PROBABILISTIC RISK ANALYSIS (PRA) FOR A HIGH LEVEL RADIOACTIVE WASTE REPOSITORY

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ABSTRACT

A probabilistic risk analysis (PRA) for a high level radioactive waste repository is very important since it gives an estimate of its health impacts, allowing comparisons to be made with health impacts of competing technologies. However, it is extremely difficult to develop a credible PRA for a specific repository site because of large uncertainties in future climate, hydrology, geological processes, etc. At best, such a PRA would not be understandable to the public.

An alternative proposed here is to develop a PRA for an average U.S. site, taking all properties of the site to be the U.S. average. The results are equivalent to the average results for numerous randomly selected sites. Such a PRA is presented here; it is easy to understand, and it is not susceptible to substantial uncertainty. Applying the results to a specific repository site then requires only a simple, intuitively acceptable "leap of faith" in assuming that, with large expenditures of effort and money, experts can select a site that would be at least as secure as a randomly selected site.

THE PROBLEM

The only meaningful way to evaluate the riskiness of a technology is through Probabilistic Risk Analysis (PRA). A PRA gives an estimate of the number of expected health impacts --e.g. the number of deaths expected to be caused -- by the technology, which then allows comparisons to be made with the health impacts of competing technologies, so a rational judgment can be made. Not only is that procedure attractive from the standpoint of scientific logic, but it is easily understood by the public.

The importance of PRAs was recognized by the U.S. Atomic Energy Commission more than 30 years ago in connection with reactor safety, and PRAs have been produced for most operating nuclear power plants. PRAs are also used in evaluating non-nuclear technologies, including space exploration programs

The importance of a PRA for a high level waste (HLW) repository has been recognized for at least 25 years, but it was immediately realized that a PRA for a repository at a given site, extending millions of years into the future, is much more difficult than a PRA for a nuclear reactor extending for 30 or 40 years. In the reactor case, every detail of the system is well known and basically unchanging with time, whereas for the waste repository, the required geological information is obtained only by test drilling at mufti-billion dollar expense. Moreover, this geological information will almost surely change over time in unpredictable ways. Earthquakes and volcanoes can occur unpredictably. Climate, weather, and rainfall are not predictable very far into the future, and these largely determine the underground hydrology which is so important in assessing repository performance. Land uplifting can occur, causing rivers to change their courses, which can profoundly affect the hydrology. Activities of animals and insects can change, causing important problems. Human use of a given land area will undoubtedly change over very long time periods, and this can easily change predicted numbers of injured people by orders of magnitude.

The U.S. Dept. of Energy (DOE) is developing a "Viability Assessment" for its proposed Yucca Mountain waste repository, which involves analyses similar to a PRA. It utilizes theoretical models with data input from test drillings and other geological information. In a recent version, there were 177 variables to which probability distributions were assigned as functions of time into the future. With such complexity, there is plenty of room for honest scientific disagreement over the theoretical models used and the probability distributions selected, enough to change the PRA results by orders of magnitude.

In a cooperative situation, these issues could be negotiated and resolved, but the situation is far from being cooperative. Every aspect will be open for outside criticism, and the process will be subject to a wide variety of pressures. Powerful groups dedicated to destroying the nuclear power industry by any available means have been doing everything possible to prevent construction of the waste repository. They are well organized and have excellent contacts with the Media. They have always been very successful in getting negative information publicized, which confuses and frightens the public. Viability Assessment and Total Systems Performance Documents produced so far by DOE effectively include PRA results (although not in very transparent form) derived from the above-mentioned 177 parameters, but they have done little to convince the opponents or the public -- neither understands them or trusts them. They give nothing that can easily be used to compare the health impact of nuclear wastes with those from coal burning, the principal alternative. Nevada politicians and even national Presidential candidates have found opposition to the repository to be necessary politically. The entire process may well be headed for failure. What is missing is a PRA that is understandable and acceptable to the public without depending on blind trust of Government-supported technologists.

AN ALTERNATIVE APPROACH

In view of the many difficulties cited above, it is impossible to develop such a PRA for a specific site. However, there is a much easier approach to the problem. A PRA will be presented here for an average U.S. site, based on taking all properties of the site as the U.S. average. The result can be interpreted as the average result of PRAs for a large number of randomly selected sites. The reason why this is very much easier than a site-specific PRA is that all of the present geological characteristics and all of the unknowable future events mentioned above are actually occurring now at various places in the U.S. A wide variety of climates, rainfalls, and weather patterns are present, earthquakes and volcanoes are occurring, land uplifting is taking place and rivers are changing their courses, all sorts of animal and insect activities are encountered, there is a very wide variety of land use by humans, etc. All of these are therefore taken into account when doing a PRA for an average U.S. site. Moreover, any changes in national average properties are very much smaller than potential changes at a particular site.

But how does this PRA for an average U.S. site substitute for a PRA for a specific site? It seems intuitively obvious that by spending lots of effort and money on site selection, the experts should come up with a site that is at least as safe as a randomly selected site. This "leap of faith" would seem to be easily understandable and acceptable to the public. So effectively, we have a PRA for our specific site, or at least a conservative estimate of its health impacts. It should be much easier to convince the public on this simple "leap of faith" than on an extremely complex and uncertain study of future conditions at a specific site.

PRA FOR AN AVERAGE U.S. SITE[1]

The PRA presented here is for vitrified high-level waste glass (HLW), following the technology used in most of the world. The reason for doing this rather than considering buried spent fuel will be discussed later. The analysis will use the linear-no threshold theory, which means that it contains an additional measure of conservatism. We will consider only the deaths from cancer, assuming no progress in curing that disease, another major ingredient of conservatism.

Our PRA consists of two basic steps, first determining the number of cancer deaths expected if all of the HLW is eaten by people, and then determining the fraction of this HLW that will enter human stomachs. The first step is a straightforward Health Physics calculation, presented in Appendix A, which results in Figure 1. This is a plot of the number of cancer deaths from the HLW produced per Gwe-y of electricity if it were all fed to people vs. the time after removal from the reactor at which this feeding takes place.

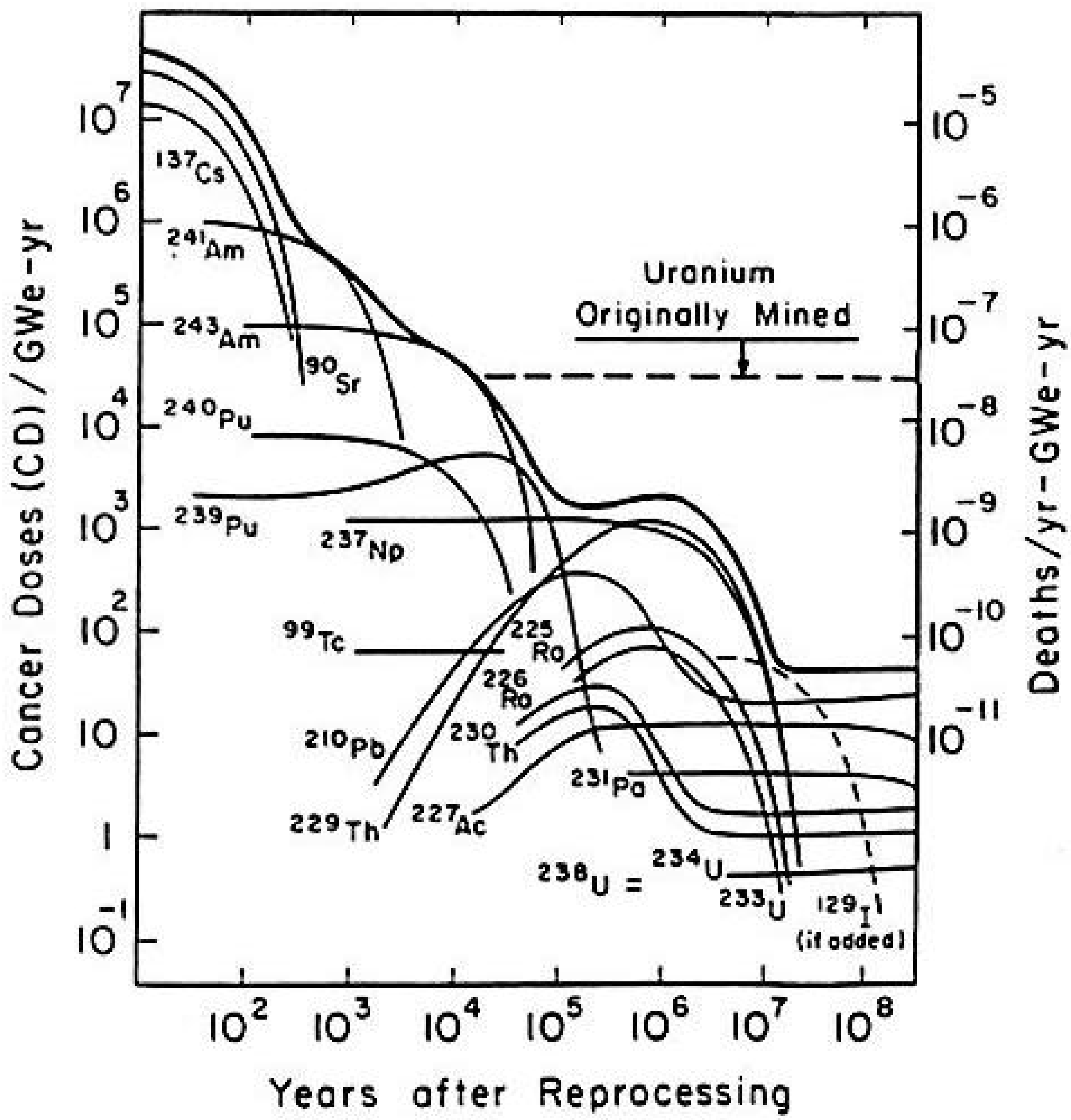

Fig. 1: Cancer doses, the number of fatal cancers that would result if all of the waste were fed to people, vs. time after reprocessing of the waste, assumed to be about one year after the fuel is removed from the reactor. Labeled curves are the contributions from the designated radioactive species, and the uppermost curve is the sum of these, the total number of fatal cancers.

The second step is to estimate the probability per year for an atom of HLW to be dissolved out by groundwater and eventually enter a human stomach. We do this by using natural rock as an analogue, and then assessing the differences between natural rock and HLW buried at the same depth, which we take to be 600 meters. For natural rock, the calculation is outlined and referenced in Appendix B. The result is the product of (1) the probability per year for an atom in the rock to be dissolved out by groundwater, and (2) the probability for an atom dissolved in groundwater to enter a human stomach. The starting point for (1) is the amount of material dissolved out of U.S. rock and soil and carried into the oceans each year. This is well known from analyses of water discharged from the Mississippi, Hudson, Columbia, Colorado, and a few other rivers; dividing it by the area of U.S. then gives the average meters of rock depth dissolved. Data from hydrological studies is used to estimate what fraction of this material is dissolved from 1 meter of depth at 600 meters, i.e. from between 599.5 and 600.5 m depth. The result is 1E-9 m of depth is dissolved from this 1 meter, which means that the probability per year for dissolution of an atom of average rock at this depth is 1E-9. An alternative completely independent calculation of this probability is outlined and referenced in Appendix B.

An estimate for (2) is obtained by assuming that the probability for an atom dissolved in groundwater to enter a human stomach is the same as that probability for a molecule of the groundwater itself, which is calculable from hydrological information as illustrated in Appendix B, where the resulting probability is 4 E-4. Thus the probability per year for an atom of average rock from 600 m depth to enter a human stomach is 1E-9 x 4E-4 = 4E-13.

But how does this apply to high level waste glass? There are ways in which this HLW is less secure than average rock. The HLW is connected to the surface by shafts and boreholes used in site selection and construction of the repository, but expert opinion seems to be that these can be sealed to be as secure as undisturbed rock. The temperature of the HLW is elevated due to radioactivity heat for the first few hundred years, which can cause accelerated leach rates and rock cracking. But the first problem is eliminated by enclosing the HLW in a casing that will prohibit contact with groundwater for a thousand years or more, and the rock cracking problem can be avoided by spacing the HLW packages far enough apart to keep temperatures well below the cracking threshold. Another difference between HLW and average rock is that the former is about three times less resistant to leaching as determined by leach rate tests. This means that the above calculated probability should be multiplied by three to give the probability per year for an atom of HLW to enter a human stomach as about 1 E-12.

It should be noted that there are also ways in which the HLW is more secure than average rock. The leach resistant casing, the backfill material (bentonite clay) which swells when wet to seal against water intrusion and which also strongly adsorbs potentially escaping radioactive materials, the fact that the site is carefully selected by geology and hydrology experts rather than being randomly selected, the ability to easily detect escaping material and take protective action long before it becomes a health menace, etc are examples of this improved security, but we conservatively take no credit for them here. Similarly, we ignore the very substantial time delays for movement of groundwater from deep underground to the surface, and the retardation in transport of radioactive materials by various rock adsorption processes which allow the radioactivity to decay away before reaching human stomachs. It is therefore with substantial conservatism that we adopt the above 1 E-12 result.

The number of expected cancer deaths per year from buried HLW is then the curve in Figure 1 multiplied by 1 E-12, which is easily obtained by simply reading that curve with the scale on the right side. Since this is the number of deaths per year, the total number of eventual cancer deaths is calculated by summing it (Le. integrating) over millions of years -- the end point of this summation is explained in Reference 1. The final result is that we may expect 0.02 eventual cancer deaths per Gwe-y of electricity generation. That is the result of our PRA.

Once we have a PRA result, we are in a position to judge whether HLW is an acceptable risk. To do this we may make comparisons with the wastes from coal burning which is our principal alternative. Coal burning is estimated to cause about 30 deaths per GWe-year from air pollution, plus similar numbers' from carcinogenic chemicals released into the ground, and similar numbers from uranium released into the ground to serve as a source of future radon exposures - nuclear power avoids future radon exposures by mining uranium out of the ground. Thus the HLW is thousands of times ((30 + 30 + 30] / 0.02) less harmful to human health than the wastes from coal burning, which surely makes its risks acceptable. Our PRA has served its principal purpose.

Therefore, a rational regulatory requirement would be that the selected site be at least as favorable, judging by readily obtainable information, as a randomly selected site. That should be cheap and easy to establish with a reasonable degree of confidence. It should also be much more understandable to the public than the present extremely complex and somewhat arbitrary system for judging the safety of a HLW repository.

If one is worried about some very low probability disaster, that is also easy to address. For less than one million dollars, we could establish an eternal trust fund to support monitoring radioactivity in the water near a repository. If a disastrous release were to occur, this monitoring system would detect it in plenty of time to avert harm to human health.

HLW VS. SPENT FUEL RODS

A serious problem in the PRA we have presented is that it deals with HLW as a glass, whereas the U.S. program (and some others) is for burying spent fuel rods. Does this make a difference? The leach rate measurements alluded to above are carried out by flowing distilled water over the materials being tested. If the results of these tests are applied to average rock, it is found that a typical grain of average rock would be dissolved away in about 1 00 years. This means that our continents would disappear in a few hundred years!! Obviously that is not a tenable idea, and it is discrepant with our calculation that an average rock at 600 m depth will last for a billion years. The explanation for this discrepancy is quite obvious -- ground water is very different from the distilled water used in the leach rate tests in that it is saturated with silica from having encountered many miles of rock consisting largely of silica. When this water encounters our HLW package. It may dissolve some silica out of the surface of the glass, but since the water is already saturated with silica, this can only occur if some of the silica previously dissolved in the water precipitates out. This precipitate would be of the most insoluble silica compound that can be formed from the materials present, and it would precipitate out on the surface of the glass. This coats the glass surface with a highly insoluble silica compound. Further leaching can then take place only by diffusion of the glass molecules through this coating, a slow process, and this causes the insoluble coating to grow thicker, which makes the diffusion process even slower. The rate of glass leaching thus decreases exponentially with time and soon is essentially stopped, making the HLW behave as ordinary rock, as we have assumed in our PRA.

But this reasoning does not apply to spent fuel rods which are not made of silica. Does this mean that they are many orders of magnitude less secure against leaching by groundwater than high level waste glass? If so, burial of spent fuel rods may be a dangerous procedure. This is not an inevitable conclusion. The spent fuel is to be encased in iron and, since rock contains a lot of iron, the ground water may be saturated with iron so as to provide coating protection for this casing. But this is a matter tha t requires investigation that has not been part of the U.S. Government programs. Would the security be greatly improved by changing the casing design to include a silica material? Several other problems in this connection have been raised previously[2], but there has been no response.

APPENDIX A: CALCULATION OF DEATHS CAUSED IF ALL OF THE WASTE ENTERS HUMAN STOMACHS

For illustrative purposes, let us calculate the number of liver cancers expected from people eating 1 millicurie (3.7×10^7 radioactive decays per second) of plutonium-239 (^{239}Pu) that is present in the waste. Since the radiation emitted by ^{239}PU, alpha particles, does not go very far - it can barely get through a thin sheet of paper --this material can cause liver cancer only if it gets into the liver. ICRP analyses of experimental results indicate that 0.01 % of ingested ^{239}PU gets through the walls of the gastrointestinal tract into the bloodstream, and of this, 45% is deposited in the liver; thus ($3.7 \times 10^7 \times 0.0001 \times 0.45$ =) 1,700 alpha particles strike the liver each second. Since, according to ICRP, ^{239}Pu remains in the liver for an average of 40 years (1.2×10^9 seconds), the total number of alpha particles that eventually strike the liver is ($1,700 \times 1.2 \times 10^9$ =) 2×10^{12}. This is multiplied by the energy of the alpha particle to give the energy deposited, 1.5 joules, which is then divided by the mass of the liver, 1.8 Kg, and multiplied by a conversion factor (1 rad = 0.01 joules/Kg) to give the dose, (1.5/1.8x 0.01=) 80 rad.

The risk of liver cancer per rad of alpha particle bombardment is estimated in BEIR and UNSCEAR Reports from studies of patients exposed for medical purposes; it is 300×10^{-6} per rad. The number of liver cancers expected from eating 1 millicurie of 239Pu is therefore ($80 \times 300 \times 10^{-6}$ =) 0.024. Since the waste produced in one year by one plant contains 6×10^4 mi((icuries of ^{239}Pu, the number of liver cancers expected if this were fed to people would be ($6 \times 10^4 \times 0.024$ =) 1,400.

But once ^{239}PU gets into the bloodstream, it can also get into the bone-45% accumulates there, and it stays for the remainder of life; it therefore can cause bone cancer. A calculation like that outlined above indicates that 700 cases are expected. When other body organs are treated similarly, the total number of cancers expected totals 2,300 if ail of the plutonium in tire waste from one year of operation of one nuclear power plant were fed to people.

The quantity of ^{239}Pu in the waste does not stay constant; it is increased by decay of ^{243}Am into ^{239}Pu, but it is reduced by radioactive decay of ^{239}Pu. These two effects cause the toxicity of the plutonium to vary with time as shown in Figure 1.

There are many other radioactive species besides ^{239}Pu in the waste; similar calculations are done for them and the results are also plotted in Figure 1. These curves are then added to give the total number of deaths expected if all the HLW generated in producing 1 Gwe-y of electricity were fed to people in digestible form.

APPENDIX 8: PROBABILITY PER YEAR FOR AN ATOM OF AVERAGE ROCK AT 600M DEPTH TO ENTER A HUMAN STOMACH

From the measured rate at which rivers carry dissolved material into oceans, it is straightforward to calculate that an average of 1.4 x10^{-5} meters of depth is eroded away each year. Hydrologists estimate that 26% of this erosion is from dissolution of rock by groundwater; the rest is from surface water. Thus (0.26 x 1.4 x 10^{-5} =) 3.6 x 10^{-6} meters of depth are dissolved annually by groundwater. The fraction of this derived from 1 meter of depth at 600 meters below the surface may be estimated from our knowledge of how groundwater flow varies with depth; it is about 2.6 x 10^{-4}. The total amount of rock dissolved from our 1 meter of depth in 1 year is then (3.6 x 10^{-6} x 2.6 x 10^{-4} =) 1 x 10^{-9} meters per year. If 1 x 10^{-9} meters is removed from 1 meter of depth each year, the probability for any one atom to be removed must bet 1x 10^{-9}, one chance in a billion per year. This result applies, on average, to all rock at 600 meter depth in the United States.

We now provide an alternative derivation for an atom of rock, which is submerged in groundwater. Consider a flow of groundwater, called an aquifer, along a path through average rock and eventually into a river. There is a great deal of information available on aquifers, like their paths through the rocks, the amount of water they carry into rivers each year, and the amounts of various materials dissolved in them. From the latter two pieces of information, we can calculate the quantity of each chemical element carried into the river each year by an average aquifer -- i.e., how much iron, how much uranium, how much aluminum, etc.

Where did this iron, uranium, aluminum, etc in the groundwater come from? Clearly, this material was dissolved out of the rock. From our knowledge of the path of the aquifer through the rock and the chemical composition of rock, we know the quantity of each of the chemical elements that is contained in the rock traversed by the aquifer. We can therefore calculate the fraction of each element in the rock that is dissolved out and carried into the river each year. As a typical example, a one square meter cross section of an average aquifer carries 0.003 grams of uranium into a river each year that it dissolved out of a 100-kilometerlong path through 300 million kilograms of rock that contains 800 kilograms of uranium as an impurity (this is typical of the amount of uranium in ordinary rock). The fraction of the uranium removed each year is then 0.003/800,000, or 3.8 parts per billion. Similar calculations give 0.3 parts per billion for iron, 20 parts per billion for calcium, 7 parts per billion for potassium, 10 parts per billion for magnesium, etc. To simplify our discussion, let us say that 10 parts per billion of everything is removed each year. This means that the probability for any atom to be removed is 10 chances in a billion each year. This is 10 times larger than our first estimate, 1 chance in a billion. This is explained by the fact that most rock is not submerged in as active an aquifer as we have assumed here, so we accept the 1 chance in a billion estimate.

We next calculate the probability for an atom in a river to enter a human stomach. The total annual water flow in U.S. rivers is 1.5×10^{15} liters, whereas the total amount ingested by humans is (2.2 liters/person per day x 365 days/year x 260×10^6 persons =) 1.8×10^{11} liters per year. Thus the probability for an atom in a river to be ingested by a human is ($1.8 \times 10^{11}/1.5 \times 10^{15}$ =) 1.2×10^{-4} or a little more than 1 chance in 10,000 per year. Almost half of our drinking water comes from wells tapping aquifers, and since flow in aquifers is much less than in rivers, the probability is larger. Also, water is used for irrigation, providing a pathway through food, and we eat fish, which have lived in rivers. When all of these pathways are added up, the probability for an atom dissolved out of rock to enter a human stomach is about 4×10^{-4}.

REFERENCES

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