in standing close to a waste package if there is no shielding between. Thin lines show the contribution of various radioactive isotopes as labeled, and the thick line shows their sum, the total radiation hazard. The former can be ignored if not understood. Dashed lines refer to the example discussed in the text.

effects of the different kinds of radiation emitted, and finally the cancer risk per rem of dose to that particular organ.

The direct feeding of waste in a digestible form to humans is hardly a realistic possibility. One might consider instead the consequences stemming from randomly dumping the wastes in a soluble

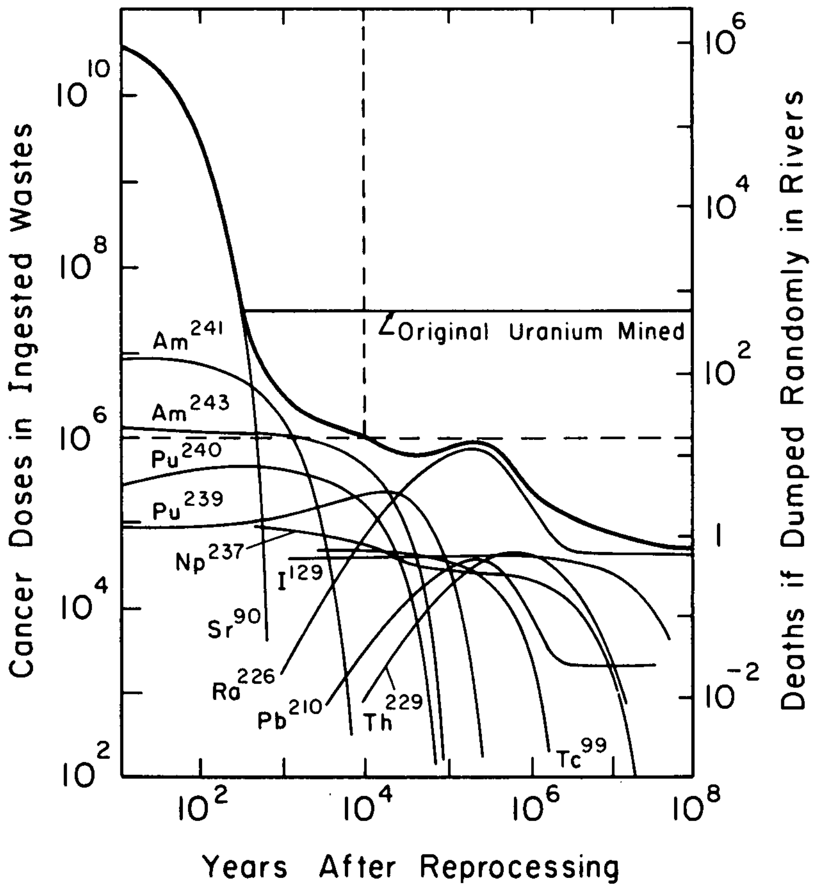

FIGURE 3

Ingestion hazard in high level waste generated in one year if all U.S. power were nuclear, as a function of time. Thin curves are contributions from individual radioactive isotopes as labeled, and the thick curve is their sum, the total ingestion hazard; the former can be ignored if not understood. The ordinate scale on the left is in "cancer doses"; for example the ordinate value of 10^6 at 10^4 years indicated by the dashed lines means that if all of the radioactive waste were converted into digestible form after 10^4 years and fed to many millions of people, 10^6 fatal cancers would result. The ordinate on the right indicates that if this material were dumped randomly into rivers rather than being fed to people, about 13 fatal cancers would result.

form into rivers throughout the U.S. Such a scenario approximates the most careless credible handling of the disposal problem. Figure 3 shows that a million fatalities would result if such a disposal plan were implemented 10 years after consumption of the fuel. Clearly, disposal in rivers is not an acceptable option.

In evaluating the inhalation hazard, by far the most important effect that must be taken into account is the induction of lung cancers. Figure 4 shows the potential hazard from the waste generated

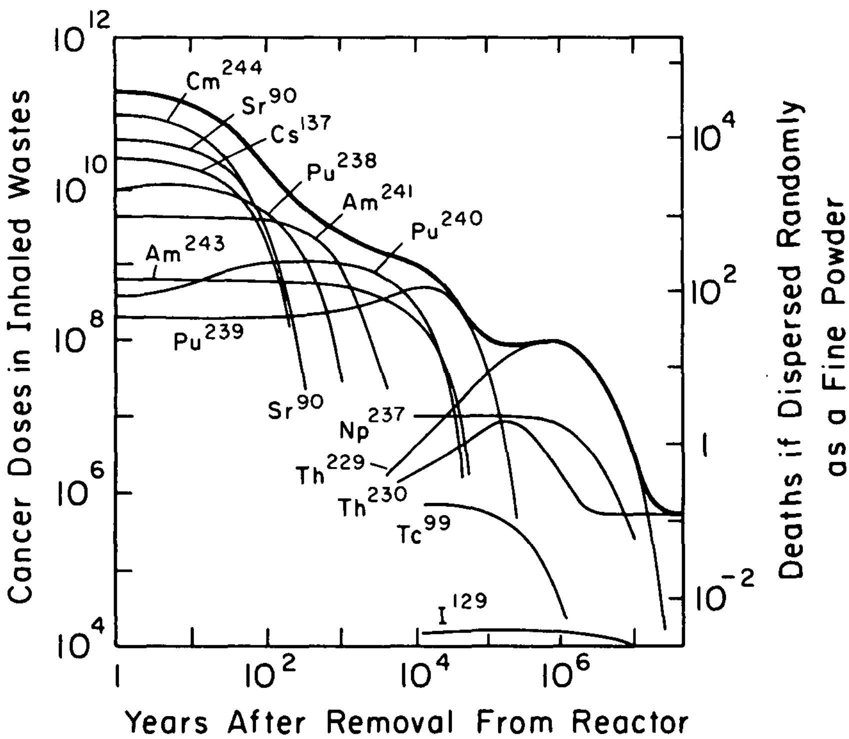

FIGURE 4

Inhalation hazard in high level waste generated in one year if all U.S. power were nuclear, as a function of time. Thin curves are contributions from individual radioactive isotopes as labeled, and the thick curve is their sum, the total inhalation hazard; the former can be ignored if not understood. The ordinate on the left side is "cancer doses", the number of fatal cancers expected if all of the material were inhaled by people. The ordinate on the right gives the number of cancer deaths expected if the material were randomly dispersed into the air as a fine powder, available to be inhaled by people.

by one year of all nuclear power in U.S., i.e., the number of lung cancers expected if all the material were inhaled by humans. This of course would be impossible. A more credible measure of the hazard is shown by the scale to the right in Figure 4. This scale shows the number of lung cancers expected if the waste were spread as a fine powder randomly over the ground throughout the U.S., and allowed to be blown about by the wind.

Much attention is given in public statements to the potential hazards represented by the scales on the left sides of Figures 3 and 4 that show the number of cancers expected if all the radioactive materials involved were to be ingested or inhaled by humans. One often hears, for example, that there is enough radioactivity in nuclear wastes to kill billions of people. To put such statements in perspective, it is helpful to compare the known hazards of nuclear wastes with those of other poisonous substances used in large quantities in the U.S. For example, ingestion of all the barium or of all the arsenic produced in this country would kill as many people as ingestion of all the radioactive waste. Inhalation of all of the radioactive waste would be thousands of times less dangerous than inhalation of all the chlorine gas produced in this country annually.[7]

Critics of nuclear power often emphasize that radioactive wastes remain hazardous for a long time. Nonradioactive barium and arsenic remain poisonous forever. Critics also argue that the other hazardous substances are already in existence, whereas nuclear wastes are a newly created hazard. Roughly half of the U.S. supply of barium and arsenic, however, is currently imported.[8] Hence, these hazards are also being introduced "artificially" into our national environment. One other important difference is that the chemical poisons are carefully buried deep underground as is the plan for the nuclear wastes; indeed, much of the arsenic is used as a herbicide and thus is routinely scattered around on the ground in regions where food is grown.

Actually such quantitative representations of potential hazards are virtually meaningless unless one also takes into account the possible pathways the hazardous agents can take to reach man. It is generally agreed the most important health hazard presented by nuclear wastes arises from the possibility that ground water will come in contact with the buried wastes, leach them into solution, carry them through the ground and ultimately into rivers and thence into food and water supplies. Human exposure would then occur through ingestion.[9] An alternative way of expressing the content of Figure 4 is to state the

7. *See* Cohen, *High Level Waste From Light Water Reactors,* 49 REVIEW OF MODERN PHYSICS 1 (1977).

8. BUREAU OF MINES, MINERAL FACTS AND PROBLEMS (1975).

9. *See* p. 10, figure 4 *infra.*

quantity that would have to be ingested to give a person a 50% chance of fatal injury. When the waste is first buried this fatal dose is only 1/1000 of an ounce. The waste at this point is highly toxic. The radioactivity, however, decays away with time. After 400 years, a fatal dose is about one ounce, making it no more toxic than some things we keep in our homes. After a million years a lethal dose is one pound. Further, the fact that the waste would be buried 2,000 feet underground greatly minimizes the threat of any ingestion whatsoever.

The problem of waste security thus is divided into a short term concern and a long term concern. The short term problem lasts for a few hundred years. During this period, the waste is quite toxic and must be effectively isolated. The long term problem extends over thousands or millions of years. During this period, the waste is very much less toxic. However, since the waste will be in one location for such a long time, an accumulation of small effects might be important.

When some people first hear that the nuclear waste must be carefully isolated for a few hundred years, they react with alarm. They point out that very few of our manmade structures can be expected to last for hundreds of years, and that the same is true of our political, economic, and social institutions. They wonder how we can rely on protecting our waste for so long. Such worries apply only to our environment here on the surface of the earth, where the concern for the ephemerality of structures and institutions is warranted. The environment at 2,000 feet below the surface differs radically from the surface environment. Deep sub-surface conditions remain essentially unchanged for millions of years.

The long term problem perhaps can be best likened to the natural radioactivity in the ground. The ground is full of naturally radioactive materials like uranium, thorium, and potassium. By adding our waste to it, we would increase the total radioactivity in the top 2,000 feet of U.S. soil by only about one part per million (from one year's waste if all electricity in the country were generated by nuclear power).

Moreover the radioactivity in the ground (except that very near the surface) is causing virtually no harm. Experiments show that this natural radioactivity is causing less than one fatality per year in the United States.[10] Adding to it by one part in a million can hardly pose any serious problems.

10. In Cohen, *supra* note 7, it is shown that all of the radioactivity in the ground is causing about 10 fatalities per year in the United States. Nearly all of this comes from rivers eroding radioactive materials from the surface, so less than 10%, or one fatality per year, comes from radioactivity deep underground.

As further perspective on the long term problem, the ingestion hazard of the original uranium mined out of the ground to supply the fuel which produces the waste is shown by the horizontal line in Figure 4. After the waste has decayed for 300 years, it is less toxic than this original uranium.

With these perspectives established, the short and long term problems must be considered in more detail. There are a number of features in the waste burial plans that would delay the release of the waste to our environment for a very long time, thus giving near-perfect protection from the short term problem. First, the rock formation chosen for burial will be one well isolated from circulating ground water, and one which geologists expect to remain isolated for a very long time. Second, the rock formation chosen will provide adequate waste isolation even in the event that water penetrates the formation. If water did enter the rock formation, it would have to dissolve away a reasonable fraction of the surrounding rock before reaching the waste. A readily soluble substance such as salt would seem to afford a very poor medium for waste burial. The New Mexico area now being considered for an experimental repository features vast quantities of salt and only meager amounts of groundwater. Thus, if all the water now flowing through the ground in that area were diverted to flow through the salt formation, 100,000 years would elapse before the salt surrounding the buried waste was dissolved.

Third, the waste will be sealed in a corrosion-resistant protective casing. Casing materials are now available which would not be dissolved even if soaked in ground water for a million years. Fourth, the waste itself will be a glass or some other rock-like material which would require thousands of years of soaking in water before dissolving. Circulating ground water causes "dampness" rather than "soaking," and therefore dissolves things hundreds of times more slowly than circulating surface water.

Fifth, ground water moves quite slowly, typically only inches per day. Ground water ordinarily travels many miles before reaching the surface from 2,000 feet underground. Hence, even if dissolved radioactive material moved with the ground water, it would take about 1,000 years to reach the surface.[11] Additionally, processes which constantly filter the radioactive materials out of the ground water cause the material to migrate about a thousand times slower than the water itself.[12] Thus, it would take most of the radioactive material

11. Cohen, *supra* note 7.
12. *Id.*

about a million years to reach the surface even if it were already dissolved in ground water. Moreover, most of the radioactive materials are highly insoluble under most geological conditions. If the materials were in solution when the water encountered normal conditions (chemically reducing, alkaline), they would precipitate out and form new rock material.

Finally, if radioactivity did reach surface waters it would very easily be detected. One millionth of the amounts that can be harmful are readily detected. Measures could be taken to prevent the waste from getting into drinking water or food.

With all these protections, it seems almost impossible for much harm to result during the first few hundred years while the waste is highly toxic. Furthermore, there is very substantial protection over the long term, for thousands or even millions of years. One way of conceptualizing the very long term risks is to assume that an atom of buried waste has about the same chance of escaping from its disposal site and entering a person's system as an atom of average rock. For average rock material *submerged in ground water* (i.e., traversed by an aquifer), the probability of escape from the rock into a river can be estimated by the following calculation:[13]

Consider a one square meter column running through and parallel to the flow of a 100km-long aquifer which flows at a rate of 0.3m per day through rock of 10% porosity. The water reaching the river through this column is readily calculable.[14] From chemical analyses of ground water we know how much of various elements is dissolved in this water–this is the amount of each element removed from the rock in the column and carried into the river each year. But we also know the total amount of rock in the column[15] (100×10^3m x $1m^2$ x $2.7 \times 10^3 kg/m^3$ (density) = 2.7×10^8kg), and from the known chemical composition of the rock we know how much there is of each element. The ratio of the quantity of an element carried into the river each year to its total quantity in the rock is just the annual escape probability we are seeking. When typical chemical analyses of ground water and of rock are inserted in this calculation, the result for nearly all elements is that the probability for an atom of rock to be carried into a river is less than one chance in 100 million (10^{-8}) per year.

This probability must be multiplied by the probability for an atom of material in a river to be ingested by a human. The ratio of the

13. *See* Cohen, *Analysis, Critique and Reevaluation of High Level Waste Water Intrusion Scenarios Studies,* 48 NUCLEAR TECHNOLOGY 48 (1980).

14. $0.3m^3 \times 0.1 = 0.03m^3$/day.

15. 100×10^3m x $1m^2$ x $2.7 \times 10^3 kg/m^3$ (density) = 2.7×10^8 kg.

quantity of water ingested by humans in the U.S. to the quantity of water flowing in U.S. rivers each year is 10^{-4}—that is, about one water molecule in 10,000 of those flowing in U.S. rivers is ingested by a human. Rather than averaging over all U.S. rivers, it might be better to consider a specific river near a waste repository. River systems and population distributions, however, change drastically over periods much shorter than the millions of years under consideration here. Use of averages therefore is probably most meaningful. Materials dissolved or suspended in river water are to a considerable extent removed by filtration and flocculation in water purification systems so that their probability for ingestion by a human is considerably less than 10^{-4}. But intake with food provides another pathway whose effects must be added. These two effects roughly cancel, leaving the probability for transfer from a river into a human to be about 10^{-4}. When this is multiplied by the 10^{-8}/year transfer probability from rock into rivers discussed above, we find that the probability per year for an atom of average rock submerged in ground water to be ingested by a human is 10^{-12}/year.

If we assume that this probability also applies to an atom of buried radioactive waste, it can be applied directly to the left side scale of Figure 3 to determine the number of fatalities expected each year. The total number of eventual fatalities can be obtained by adding up these yearly contributions. A more sophisticated procedure involves applying some correction for the time delays we have discussed previously. With this allowance for time delays, we can predict that the waste produced by one large power plant in one year will eventually cause an average of less than 0.001 fatalities.[16] This is 25,000 times fewer than the 25 fatalities per year we now accept from each coal-burning power plant. This calculation implies that if all U.S. electricity were derived from nuclear power for a million years, all of the accumulated waste would cause much less than one fatality per year in the United States.

The problem that seems to be causing so much concern must be due to ways in which buried radioactive waste differs from average rock. There are basically two differences. First, we must dig a shaft in order to bury the waste, giving a connection to the surface not present in average rock. Second, the radioactive waste emits heat, which is not a property of average rock. The first problem is a matter of our ability to seal the shaft. There now seems to be a high degree of confidence in the technical community that the shaft can be sealed to make the burial site as secure as if the shaft had never been

16. *Id.*

dug.[17] A demonstration of shaft sealing with accelerated simulation tests of very long term security is planned for the near future.[18]

The heat radiated from buried waste is enough to raise the temperature of the surrounding rock by approximately 200° Fahrenheit. Some sources have theorized that such temperatures might crack the rock, thereby producing new pathways by which ground water can reach the buried waste and through which the dissolved waste might escape. This problem has been studied intensively for over a decade, and the conclusion seems to be that possibility of cracking and seepage poses no serious risks.[19] These studies, however, are continuing. Two easy methods can be used to remedy temperature increases if further studies indicate the desirability of doing so. The waste can be distributed over a wide area so as to dilute the heating effect, or burial can be delayed to allow some of the radioactivity to decay away. The latter option is especially effective since the rate of heat emission, according to Figure 2, is decreased tenfold after 100 years, and 100 fold after 200 years. Also, the protective casings in which the waste will be enclosed are capable of resisting breaches or corrosion by high temperature ground water for as long as those high temperatures persist.

In certain ways, buried waste presents fewer risks than average rock. For example, the geological environment for the waste will be carefully selected and therefore will be the safest environment possible. The waste will be buried in a region with little or no circulating ground water, while average rock is submerged in circulating ground water. Further, the waste will be enclosed in a protective casing.

It is perhaps worth mentioning that there are other alternatives available for disposal of radioactive waste. Probably the best of these is burial in the ocean floor, which would seem to be even more secure than land burial. The *easiest* alternative would involve converting the waste into glass and simply dropping it in the ocean.[20] Some harmful effects to man would occur through contamination of sea food. Such contamination would lead to an average of only 0.17 eventual fatalities due to waste produced in one year by a large nuclear power plant, which is less than one percent of the 25 fatalities per year we

17. These comments are based on the author's many private conversations with involved scientists. These issues also were discussed at some length at the 1980 National Waste Terminal Storage Information Meeting, Sheraton-Columbus Hotel, Columbus, Ohio, December 9-11, 1980.

18. Information meeting for Office of Nuclear Waste Isolation, Columbus, Ohio, December, 1980.

19. *Id.*

20. Cohen, *Ocean Dumping of Radioactive Waste*, 47 NUCLEAR TECHNOLOGY 163 (1980).

now accept from wastes released by a coal fired plant. It has been shown that dumping our waste in the ocean would have no significant effects on ocean ecology.[21] The oceans are already full of radioactivity from natural sources. Thus, our waste would never increase the radiation exposure to ocean animals by as much as one percent.[22] While ocean dumping is not the safest method of waste disposal, it is "guaranteed" to be a hundred times safer than our present method of disposal of wastes from coal burning. No one can claim that we don't know how to drop something in the ocean.

The question and hazards of waste burial can now be viewed in perspective. As suggested above, uranium mined out of the ground is more toxic for ingestion than radioactive waste after the waste has aged 300 years. The most important radioactivity hazards from uranium is not its potential ingestion, but rather the fact that it serves as a "perpetual" source of radon gas. Radon is a naturally radioactive gas emerging from the natural decay of uranium which, according to currently accepted estimates, is causing many thousands of lung cancers each year in the United States. Thus, removing uranium from the ground will eventually save 140,000 lives for each year of all nuclear power in the U.S. This total will not be reached for many millions of years, but even over the next 500 years, about 22 lives will be saved. The 0.3 lives estimated to be lost eventually due to the nuclear waste would be saved every 7 years.[23]

Thus, on any long time scale, nuclear power must be viewed as a means of cleansing the earth of radioactivity. This fact becomes intuitively clear when one considers that every atom of uranium is destined eventually to decay with the emission of eight alpha particles (helium nuclei), three of them rapidly following the formation of radon gas. Through the breathing process, nature has provided an easy pathway for radon to gain entry into the human body. In nuclear reactors, the uranium atom is converted into two fission product atoms, which decay only by the emission of a beta ray (an electron) and in some cases a gamma ray. Roughly 87 percent of these emission processes take place before the material even leaves the reactor. Moreover, beta rays and gamma rays are typically 100 times less damaging than alpha particle emissions because their energy levels are lower (typically by a factor of 10). Also, they deposit energy into tissue in a less concentrated form, making their biological effectiveness

---

21. *Id.*
22. *Id.*
23. Cohen, *The Role of Radon in Comparison of the Environmental Effects of Nuclear Energy, Coal Burning, and Phosphate Mining,* 40 HEALTH PHYSICS 19 (1980).

10 times lower. The long-term effect of burning uranium in reactors is hence a reduction in the health hazards attributable to radioactivity.

Conversely, coal contains an average of about one part per million of uranium, which is released into the environment when the coal is burned. The radon gas from the uranium released by one year of an all-coal-powered U.S. electric-generating system would cause about 17 fatalities over the next 500 years.[24]

None of the estimates given so far accounts for the possible release of nuclear wastes through human intrusion. That possibility deserves consideration. Buried waste would not be an attractive target for saboteurs because of the great amount of time, effort, equipment and personal danger that would be needed to remove it. Only release through inadvertent human intrusion, such as drilling or mining, needs to be considered. The current plan calls for retaining government ownership of repository sites and maintaining surveillance and long lasting warning signs, so that this problem would exist only if there were a total collapse of the government. One of the criteria for the choice of a repository site is the absence of valuable minerals and the prospect of discovering them. Nevertheless, if random exploratory drilling took place in the area at the rate of the current average "wildcat" drilling for oil in the U.S., the effects would still be much less significant than those resulting from release in ground water. If there were mining in the area (presumably for minerals not now regarded as valuable), the operations would need to approach a scale equivalent to the entire current U.S. coal mining enterprise before their effects would equal those of a ground water release.

Wastes buried in salt might seem to be a poor risk against the possibility of intrusion by mining, since salt is widely mined. The quantity of salt underground, however, is so huge that on a random basis any given area would not be mined for tens of millions of years. Again, the probability of release through salt mining is comparable to the probability of release through ground water. Release through salt mining would introduce the wastes in an insoluble form. If ingested, wastes released through salt mining would be much less likely to be taken up by the body than waste released by groundwater. A potential for ingestion would seem to exist through the use of salt in food, but only 1 percent of the salt mined in the U.S. is used in food. Further, this salt is purified by allowing insoluble components to settle out. Thus, exposure through the consumption of salt would be reduced roughly to the level of exposure caused by the use of salt in industrial processes. All in all, then, the probability of the release of

24. *Id.*

stored nuclear wastes through human intrusion is less than that of waste release through ground water.

Some critics argue that requiring future generations to guard against the release of radioactive wastes places an unjustifiable burden on our descendants. The estimate of the health effects of nuclear wastes developed thus far does not account for any guarding at all. The estimate was derived from a comparison with average rock. No one is watching this country's rock materials to prevent them from getting into rivers through various earth moving operations. Therefore, guarding buried nuclear wastes would only reduce that already small risk.

Even if guarding should be considered advisable, it would not be very expensive or difficult. Once the repository is sealed, the guarding would consist only in making periodic inspections of the surface area—about 10 miles square for the wastes from 1,000 years of all-nuclear power—to make sure that the warning signs are in good order and to see that no one has unexpectedly undertaken mining or deep drilling. In addition, occasional water samples might be drawn from nearby rivers and wells to check for increased radioactivity. Hence, keeping watch on the wastes accumulated over 1,000 years of all-nuclear electric power in the U.S. would provide a job for only one person at a time.

Perhaps the best way to put into perspective the burden we are placing on our descendants by storing nuclear wastes is to compare that burden with others we are placing on them. Probably the worst will be the burden resulting from our consumption of the earth's high grade mineral resources. Within a few generations, we shall have used up all the world's economically recoverable copper, tin, zinc, mercury, lead and dozens of other elements, leaving fewer options for our descendants to exploit for materials. Moreover, we are burning hydrocarbons—coal, oil and gas—at the rate of millions of tons each per day, depriving our descendants not only of fuels but also of feedstocks for making plastics, organic chemicals, pharmaceuticals and other useful products. These burdens are surely far heavier than any conceivable burden resulting from the appropriate burial of nuclear wastes.

The comparison between the burdens to future generations resulting from the storage of waste and the depletion of resources is particularly pertinent because the only way we can compensate our descendants for the materials we are denying them is to leave them with a technology that will enable them to live in reasonable comfort without these materials. The key to such a technology must be cheap

and abundant energy. With cheap and abundant energy and a reasonable degree of inventiveness, man can find substitutes for nearly anything: virtually unlimited quantities of iron and aluminum for metals, hydrogen for fuels and so on. Without cheap and abundant energy, the options are much narrower and must surely lead back to a quite primitive existence. We who are alive today owe our descendants a source of cheap and abundant energy. The only such source we can now guarantee is nuclear fission.