Environmental hazards in radioactive waste disposal

It is often said that disposal of the radioactive wastes from nuclear power plants is an "unsolved problem," that these wastes must be carefully watched for hundreds of thousands of years, that any slip can lead to devastation and that guarding these wastes will be a heavy burden on our progeny. Very expensive schemes have been proposed for destroying these materials by nuclear transmutation, or by rocketing them out of Earth's gravitational field. It is my purpose here to review some numerical estimates of this long-term hazard to put the problem into proper perspective.[1]

These wastes are the long half-life fission products and actinides produced by neutron capture reactions on uranium. To be definite, we will consider the wastes generated by pressurized water reactors, the type now in most common use, but wastes from other reactors are of the same order of magnitude. In addition, we limit our considerations to the dangers from ingestion with food or drink; it may be shown that this is the most important source of concern.[1]

The curie quantities of each radioactive isotope in the waste at various times after its generation were calculated by use of Oak Ridge National Laboratory computer code ORIGEN.[2] These were then converted to dosage to various body organs if ingested by adults by use of ICRP Publication-2, and these doses were converted to cancer-causing doses by use of the cancer induction probabilities derived from the BEIR Report. It may be noted that the number of cancers induced is independent of the number of people ingesting the material. This is a general consequence of the "linearity hypothesis"; if n times as many people ingest a given total amount of radioactive material, the probability of each getting cancer is multiplied by $1/n$, so that the total number of cancers is unchanged.

The results are plotted in figure 1 for wastes generated from production of 400 million kilowatt-years of electrical energy, almost twice the present annual US consumption. We see from figure 1 that for the first few hundred years the principal danger is from Sr^{90} (28-year half-life), and after that decays away, the hazard is from americium and plutonium isotopes (although 99.5% of the plutonium is removed in the fuel reprocessing) until after 20 000 years at which time Ra^{226} becomes the dominant problem.

Hazards from wastes generated in production of annual US consumption of electricity a few years hence in terms of total number of cancer cases induced by complete ingestion (left) and deaths resulting (right) when wastes produced by annual US power consumption are buried 600 m deep in salt formations. Figure 1

One can easily make this material sound very dangerous even after 500 years when the Sr^{90} has decayed away; if all of it were ingested by people, we see from figure 1 that 10^7 cancer deaths would result, and if it were dissolved in a city water supply of which typically one part in 200 is ingested, there would be about 50 000 cancer deaths. On the other hand, the arsenic trioxide imported into this country annually is sufficient to cause about 5×10^9 fatalities, and it is not buried deep underground—in fact, being an herbicide, it is scattered around on the ground in areas used for growing food—nor does it decay away. After 500 years of decay, the waste that would give a 50% probability of death if ingested would weigh about half a pound, which makes it less poisonous than many natural minerals and commonly used materials.

There is every intention to handle the radioactive wastes from reactors with great respect, and a great deal of research has been devoted to techniques for disposing of it safely. There have been many excellent proposals, but the idea that has received the most attention is to incorporate the material into a Pyrex glass and bury it some 600 meters below ground in an appropriately chosen geological formation. The principal fear in this situation is that the material will be contacted and leached away by groundwater, carried through aquifers into rivers, and thus get into water supplies.

In most discussions, the primary emphasis has been placed on choosing a geological formation in which the likelihood of groundwater reaching the waste is minimized. From this, the impression is often derived that if the wastes *were* contacted by groundwater, the results would be swift and catastrophic. However, this is not the case, as there are important time delays before the waste can reach surface waters by this route. In the first place, the time constant for leaching is about 10 000 years; this alone is sufficient to prevent any appreciable fraction of the Sr^{90} from reaching water supplies. In the second place, if the material were leached into groundwater, it would move very slowly. A typical speed for water in a deep aquifer is not more than 0.3 meters per day—more than 1 meter per day is quite exceptional and 0.03 meters/day is not unusual. Water from this depth would have to travel typically 100 kilometers before reaching the surface; so it would take the water into which the waste is leached many hundreds, or even thousands, of years to reach the surface.

But the radioactive materials do not move through the ground nearly as rapidly as the water. They are held up by ion exchange with the rock or soil material typically by factors of 10^{-2} for Sr, 10^{-3} for Cs, 10^{-4} for Pu and Am, and 5×10^{-3} for Ra. For Sr, a minimum holdup factor is about 1/50, so that once leached into solution, it would typically not reach flowing water for tens of thousands of years. This, in addition to the leaching time and the original location in an area expected to be free of groundwater for the forseeable future, gives a triple guarantee that no appreciable fraction of the Sr^{90} will ever reach water supplies (the same is true for Cs^{137}, which has a similar half-life and moves even more slowly). The

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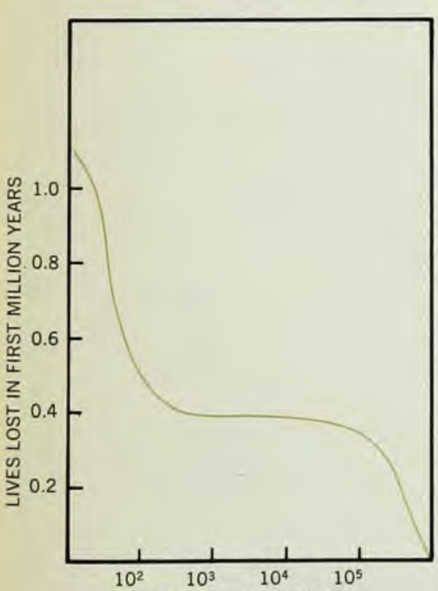
principal danger is then from Am, Pu, and Ra, and according to the above numbers, they are typically delayed from reaching the surface for millions of years. If the material is buried in salt the ion-exchange holdups would be reduced by perhaps an order of magnitude because the water would be saturated with salt; but on the other hand, the time required for the salt encompassing one year's waste to be dissolved away is about 100 000 years.

We now undertake an evaluation of the danger from these wastes by introducing a model that allows us to calculate an upper limit on the number of deaths that may be expected from them. In the model we assume that the wastes are buried at random locations throughout the US at a depth of 600 meters. We then assume that the probability of an atom of this waste reaching and irradiating people by ingestion is no more than that for an average atom of radium in the rock or soil above it. The latter probability is readily calculable from the known amount of uranium in average rock (2.7 parts per million) and the known effect of ingested radium on Man; the most significant dosage to the average American from the latter is about 10 mrem to the bone, which should cause about 12 cancer deaths per year in the US. The number of cancer-causing doses of radium in the ground down to a depth of 600 meters is about 3×10^{13}, so we conclude that the average annual probability for radioactivity in the ground down to a depth of 600 meters to be ingested by Man is effectively $12/(3 \times 10^{13}) = 4 \times 10^{-13}$. Multiplying the scale on the left of figure 1 by this factor gives the scale on the right side, which is the number of cancer deaths per year expected from the wastes generated by one year of all nuclear power in our model.



Deaths from radioactive waste during 10^6 years after burial in salt formation as function of time required for radioactive material to reach drinking water. Figure 2

While this calculation gives the correct result, it glosses over details that are of some interest. The quantity of radium reaching rivers may be estimated from water run-off in the US, 1.5×10^{15} liters/year, and the average Ra content in rivers, 2×10^{-13} gm/liter; taking the product gives 300 grams per year leached. Since the total Ra in the top 600 meters of the U.S. is 1.3×10^{10} gram, the average probability of leaching is $300/1.3 \times 10^{10} = 2.3 \times 10^{-8}$ per year; that is, the average life of rock in the top 600 meters is 43 million years.

The water ingested annually by people in the US is 1.6×10^{11} liters or 10^{-4} of the run-off, but flocculation and water-softening processes remove the bulk of the radium so that only 1.5×10^{-5} of the Ra in the run-off is ingested with water, corresponding to 4×10^{-13} of the radium in the top 600 meters of earth per year. This calculation does not include ingestion with food, or the digestibility of the material, but it gives the same result as our previous calculation and is perhaps more transparent.

When figure 1 is considered using the right-side scale, the hazard seems much less awesome. Moreover, even this estimate is probably grossly exaggerated, since nearly all erosion takes place near the surface of the earth where vegetation and freeze–thaw cycles break up the rock, where water from rainfall penetrates readily, and where river currents and winds exert large mechanical forces; material at 600-meter depth is thus much less likely to be eroded than an average equal volume of material above it which includes material near the surface. We therefore conclude that our model gives an *upper limit* estimate on deaths caused.

The total number of deaths that may be expected from one year of all nuclear power in the model can be obtained by integrating the curve in figure 1 using the scale on the right. This integration is, of course, sensitive to its upper and lower limits. Figure 2 gives the integration for the first million years as a function of its lower limit, N_1, the number of years before waste first begins to reach Man.

In view of our previous discussion of time delays, it would be almost impossible for much of the waste to reach the surface in less than 100 years, so there would not be more than 0.4 deaths in the first million years. Since a typical value for N_1 for the long half-life isotopes is millions of years, it seems probable that not more than 10% of the waste has N_1 less than 3×10^5 years, which would reduce the net number of

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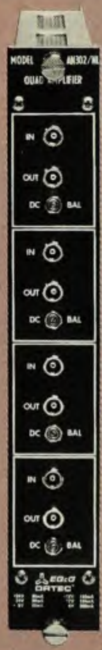

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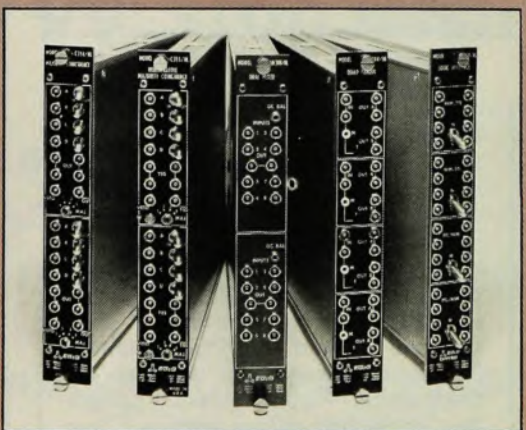

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deaths by another order of magnitude. This again indicates that our estimate is probably much too high.

In addition to the lower limit we have been discussing, the integration in figure 2 may also have an upper limit, based on a cure being found for cancer. Of course, if this cure is found in a number of years less than N_1, there will be no deaths from the wastes. If it is found in 10^5 years, the number of deaths is reduced by about one order of magnitude. The question of a cure for cancer was investigated by asking several cancer-research workers for their opinion. In most cases, they replied that a cure for cancer is quite probable within a thousand years, although some said that there is no way to estimate such a probability at this time. None said that it was highly improbable.

In discussing effects over very long time periods, account should be taken of the fact that uranium, which is the source of a great deal of radioactivity in our environment, is consumed in generating nuclear power; the exposure from uranium and its daughters is reduced by about one part in 10^8 for each year of all-nuclear power from light-water reactors. Natural radon, a uranium daughter, administers an average annual dose of 150 mrem/year to the tracheobronchial tree; from the BEIR Report such radiation causes 39×10^{-6} cancer deaths per man-rem, so the effect is $0.15 \times 2 \times 10^8 \times 39 \times 10^{-6} = 1200$ deaths per year in the US. According to this calculation, one year of all nuclear power would save 10^{-8} of this or 12 lives per million years, but if the burn-up of U^{234} in reactors is taken into account, there is an additional saving of 300 lives during the first million years, almost three orders of magnitude more than the 0.4 fatalities caused by the waste. If considerations are extended beyond the first million years, the ratio of lives saved to lives lost is $120/1.2 = 100$ in the next ten million years, $1200/4 = 300$ in the next 100 million years, and so. On any long time scale, nuclear power is clearly a device for *cleansing* the Earth of radioactivity.

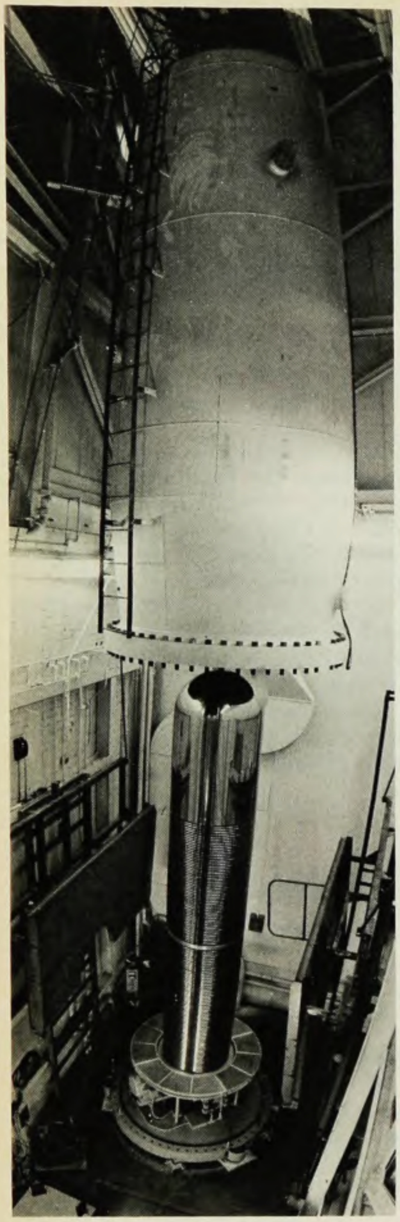
Of course, the actual plans are to handle wastes with much more care than our random burial scenario. The most widely discussed plans involve concentrating all wastes into one, or perhaps a few, small areas; in view of the linearity hypothesis in calculating radiation effects, there is no reason why this, *per se*, should increase the average risk, although it would, of course, greatly increase the potential for fluctuation. Since the areas are carefully chosen to minimize the geological risks, the average effects would be considerably reduced. It is, of course possible that there will be a release causing 1000 fatalities, but the probability must be much less than 0.4/1000 that it will occur within a million years.

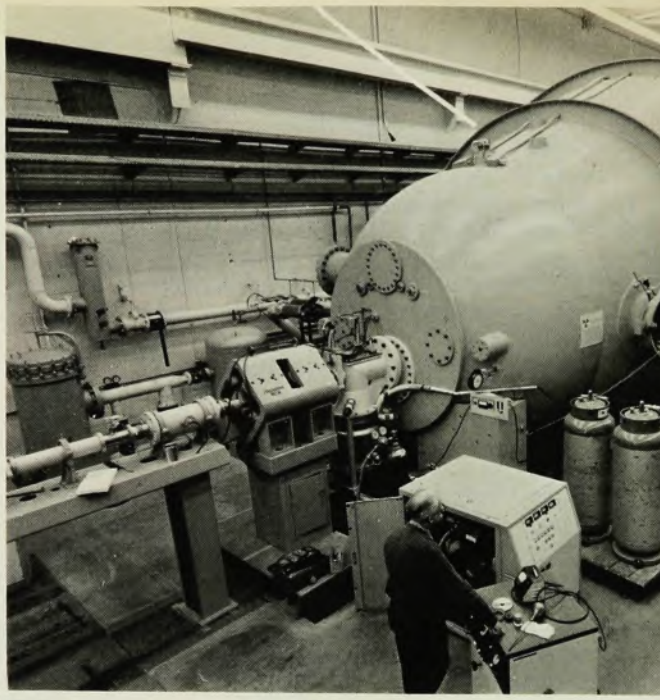
We now turn to the question of how carefully a repository should be watched. It should be recognized at the outset that our model was based on the assumption of *no* watching. Thus, the purpose of watching would be essentially to reduce the toll below the estimates we have given. A realistic surveillance program would probably consist of periodic inspections to assure against mining and drilling in the area of the repository, plus sample collections from nearby wells and rivers to measure their radioactivity. A program of this type could maintain surveillance over a thousand years of waste (covering an area of 500 square kilometers) with the service of a single employee. Of course, more intense and active attention would be appropriate during the first hundred years or so, especially until the technology becomes firmly established.

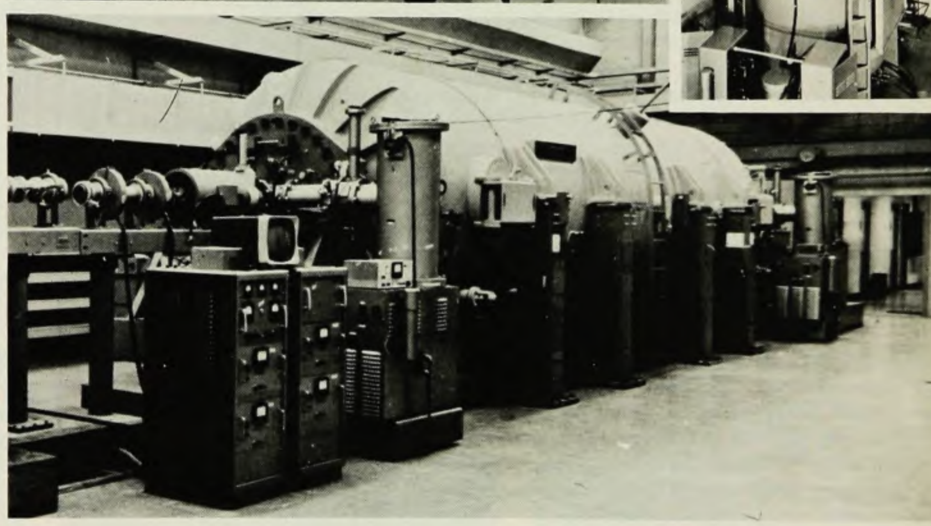
It is often said that watching our wastes will impose a great burden on our progeny. Surely the burden we have described is minuscule, and indeed it could be dispensed with entirely. As our distant progeny look back on the late twentieth century, they will never notice the tiny amount (one part in 10^{10} in our model for each year of all-nuclear power) by which we will have increased the radioactivity in their environment. We will rather be remembered as the ones who consumed all the high-grade mineral ores—all of the copper, nickel, zinc, tin, lead, mercury and so on—and worse than that, literally burned up at a rate of millions of tons per day those once plentiful hydrocarbons—coal, oil and gas—that are valuable as feedstocks for producing petrochemicals. The only thing that might save us in their eyes would be supplying them with a technology that will allow them to live in reasonable comfort without those resources; if we fail to do this, we are indeed deserving of their curses. The key to such a technology is, clearly, cheap and abundant energy, and unless great economies can be achieved in harnessing the radiation from the sun, the only source we have for this is nuclear energy.

References

1. This letter is based on a much more complete article being submitted for publication in *Reviews of Modern Physics*. Quantitative estimates given here are justified therein. Preprints of that paper, and of a more complete version of this letter (including quantitative justifications) are available from the author.
2. J. J. Bell, ORIGEN, ORNL 4628 (1973), unpublished. The author is greatly indebted to Charles Kee (Oak Ridge National Laboratory) for making the pro-







gram available and for assistance in using it.

BERNARD L. COHEN
University of Pittsburgh
Pittsburgh, Penn.

Developing countries ignored

It is regrettable though not surprising that, in your 1300-word report on Dixie Lee Ray and her assignment to formulate international science policy in the State Department, not one of those words pertained to the three-quarters of the world's population living in less developed countries, or to the international assistance to and scientific cooperation with these countries. Indeed, the phrase "international science policy" means, to most people, UN treaties on ocean beds, cumbersome exchange agreements with Roumania, or scientific attaches in Bonn or Tokyo, so that "we" form an increasingly more tightly knit scientific community, whereas "they" continue to be ignored and isolated.

MICHAEL J. MORAVCSIK
University of Oregon
Eugene, Oregon

Critical comments on fusion

The fusion reactor should not only provide a very large and probably cheap energy source with new possibilities of application, but should also possess favorable properties in respect to safety and environmental problems. It is recognized that, with the present limited resources of fusion research, the fission breeder is likely to come into practical operation before the fusion reactor has been realized on full scale. Nevertheless the potentialties of fusion energy and the future needs of new energy sources are important enough to justify itensified fusion research along broad lines, regardless of the existence of the fission breeder and other possible alternatives of energy production.

Important general progress has so far been made in fusion research and technology. With special devices such as Tokamaks, Stellarators, theta pinches, magnetic mirrors, laser fusion schemes, and some other systems, considerable further steps have been taken on the way to high plasma temperatures and large products of plasma density and confinement time. However, the general development of fusion physics is at this stage as important as maximum experimental-parameter data obtained by means of individual devices, because *none* of the present specific confinement schemes has, for certain, provided a final solution of the fusion-reactor problems.

A considerable part of the international fusion-research program is now devoted to large experiments with magnetic bottles having a main toroidal field component, as well as to a number of large laser-fusion devices. In particular, for these bottles that now are widely considered to represent one of the most promising lines, attention should be drawn to the following full-scale reactor problems:

So far only small total beta values have been reached in Tokamaks and Stellarators, leading to large required magnetic field strengths and associated cyclotron radiation losses, considerable mechanical coil stresses, and a slightly screw-shaped field line structure having long magnetic connection lengths between "bad" and "good" regions and being sensitive to disturbances that affect the field and plasma symmetry.

The complicated transport processes prevailing under normal experimental operation are not yet fully understood, but appear to be consistent with anomalous phenomena due to weakly pronounced instabilities.

Violent and so far unexplained "disruptive" instabilities arise when certain parameter values are exceeded. In particular, there is a density limit that has not yet been exceeded in hot Tokamak plasmas. This limit is possibly associated with the critical ion density dividing "permeable" plasmas from those being "impermeable" to neutral gas. Thus, high-temperature experiments have so far been conducted under conditions not necessarily representing those of full-scale Tokamak reactors, which have to operate far inside the "impermeable" ion density range.

Tokamak operation by means of a "boot-strap" mechanism has not yet been demonstrated. If the impurity problem cannot be solved, pulsed operation should in any case become necessary, but this reduces the chances of achieving a practically useful reactor.

The magnetic-field windings introduce complications in the replacement and repair of construction details.

The present concentration of the main activities and resources of fusion research to rather narrow lines and to a few large projects at the expense of basic investigations is *not reconcilable* with a corresponding necessary knowledge in fusion physics and technology. In the case that none of these projects is able to keep the promise of being a solution of the reactor problem, fusion research as a whole may end up in a difficult dilemma. The situation is partly a result of attempts to accelerate this research towards its final goal under the contemporary constraints of limited resources.

Needless to say, a substantial increase in available funds is strongly needed for the fusion reactor to come in

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