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RADIOACTIVE WASTE DISPOSAL IN GEOLOGICAL FORMATIONS

F. GERA*
CNEN - CSN Casaccia
Rome, Italy

1. Introduction

Many discussions on radioactive waste management suffer from the use of confusing terminology. In this paper the term "disposal" means the release or emplacement of waste materials with no intention of recovery at a later date. Disposal can be irreversible, for example, the environmental release of effluents, or can retain a certain degree of retrievability, for example, in many schemes for the geologic disposal of solid wastes. On the other hand "storage" means the emplacement of waste materials in such a manner that later retrieval can be carried out and with the intention of doing so.

The objective of waste management is to prevent harm to man and the environment. Disposal is the final waste management step. The current approaches to radioactive waste disposal are:

- release of low level effluents in such a way as to ensure dilution to non-hazardous levels;
- containment until radioactive decay has reduced the radioactivity in the waste to levels compatible with the environmental capacity.

*Presently on assignment to the OECD Nuclear Energy Agency, 38 Boulevard Suchet, 75016 Paris, France

For long lived wastes, only appropriate geological formations are usually considered capable of providing containment with the required reliability. The geologic disposal of liquid and even gaseous radioactive wastes has occasionally been proposed; but the present tendency is to minimize the mobility of radioactive wastes by incorporating them into solid matrices. Consequently, the main problem facing the nuclear industry is the safe disposal of solid radioactive wastes.

Several countries are experiencing active opposition to the further development of nuclear energy by vocal groups of concerned citizens. The nuclear opponents' arguments are based on the risk of accidents at nuclear plants and on the purported lack of an adequate solution for the disposal of long lived radioactive wastes. As far as the radioactive waste problem is concerned, the most frequent objections are either philosophical or technical in nature. It might not be possible to satisfy all critics on philosophical grounds since highly subjective points of view are possible; but the technical objections are often unfounded and the whole controversy is characterised by a remarkable lack of perspective.

2. The Radioactive Waste Problem

By far the greatest amount of radioactive wastes will be produced by the electro-nuclear industry. Table I shows the volume and the radioactivity content of wastes resulting from the production of 1000 MW-years of electricity [1]. These data apply to light water reactors (LWRs) fuelled by enriched UO_2. In the case of LWRs using UO_2-PuO_2 fuel the waste production is very similar, with the exception of transuranium (TRU) wastes and ore tailings, which are produced in amounts roughly five times greater and 30% smaller respectively.

The high level wastes (HLW) constitute the most difficult technical problem, since they combine the requirements of decay heat dissipation and long term containment. High level wastes contain more than 99.9% of non-volatile fission products, about 0.5% of uranium and plutonium, and practically all the other actinides formed in the fuel by transmutation of uranium and plutonium. Additional waste categories requiring long term containment are the cladding hulls and the TRU wastes.

In order to provide a proper perspective to the following discussion, it is essential to define the duration of required isolation of long lived wastes [2]. A possible approach is to calculate the time required for the ingestion hazard potential in the waste to reach the level of the ingestion hazard potential associated with the natural radioactive materials that had to be mined in order to produce the fuel which gave origin to the waste. The hazard potential is assumed to be indicated by the number of limits of annual intake (LAI) present in the waste [2]. These calculations, for HLW, result in time periods of a few thousand years. However at that time the inhalation hazard potential in the waste (number of LAI inhalation) would be still much greater

Table I Fuel Cycle Wastes from the Generation of 1000 MW-years of Electricity by Enriched UO_2 Fuelled LWRs

(From Blomeke and Kee, 1976[1])

	Volume (m^3)	Activity (MCi)	Mass of Actinides (tons)	Thermal Power (kW)
High level solidified	3.0	78	0.19*	390
Cladding hulls	2.6	0.87	0.017	3.6
Noble gases	0.1	0.27	-	0.405
Iodine	0.043	1.1×10^{-6}	-	6.7×10^{-7}
LWR tritium (water)	140	0.00074	-	2.3×10^{-5}
F.P. tritium (solidified)	0.31	0.016	-	0.00057
Carbon 14	-	2×10^{-5}	-	-
Low level TRU	3.5	0.0035	0.0003	0.002
Intermediate level TRU	8.7	0.011	7.7×10^{-5}	0.054
Low and intermediate level	535	0.002	-	0.0065
Ore tailings	57,000	0.006	9.2	0.014

*Includes uranium

than in the natural radioactive source materials; in addition, the radionuclides in the waste are in a more concentrated form and the environmental behaviour of some new elements is rather poorly known. In consideration of all this it seems wise to aim at disposal systems capable of containing the waste for significantly longer time periods. Calculation of the variation with time of the hazard potential associated with the waste shows that up to about a hundred thousand years, a significant reduction in hazard potential takes place. Afterwards, the reduction in hazard potential becomes very slow and little additional change occurs over the following few million years [2]. These considerations seem to indicate that the disposal of long lived wastes can be appropriately designed on the basis of a containment time in the order of a hundred thousand years.

This conclusion is supported by the comparison between the ingestion hazard potentials associated with a waste repository after 100,000 years of decay and a large pile of uranium ore tailings. The assumptions are:

- The tailings pile had been accumulated in ten years of operation of an uranium mill with a nominal capacity of 7000 tons of ore per day (average ore grade 0.2% U_3O_8).

- The waste repository contained all HLW, cladding hulls, and TRU waste produced by the US nuclear power industry up to the year 2010.

The two ingestion hazard potentials turn out to be in the same order of magnitude. Since Ra^{226} is the critical nuclide in both cases the comparison can be considered as fairly meaningful. Obviously, the relevant difference lies in the fact that the waste is emplaced in a geological formation at least a few hundred metres below the surface, while ore tailings are dumped at the surface where they undergo leaching and erosion; therefore today's tailings piles are certainly more hazardous than future repositories after 100,000 years of decay. The uranium ore tailings disposal practice, while apparently primitive and somewhat objectionable, is not known to have resulted in significant radiological consequences; which confirms that much less mobile waste in a 100,000 years old repository would represent a very small risk indeed.

Ore tailings are somewhat of a problem due to their large volume. Obviously the best disposal solution would be to reintroduce them underground, provided that excessive leaching by ground water would not take place.

The low and intermediate level non-transuranium bearing wastes decay to non-hazardous levels of radioactivity in a few hundred years. In consideration of their fairly large volume, they constitute mainly a logistic problem, which would be significantly alleviated by the widespread adoption of incinerators.

The other waste categories in Table I may require specific disposal procedures, but they do not change the overall magnitude of the waste problem.

In conclusion, the actual commitments resulting from the generation of 1000 MW-years of electricity by LWRs are:

- Disposal of some hundreds of cubic metres of short lived wastes; target containment time: a few hundred years.

- Disposal of a few tens of cubic metres of long lived wastes; target containment time: about a hundred thousand years.

3. The Disposal Options

For short lived wastes, the possible disposal solutions are:

- shallow land disposal in trenches or concrete pits;

- sea dumping;

- emplacement in deep cavities, free from circulating ground water.

Each one of the three alternatives can provide an adequate solution, albeit at different costs.

Shallow land disposal requires careful definition of the wastes that can be buried in order to prevent long lived nuclides from being introduced in the disposal sites in excess of pre-determined limits. Over many years of nuclear development the land areas committed to shallow disposal might become significant, which, for many countries, might turn out to be a serious problem.

The capacity of the oceans to receive properly conditioned short lived wastes without adverse consequences is indeed great. However, the practice of sea dumping meets with some philosophical objections and it is quite possible that international agreements might eventually restrict it to very low level wastes or even prohibit it.

Emplacement in deep, dry cavities is the preferred solution if suitable excavations already exist; for example, the Asse Salt Mine in the Federal Republic of Germany. If deep cavities must be produced for the special purpose of disposing of the short lived waste, this solution proves to be more expensive.

However, regardless of the disposal option implemented, present management practices, which place little emphasis on volume reduction, are noticeably near-sighted. There is little doubt that, in the future, maximum practicable volume reduction will be the essential requirement in the management of short lived wastes, at least in most countries.

Several concepts have been proposed in recent years for the disposal of long lived wastes. Most of them are variations on the geologic disposal theme, although some attention has also been given to more elaborate options such as waste partitioning followed by extra-terrestrial disposal or nuclear transmutation of the actinide fraction /3/. It is too early to reach a conclusion on the merit of advanced disposal concepts, since the partitioning technology is not yet completely in hand and no reliable estimates exist of the risks associated with the various management steps. It is obvious that extra-terrestrial disposal and nuclear transmutation will be considered attractive options only if they can be shown to reduce the overall risk associated with waste management. So far this has not been done; on the contrary, it has been maintained that the overall effect might well be an increased risk in comparison with disposal of the unpartitioned waste in appropriate deep geological formations /4/ /5/.

Geologic disposal concepts can be divided into various categories:

- disposal into geological formations underlying the sea bed;
- disposal in glaciated areas;
- disposal into geological formations underlying land areas.

3.1 Sea Bed

Disposal underneath the bottom of the sea, either in the sediments or in the bedrock, combines the advantages of containment within geologic media with those of remoteness from man and of an enormous dilution capacity for any radionuclides that might eventually migrate to the water column. The preferred areas would appear to be in mid-plate, mid-gyre regions of the deep ocean floor /6/. In general, the distance from the plate boundaries would provide the necessary assurance of long term tectonic stability. The emplacement technology is not yet available; but the development of viable procedures does not appear beyond the scope of human ingenuity. Disposal under the sea bed would be ideally suited to the development of international repositories, provided the philosophical objections to the concept could be overcome at the international level.

The emplacement of carefully conditioned high level waste on the sea bottom has been proposed by some as an additional disposal alternative. However, regardless of the technical feasibility of producing solid matrices capable of providing long term containment with the necessary reliability, the philosophical objections appear so strong that it is most doubtful that the practice will ever be authorised.

3.2 Glaciated Areas

Various emplacement concepts have been proposed for the disposal of high level wastes in glaciated areas [7]. A typical example involves the waste container melting through the ice to the ice/rock interface and being sealed off by re-freezing of the ice behind it.

The reliability of containment could be further enhanced by emplacement of the waste in the frozen bedrock underlying the ice-sheet. This has the advantage of removing the waste from the ice-sheet which, in a geological sense, is a potentially mobile structure. Antartica is the prime candidate for these concepts as it has the advantage of great extent, a huge ice cap, no inhabitants and a hostile environment, and is therefore unlikely to be utilised by future man. It has been continually glaciated for at least 5-6 million years. The unfavourable aspects of the scheme relate to the limited understanding of the geophysics of large ice-caps and the mechanisms controlling the long term climate on earth. From a technical viewpoint the concept is feasible. However, a major investigation of the geological and hydrological aspects would be required before such a scheme could be implemented. Changes in the present international legal and political situation with regard to Antarctica would also be required to enable disposal in that area.

3.3 Geological Formations Underlying Land Areas

Disposal in geological formations under land areas is obviously the easiest option. Several emplacement concepts have been proposed; some of them would require a significant developmental effort, but a few are completely feasible with present technology [3]. The best known emplacement concept is the conventional mine, consisting of a horizontal array of long pillars with the waste canisters placed in holes drilled in the floor of the intervening rooms. This concept was originally proposed for bedded salt formations, but it could be applied to different rock types as well. However, the choice of the emplacement concept is of secondary importance, provided at least one viable alternative exists. The truly important question is the capability of certain geologic formations to contain the waste for a hundred thousand years or more.

The rock types presently under consideration for the disposal of long lived wastes are:

- rock salt;
- argillaceous sediments;
- hard rocks (mostly igneous and metamorphic, but limestone and anhydrite have also been proposed).

Ground water is the main potential vehicle for the transfer of radionuclides through the geosphere; consequently the isolation of the waste from circulating ground water is the essential prerequisite of geologic disposal schemes. Many geologic environments could provide the waste with a certain degree of isolation from ground water.

Rock salt is usually completely free from circulating ground water, therefore a suitable salt formation could provide practically absolute containment of the radioactive substances. The plasticity of salt ensures that openings and fractures will be effectively sealed. On the other hand the high solubility and the potential uses, either as a raw material or as a storage medium, are considered by some as possible drawbacks.

Argillaceous sediments, at the depth of interest, are always water saturated; the velocity of the interstitial water ranges from practically zero to very low values. However, over geologic time periods water migration over significant distances is possible. The sorption capacity of clay minerals provides an effective retention mechanism and most radionuclides leached from the waste would decay within short distances. The actinides in particular would not be able to migrate at all.

The other great advantage of many argillaceous sediments is the plasticity which would provide a self-healing mechanism. The disadvantages of argillaceous formations are the mining problems and the less effective containment of certain radionuclides, for example ^{99}Tc and ^{129}I. Undoubtedly there are important questions about the effects of heating and radiation on the rock and the pore fluids; this is a result of the limited R & D effort that has been spent on disposal in argillaceous sediments. Waste in argillaceous sediments would be isolated from circulating ground water only in a relative sense, but this is not believed to jeopardize the containment capability of this rock type.

As a matter of fact, the capability of argillaceous sediments to contain the critical radionuclides over their radioactive lives has received striking confirmation by the study of the Oklo phenomenon. At Oklo, in the Gabon, uranium masses with a ^{235}U content significantly lower than the normal value have been discovered. This can be explained only by past conditions capable of sustaining a chain reaction and the fission of the missing ^{235}U. The uranium mineralizations are found in a sandstone bed contained in shale. The chain reaction took place about 1.8 billion years ago, lasting approximately half a million years. Detailed geochemical studies have shown that the important long lived nuclides were effectively contained in the reaction zones. ^{239}Pu, in particular, can be proved to have decayed in the exact location of its generation.

Hard rocks can be extremely impermeable when massif; however, they are usually intersected by a network of joints and fractures, which can cause extremely high hydraulic transmissitivites. There is some evidence that in tectonically stable areas crystalline formations deeper than about 1000 m can be free from circulating ground water, since the fractures are kept closed by the overburden pressure and are sealed by secondary minerals. Assuming that large masses of dry hard rocks are identified, there is no doubt that suitable procedures for the emplacement of radioactive wastes could be developed.

The lack of plasticity of hard rocks is responsible for all the difficulties that could be met with this type of rocks. Since the creep of hard rocks is negligible, no significant closure of mined cavities and shafts would take place. Consequently, the cavities back fill and the plugging of shafts and boreholes would not be self-improving with time as in plastic rocks. If tectonic movements were to take place, old fractures might be reactivated or new ones might be formed; in either case, pathways for the migration of ground water could be formed and no mechanism would be available for the sealing of the fractures, with the exception of secondary minerals deposition, which is an exceedingly slow process. In addition there are questions about the possible effects of heat on the disposal formation with particular reference to thermal expansion and its consequences for the sealed fractures. However, in particularly favourable geologic situations hard rocks might be able to provide sufficiently reliable containment even in case of faulting. An example might be an intrusive mass surrounded by thick clays. It is also likely that some of the doubts about disposal in hard rocks will be eliminated as the results of R & D work, now being started, become available.

Regardless of the nature of the disposal formation, the safety analysis of any geologic disposal scheme will have to rely on a convincing demonstration that the wastes will be contained for at least 100,000 years. This appears to require the capability of making reliable geologic predictions. Most geologic processes are deterministic in nature; however, natural systems are so complex and geologic changes are function of so many parameters that, in practice, present capability of making reliable geologic predictions is indeed limited. On the other hand, on the basis of present rates of geologic processes and of the magnitude of geologic changes that have taken place during the Quaternary period, it is possible to estimate the maximum changes that the repository area might undergo over a 100,000 years period [8]. For example, nobody can say how many metres of overburdon will be removed by erosion over the repository, or what thickness of salt will be removed by dissolution from the top of the disposal formation, or how many metres will be the total displacement on a certain fault; but sound geologic considerations permit the definition of values that cannot be exceeded in a 100,000 years period. Therefore the obvious task is to design a geologic disposal system capable of withstanding these extreme geologic changes without loss of waste containment.

It must be emphasised that the safety analysis cannot neglect the possible effects of man's actions. Future man could interfere with the waste containment system in two different ways:

- Changing the environmental parameters which control the rate of geologic processes and therefore bringing about truly exceptional changes. For example, man could induce climatic changes, or increase erosion rates, or increase the amount of ground water coming into contact with the disposal formation.

- Directly intruding on the waste by drilling or mining through the disposal zone.

The first class of possible effects of human activity can be accounted for by increasing, as appropriate, the magnitude of the extreme changes that the repository must be able to withstand without loss of containment.

On the other hand, the risk of direct intrusion by man falls outside the realm of scientific analysis. The intrusion could be either intentional or accidental. An intentional intrusion would appear to presuppose the technical capability of avoiding harm and eventually of restoring the containment. An accidental intrusion would imply the loss of records about waste repositories and therefore a major break in the continuity of human society, which is quite possible over the long term. The probability of accidental intrusion, a truly imponderable event, could be minimized by selecting disposal formations in areas which appear to have negligible resource potential and which are not easily accessible. But in the end, human intrusion remains the only risk that cannot be evaluated. Therefore, there is no choice but to have faith in the technical capability of future generations and trust that if they were to run into an old repository they would also be able to take remedial actions. However, it must be emphasised that if the intrusion were to occur after a few thousand years of decay the risk would not be significantly different from that associated with many natural deposits of toxic substances.

4. Conclusions

In conclusion it is justified to reject the statement that there is no solution to the radioactive waste problem. Many geologic formations are capable of ensuring waste containment for 100,000 years or more. The emplacement technology is completely available. Alternative emplacement technologies or more elaborate waste management schemes might become feasible in the future, but this does not affect the conclusion that geologic disposal meets the needs of today's nuclear industry. The fact that no repository of long lived waste is presently in operation is a proof of the thoroughness of the site confirmation studies and not of the lack of a viable solution. On the other hand, it must be pointed out that operation of a waste repository, even for several decades, would not prove the capability of the formation to contain the waste for 100,000 years or more. The only possible demonstration of the adequacy of the disposal system is conceptual in nature and consists of showing that even the most extreme geologic changes would not lead to hazardous consequences.

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