TIME PERIOD OF CONCERN FOR JUDGING THE LONG-TERM HAZARDS OF GEOLOGICAL DISPOSAL OF RADIOACTIVE WASTE

E. R. Merz
Institute of Chemical Technology
Kernforschungsanlage Julich GmbH
D-5]70 Julich/Fed. Rep. of Germany

ABSTRACT

Although time perspectives between 10^3 and 10^7 years are under discussion for performing repository safety assessments, the persuasion is growing that a time frame of about 10,000 years should be appropriate. Beyond this time the uncertainties in forecasts and future assessments are greater the longer the periods of time they are applied to. It therefore becomes very questionable whether there is any use in continuing long-term assessments solely on the basis of risk to hypothetical individuals who constitute a critical group well beyond this time. It has been proposed in the Federal Republic of Germany to calculate individual dose rate exposures over a time period of 10,000 years based on realistic site-specific scenarios. No dose rate calculations regarding post 10,000 year releases are recommended, but qualitative forecasts concerning a safe isolation of waste should be made up to 10^6 years using best estimates of geological and hydrogeological data, especially based on ground water travel times. Two main arguments have been put forward to support this approach:
(1) a comparison of the waste repository with natural analogues, and (2) the orientation to future geological alterations influencing the repository system. Beyond these arguments there is no unambigous way to define a clearcut time period appropriate for performing dose rate calculations in the safety analyses.

INTRODUCTION

After the operational phase of a repository for radioactive wastes, that means once the repository has been sealed, a long-term radiological risk remains. Due to the radioactive decay, it decreases with time but must nevertheless be quantitatively assessed.

The most effective way to put a containment and isolation approach into practice is to confine the radioactive waste in a stable waste form, and to isolate the waste form from the biosphere by additional engineered and natural barriers. This approach to radioactive waste management should, in principle, ensure that any return of radioactivity to the biosphere, even over very long periods, will only occur at safe and acceptable levels. For long periods up to one thousand years there would be a high degree of confidence that the radioactive waste would be totally isolated from the environment (1).

The published literature varies widely on the subject of the time frame over which radioactive waste disposal alternatives should be evaluated or compared. If the future could be predicted with reasonable assurance, then a very long time frame would provide a more complete comparison between alternative disposal systems. Some scientists have attempted to compare radioactive waste disposal sites for periods of up to one or even 10 million years. However, such results contain very large uncertainties because of the difficulty of making such long-term predictions about either the engineered components or the natural barriers. At the opposite extreme, other experts have only considered time periods in the order of 500 years, arguing that reliable predictions can only be made for time frames of this length and that the longer term performance is less important.

The long-term radiological impact of waste disposal depends on events and processes which may cause a release of radionuclides into the environment or influence the rate of release or transport through it. Some of these incidents are almost certain to occur, others have time-dependent probabilities of occurrence.

In order that all such incidents could be taken into account on a rational basis, it would be desirable that the protection of man should be expressed in terms of risk. However, with the knowledge presently available it is impossible to quantify the probabilities of most natural geological containment failure mechanisms or to determine how these probabilities might vary with time. Also, neither the probability of thermal and radiation effects, nor mechanical stresses causing failure of the geological containment can be estimated with sufficient reliability.

Because of the very large uncertainties it is pointless to try to make precise projections of the actual risks due to radionuclide releases from repositories after about 10,000 years. Therefore, no attempt has been made to calculate overall risks for the sake of deducting a cut-off time for performing a safety analysis.

ASSESSMENT OF REPOSITORY PERFORMANCE

It is generally considered that, if radioactivity is released from buried waste, it is most likely to result from ground water entering the repository and gaining access to the waste form, dissolving some radionuclides and then transporting them to the surface. Other methods of release generally considered to be of much lower probability are the exposure of waste by some catastrophic natural event or through future mining operations. These may be largely avoided by locating waste repositories at sufficient depth in an area known to be seismically and volcanically stable, and in a geological environment unlikely to contain minerals of economic value.

The assessment of long-term waste confinement first requires an identification of the various potential mechanisms, rates and pathways by which radionuclides could leave a repository and migrate through the various barriers to enter the human environment and bring about radiation exposure either directly or indirectly. Once these factors are identified, estimates can be made of the radiation doses that could arise through these mechanisms.

Classification of Geological Events

Possible events which could lead to repository failure can be divided into four groups:

1. natural rapid events uninfluenced by the existence of the repository or by human actions, e.g. meteorite impact, volcanic activity;
2. natural geological events or processes independent of repository existence, e.g. erosion, subsidence, faulting, climatic changes;
3. geological events or processes caused by the repository, e.g. thermal and radiation effects on rocks;
4. human actions, direct or indirect, e.g. drilling for mineral resources, reservoir construction, sabotage, war.

TABLE I

Summary of geological containment failure mechanisms

Scenario Mechanism Potential Cause of Containment Failure	Probability of Event Occurring	Possible Consequences
Rapid natural events		
Meteorite impact	$2 \cdot 10^{-14} y^{-1}$	Direct release to atmosphere and/or leaching into ground or surface water
Volcanic activity	$5 \cdot 10^{-11} y^{-1}$	Direct release to atmosphere, hydrothermal transport in deep ground water
Slow natural processes		
Seismic events and faulting	$1 \cdot 10^{-5} y^{-1}$	Ground water ingress
Erosion	1	Increased vulnerability to other failure events and transport mechanisms
Climatic changes with glaciation	Almost certain in less than $2 \cdot 10^{4}$ y	Reduction in rock strength, hydrological changes leading to ground water ingress, also increased erosion
Pluvial episodes	Unknown	Possible increase in probability of ground water ingress
Arid episodes	Unknown	Probably none
Uplift	Unknown	Increased erosion, hydrological changes leading to ground water ingress
Subsidence	Unknown	Probably none
Repository- and waste-induced effects		
Thermal effects	Unknown	Fracturing allowing ground water ingress
Radiation effects	Low	Fracturing allowing ground water ingress
Mechanical stresses	Unknown	Fracturing allowing water/solution ingress
Events caused by man		
Nuclear warfare	Unknown	None expected
Sabotage	Unknown	Probably none
Drilling	Unknown	Small-scale release to surface

Table I summarizes the events which have been identified by HILL and GRIMWOOD (2) as potential causes of failure of geological containment and the possible consequences leading to transport of waste to the biosphere. The inherent difficulties in performing long-term risk analyses stem from the lack of assigning probabilities to the individual events.

Complexity of a Repository Safety Analysis

An overall safety analysis for a repository not only requires the identification of geological containment failure mechanisms but a complex array of geological, hydrological and geochemical data. Much of this can be provided by the existing general background of knowledge of these sciences. However, equally important data required for the analyses can be obtained only from detailed knowledge of the properties of the proposed disposal sites. This requires an extensive preliminary program of testing and evaluation of repository sites.

The principal factors governing the overall performance of a repository are depicted in Table II.

TABLE II

Processes and factors governing the overall performance of a repository

Hydrological environment (in particular, the routes of movement of ground water through the repository and its neighborhood)
Waste form and engineered barriers
Oxygen potential of the rocks and ground water or brine both within the repository and in the surrounding rocks
Composition of the ground water and brine
Solubilities of radionuclides in ground water and brine
Time scales for movement of water and brine from the repository to the biosphere
Retardation factors for individual radionuclides due to adsorption-desorption phenomena on clays and other minerals as water and brine solutions diffuse along various pathways to the biosphere
Degree of dilution of ground water and brine solutions emerging from the repository with non-contaminated ground water from environments away from the repository

All of these factors must be assessed on the basis of the best available evidence, including realistic estimates of their uncertainties. When this data base is assembled, calculations of the release of radionuclides to the human environment may be carried out using mathematical models which simulate the overall system. These models have been of two types: consequence analyses and scenario analyses (3).

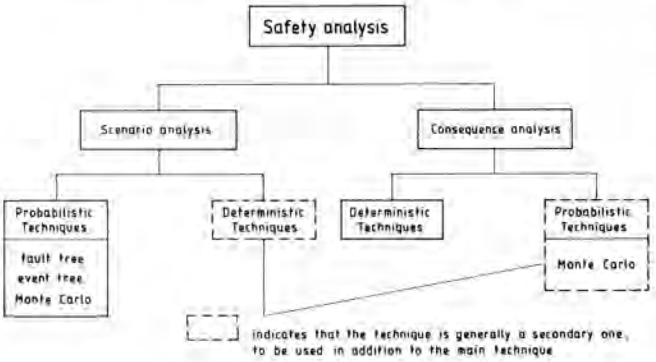

Fig. 1. Components and techniques of safety analysis

Figure 1 shows the components of safety analysis and the techniques which may be used at each stage.

Deterministic Analysis Techniques

Deterministic analysis techniques are the classical methods used in predictive mathematical modeling of system behavior. In order to use these techniques it is necessary to have sufficient understanding of the processes at work on and within a system to be able to formulate the mathematical equations describing the principal processes. Detailed knowledge of each process is not necessarily required, since it will often be possible to develop a mathematical model which adequately predicts the behavior of a system or system component from a general understanding of the basic processes involved. Deterministic techniques are particularly useful in modeling the effects of continous processes and can be applied to both steady state and dynamic conditions which change with time.

Probabilistic Analysis Techniques

Probabilistic analysis involves a set of statistical techniques for studying effects. Parameters whose values are uncertain, events whose occurrence are random, and features which may or may not be present can be treated statistically. For example, the frequency or probability of occurrence of an airplane crash at a specific repository site may be estimated. Various methods are available for considering how the probabilistic variations in components of a system act together to cause variation in the system as a whole. These include fault/event tree analysis and Monte Carlo analysis.

It is important to recognize that probabilistic analysis and deterministic analysis are complementary techniques and that, as a general rule, both should be used in scenario as well as in consequence analysis.

Consequence analyses are primarily deterministic in nature, however, when distribution functions of environmental transport parameters are considered, consequence analyses also have probabilistic components. If sub-models of particular system components are used, these must be able to be readily interfaced to produce a model of the whole disposal system.

A scenario analysis is necessarily probabilistic because the probabilities of occurrence of various events and processes have to be taken into account. However, it also has deterministic components, since sub-models will need to be used to predict the effects of various events and processes on the disposal system and hence to provide the input data for release and transport calculations.

Lessons to be Learned Concerning the Time Period

From the outcome of numerous risk assessments of radioactive waste disposal systems, it may be concluded that the risks identified over relatively short time spans, such as a few hundred to one thousend years, do not adequately portray important differences between alternative sites or disposal systems. This is because the ground water travel times would probably be sufficiently long at most sites so that no significant radionuclide releases would be predicted over this time period.

If the consequence analysis technique is carried out further into the future using a time frame up to about 10,000 years, then in most cases substantial differences between different sites could be observed. Underlying chemical, physical and geological processes are either known from experiments and observations, or can be predicted with sufficient confidence for this time period. Beyond 10,000 years the uncertainties in forecasts and future assessments become greater the longer the periods of time they are applied to. Applying probabilistic instead of deterministic techniques does not change this situation in the least. Therefore, it is recommended that safety analyses be divided into two categories:

1. A time frame of up to 10^4 years for which the consequence analysis technique provides reliable quantitative results in the form of release data and radiation exposure values.
2. Beyond 10^4 years up to the maximum of 10^6 years where the safety analyses are performed only in a qualitative manner without any exposure calculations since they would become highly speculative. An absolute time cut-off is applied for time frames greater than 10^6 years.

Although this selection is largely arbitrary, the adoption of the 10,000 years limiting value seems to be a scientifically justifiable approach.

SUPPORT FOR THE TIME FRAME ASCERTAINMENT

The selection of the 10,000 years limiting value for making quantitative safety analyses by calculating radiation doses to man from radionuclide release and transport phenomena calls for supporting arguments. A desirable method would be a comparison of the hazard potential and risk, respectively, with a natural analogue. Thus, in the past a toxicity index has been derived in order to compare it with natural standards (4).

The purpose of a toxicity index is to allow a simple comparison of the toxicity of a repository with known standards, without having to take account of all the processes and mechanisms which control the release and migration of radionuclides from the repository to the biosphere. It is important to point out that although radiotoxicity is a measure for hazard potential, it does not display the actual risk which is additionally dependent on the retardation efficiacy of the multibarriers.

Two types of comparison are generally made: with natural uranium bodies and with toxic heavy metal deposits. An additional argumentation for a cut-off limit is based on drastic climatic changes with glacial and interglacial episodes.

Risk from Uranium Ore Bodies and Mill Tailings

A general criterion has been suggested for deep geological repositories containing radioactive wastes in the sense that the repositories should impose no greater radiological risk than that due to naturally occurring uranium deposits. Although the true hazards of radioactive wastes are not measured by comparing the total ingestion toxicity index for the uranium ore used to fuel the reactor to generate these wastes. In Fig. 2 the toxicity indices are shown relative to the *ingestion* toxicity of the ore. The ore toxicity is due mainly to the Ra-226, which is in secular equilibrium. Also shown are the relative toxicity indices for the uranium mill tailings, which contain Th-230 and Ra-226 separated from the uranium ore, and for the depleted uranium from isotope separation, neglecting the likely later use of this uranium as fuel for breeder reactors. Because the uranium ore ingestion toxicity is dominated by Ra-226, all of this toxicity is transferred to the mill tailings and is preserved for over 100,000 years because of the long half-life of Th-230. The tailings toxicity then decays to a lower value due to the residual uranium, e.g., about 5 %, which remains with the mill tailings.

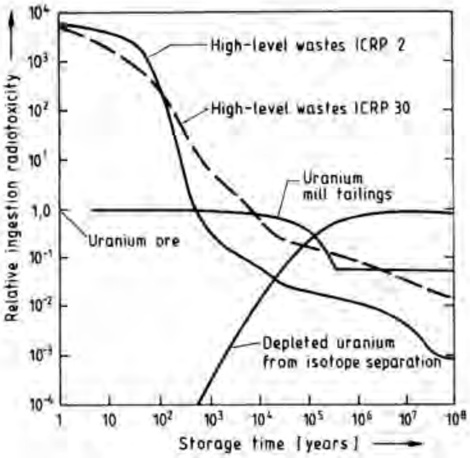

Fig. 2. Relative ingestion toxicity of solid residuals from LWR fuel cycle (uranium fuel, 0.5 % of U and Pu in high-level waste)

The decrease of the ingestion toxicity of the high-level waste is dependent on the gross decay rate of fission products and the conversion factors applied. In the diagram the values issued by ICRP recommendations No. 2 and the latest one No. 30 are used to calculate the relevant curves. With the former data the high-level waste decays to a level below that of the initial ore after less than 1000 years, whereas with the more recent data the point of intersection lies close to 10,000 years. This difference is due to new metabolic data as well as new radiobiological knowledge, and as a consequence thereof, modifications for exposure calculations via the ingestion path. It may thus be argued that after about 10,000 years there no longer exists a net increase in radiotoxicity potential.

Another perspective to justify the proposed time period is based upon a comparison of the risks from a high-level waste repository with those from an undisturbed uranium ore body. In this assessment, it is assumed that uranium dissolved by the ground water eventually reaches an existing water path. The uranium itself and some of its daughter products move along the aquifer and finally may enter into the biosphere. The same propagation model is applied for the mobilized waste radionuclides. Figure 3 compares the toxicity of uranium ore required for the production of fuel with the relevant waste arising from reprocessing, and the spent fuel itself.

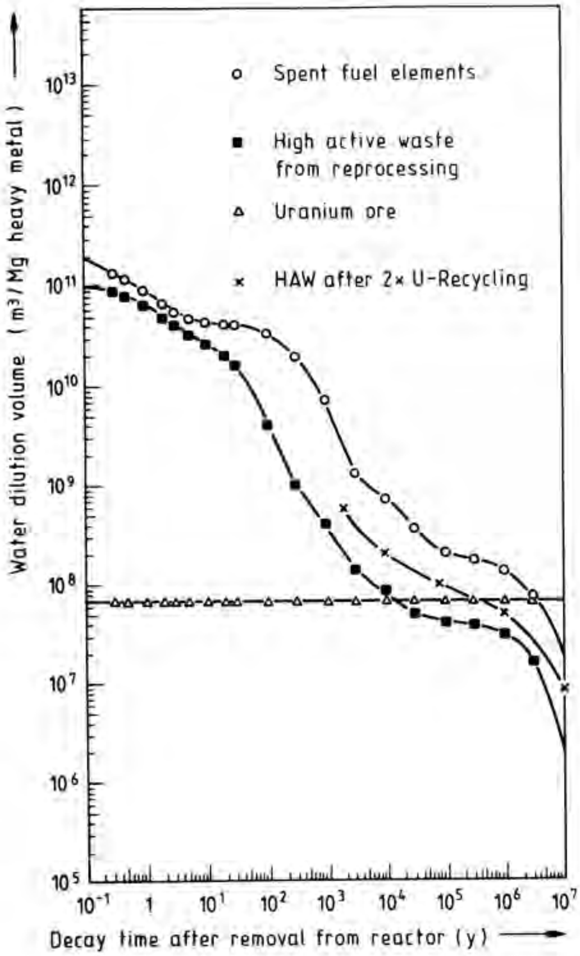

Fig. 3. Toxicity of nuclear wastes relative to the amount of uranium ore (0.2 % U content) required for the production of fuel (adapted from HAUG) (5).

Risks from Hazardous Minerals and Heavy Metal Deposits

Radioactive wastes are occasionally compared with other non-radioactive hazardous materials like ore bodies, fly ashes and incineration slags, or with any dumping site containing chemotoxic materials, e.g. compounds such as cyanide, arsenic, mercury, cadmium, lead. Calculating the toxicity index for such buried waste, assuming a uniform distribution over the areal extent of the underground repository, and comparing it with an equal size nuclear waste repository, it can be shown that they exhibit rather similar toxicities after periods from 10^3 to 10^5 years decay time for the radioactive material (6).

Another approach compares radioactive wastes from nuclear power production with the wastes arising from coal burning. The results of a recent study by the PTB in Germany is shown in Fig. 4 (7).

The principal limitation of such a comparison is obvious since many important factors of a disposal system are omitted from the analysis. The mobilization, pathways and dispersion of hazardous species between the repository and the local human environment may be rather different, although the toxicity contents in the disposal areas are of comparable dimensions.

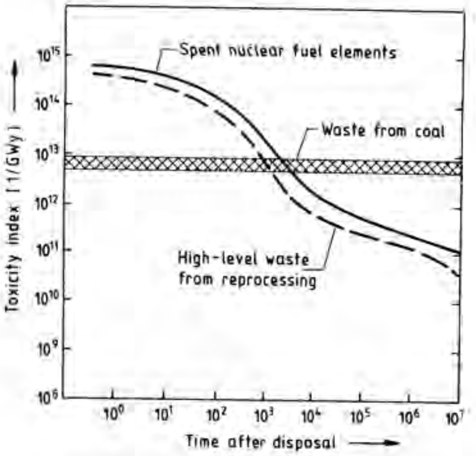

Fig. 4. Relative toxicity indices as a function of time for wastes arising from nuclear power production and wastes from coal-fired plants which are released to surface waters and thus enter into the human biosphere

A more important objection to such a vindication is the fact that it yields no independent absolute measure of a hazard or risk.

Risks from Climatic Changes

Phenomena which over the ten thousand years of interest may change important barrier parameters are events with time-dependent probabilities of occurrence that change the behavior of a disposal system or that give rise to new exposure pathways. Very few such events are random in time, and more geological events of potential influence on a disposal facility, such as changes in sea levels or glaciation, appear to have a predictable periodicity (8).

A model of future climate based on observed oribital-climate relationships predicts that, ignoring anthropogenic effects, the long-term trend over the next 10,000 to 20,000 years is towards extensive glaciation of the northern hemisphere and a cooler climate. It is therefore extremely probable that the repository sites in Germany will be affected within this time frame.

Subsequent effects may influence geological containment. Perhaps the most obvious one is increased erosion. Another certain consequence is that glaciation causes great changes in drainage patterns, but predictions of these hydrological changes are difficult. Figure 5 gives an overview of the geological time perspective in the past and for the future.

Using geological forecasts it seems logical to limit the time frame for dose calculations to 10,000 years.

CONCLUSIONS

A justification for the selection of the 10,000 years time period on the basis of a comparison with other hazard potentials, e.g. uranium ore bodies, toxic heavy metal containing ashes and slags from fossil-fired power plants is of a qualitative nature only. It provides by itself no quantitative measure of a risk.

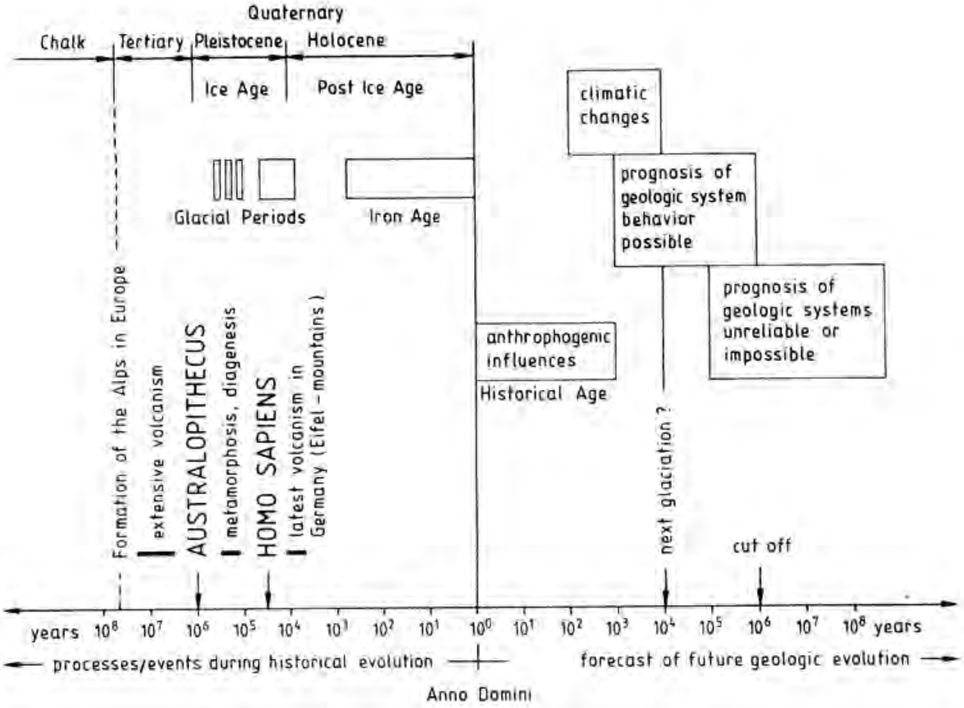

Fig. 5. Schematic diagram of geological perspective

However, its usage supports public acceptance of nuclear power utilization.

A direct justification for the 10,000 years time period is based upon geological reasoning. Forecasts of future developments are only possible for this time span with sufficient reliability.

Reliable quantitative data can only be derived from a site-specific safety analysis comprising the integrated system: "overall geological situation-repository layout-waste package".

A successive procedure is recommended:

- Quantitative radiation exposure calculations via release and dispersion data up to a time frame of 10,000 years. Protection goal: individual dose limit ≦ 0.3 mSv/yr, no risk upper bound commitment.
- Best estimate considerations about the geological, hydrogeological and geochemical behavior of the multibarrier system for the time period between 10^4 and 10^6 years. Only release rate, but no radiation exposure estimates.
- Cut-off at 10^6 years since the residual risk is equal to or less than the overall general geological underground hazard potential.

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