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RELIABILITY OF RISK ASSESSMENTS FOR GEOLOGICAL DISPOSAL OF NUCLEAR WASTE

Some aspects regarding the reliability of risk assessments for geological disposal of nuclear waste are investigated. The input for the study is given by the opinions of some interviewed Dutch experts and existing literature. The Dutch risk assessment PROSA is used as an example, but the conclusions are seen to be valid more generally. In the PROSA study an integrated risk criterion is used. It is found that apart from its benefits the use of this criterion can lead to a too absolute interpretation of the risk figures, suggesting a larger reliability than can be justified.

(687.5946) W.J. Slooten - The various uncertainties in calculating risk figures for this subject are discussed. One main source of uncertainty is dealing with very long time scales that are relevant in case of geological disposal. The farther in the future we try to predict the behaviour of the burial site with the waste, the larger are the effects of the assumptions and uncertainties. The assumptions and uncertainties fall into two classes:

Country	Expected start of disposal
U.S.A.	After 2017
Finland	2020
Sweden	2020
France	2025
Belgium	2030
Russia	After 2025
Germany	2035
Japan	2035
Canada	After 2035
Switzerland	2040
U.K.	2040
	Source: NEA 2008

parametric and conceptual. Risk studies usually deal pretty well with parametric uncertainties, but conceptual uncertainties are often not dealt with or even not perceived. In any case they are very difficult to grasp. Conceptual assumptions limit the reliability of risk studies often in an unknown way. The usual industrial practice of dealing with risks (known or unknown) is to monitor the system all the time it is operating. However, for a nuclear waste repository this is not possible, because of the extremely long time scales. This puts a question mark behind the very concept of permanent geological disposal. Therefore it is advisable to postpone a decision about permanent disposal and wait until we have a better view on the safest solution. For now it is better to focus on a relatively safe interim solution for the next decades. Also it is common sense to stop the production of nuclear waste as soon as possible simply because we do not have a safe solution for it.

1. Introduction
Most countries that produce nuclear waste see permanent disposal in the deep underground as the primary option to deal with the waste. The idea is to

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isolate the waste from the biosphere for a very long time until the radioactivity has almost disappeared. Because of the very long half-lives of several components of the waste the isolation period should be of the order of a hundred thousand years. To evaluate the safety of geological disposal many assessments have been carried out. In these assessments the possible geological developments of the storage site and the behavior of the waste in connection with the possible release of the waste in the biosphere are studied.

In the Netherlands the government initiated in 1984 a research programme called OPLA (OPberging te LAnd, disposal on land) to study the safety of disposal of nuclear waste in underground rock salt formations. In the framework of the OPLA programme in 1993 an assessment was published called PROSA (PRObabilistic Safety Assessment)[1]. This study evaluated the safety of underground repositories using a radiological risk criterion.

Also in 1993 the Dutch minister of environmental protection put forward the additional criterion that disposal of high toxic waste is only allowed when the storage is retrievable, this means that the waste can be recovered if desired. To study the consequences of this additional criterion, the commission CORA (Commissie OPberging Radioactief Afval, radioactive waste disposal commission) carried out a research programme 'Terugneembare berging, een begaanbaar pad?' (Retrievable storage, a passable path?)[2]. This report was published in 2001.

In 2009 the Dutch minister of environmental protection declared that this year a new research programme will start, called TOBRA (Terugneembare Ondergrondse Berging Radioactief Afval, retrievable underground storage of radioactive waste) where the technical and ethical aspects of retrievable storage will be further worked out to support a final decision on the storage of nuclear waste. This programme will last for 8 to 10 years.

In this article we want to explore the reliability of risk assessments for geological disposal of nuclear waste. The PROSA study from 1993 will serve as an example. PROSA was meant to lay a foundation for a risk based method to evaluate the safety of disposal concepts. In the CORA report, that focused mainly on retrievability, this method was not developed much further. Without doubt future research will build on the foundation laid down by PROSA. But how reliable is this foundation?

'Salt formations currently are being considered as hosts only for reprocessed nuclear materials because heat-generating waste, like spent nuclear fuel, exacerbates a process by which salt can rapidly deform. This process could potentially cause problems for keeping drifts stable and open during the operating period of a repository.' (U.S. NRC, Waste Confidence Decision Update 2008)

In the period 1995 - 1997 the author held various interviews with Dutch experts in fields related with this subject. These expert opinions form the core this article. In the interviews many times the question of the reliability of risk assessments came up as a point of discussion. Can we have any confidence that our predictions have a correspondence with what may actually happen in the very far future?

The question of the reliability of risk assessments was also recognized by a commission of the Dutch Health Counsel which published in 1995 a report 'Niet alle risico's zijn gelijk' (Not all risks are equal)[3]. Dealing with the notion of risk, the report concluded that in fact two levels of uncertainty must be distinguished. The first level includes the uncertainties in the many parameters used in the model calculations. The second level of uncertainty is more general and fundamental and includes a consideration of the uncertainties of the methods and models. The report calls this last kind of uncertainty "often the most uncertain of the various kinds of uncertainty and seldom expressible in measure and number" (translated from Dutch by the author). In this article we will focus on this second kind of uncertainty.

2. The Dutch PROSA study

PROSA studied disposal concepts in a general way, working with general models for salt formations and disposal mines following the decision of the Dutch government that the first phase of the OPLA research project should not contain field explorations but should limit itself to desk studies and laboratory research. The aim of the PROSA project was to evaluate the post-closure safety of some possible disposal concepts, which should be used to recommend further relevant research.

The PROSA study is a scenario analysis. A set of scenarios is studied that lead to the release of radionuclides into the biosphere and subsequent exposure to radioactivity of human beings. The difficulty of a scenario analysis is to find a set of scenarios that is more or less complete, and covers the most important possible developments of the repository with the waste. PROSA develops a method of scenario selection to find a relevant set. Therefore the repository is seen as a multi-barrier system. The waste has to overcome three barriers to reach the biosphere: the engineered barriers (waste form, container, borehole backfill, etc.), the isolation shield (the body of the salt formation) and the overburden (the geological formations between the salt formation and the biosphere, including the groundwater system). It is assumed that for each barrier there are two possible states: the barrier is present or the barrier is not present (bypassed). Having three barriers and two possible states of each barrier there are eight possible multi-barrier states. Each multi-barrier state is identified by a unique combination of present and bypassed barriers.

Each multi-barrier state is the result of one or more scenarios that lead to this state. For each scenario the primary processes that attack or destroy the barriers that are bypassed in that state are identified. Secondary processes that influence the transport and the state of the radionuclides supplement the primary ones. The processes are chosen from a list of about 150 so called FEPs (Features, Events and Processes) that are selected from existing literature. FEPs that are not relevant for the Dutch situation or that have a very low probability are left out. Although in most scenarios one or more barriers are at first not bypassed, eventually every scenario leads in the end to the release of radionuclides into the biosphere as a result of the natural geologic evolution of the site.

In this way a list of 22 scenarios is found that is assumed to cover the most important ways in which radionuclides might escape from the repository and reach the biosphere. The 22 scenarios are grouped into three distinct families. In subrosion (subsurface dissolution) scenarios the dominant process is the slow subsurface dissolution of rock salt in groundwater. In flooding scenarios (also called water intrusion scenarios) the groundwater enters the repository through fractures in the salt body. In human intrusion scenarios the barriers are bypassed by future human activities like drilling, etc. where it is supposed that future generations might use the geological formation for other purposes, unaware of the existence of the waste.

Only 7 scenarios are selected for further analysis. Scenarios that contain processes for which no proper models are yet available are left out. This is the case for glaciation (the effects of a glacial period) and for gas production as a result of chemical processes around the containers. For other scenarios it was decided not to analyze them in detail because it was assumed that they are 'covered' by another scenario. This means that the results are expected to be the same. This is done for the scenarios where radiation damage plays a role. Radiation damage is the radio-chemical change of the crystal structure of the rock salt with the result that radiation energy from the waste is captured and stored in the surrounding salt. Under some conditions the energy can be released explosively. It is assumed that these explosions only can occur in the first phase of the storage period (the first thousand years). According to the PROSA study the effects are limited to the direct neighborhood of the waste so this will not result in cracks that extend to the groundwater system. Because of the creep of the rock salt these cracks will close again. So by the time that the groundwater reaches the burial place by the natural process of subrosion the effects of radiation damage are assumed to be gone. Therefore the subrosion scenarios with radiation damage are expected to give the same results as the subrosion scenarios without radiation damage.

PROSA is a probabilistic safety assessment. This means that probability distributions are used for various model parameters that are not known accurately. PROSA does not calculate probabilities of occurrence for the different scenarios. The question that PROSA tries to answer is: do scenarios exist that lead to an unacceptable radiological risk in the future? For each scenario the radiological risk is calculated, assuming that the different steps of the scenario occur. The radiological risk is defined as the probability of a person to die as result of the exposure to radiation. I.e. the report deals primarily with consequence analysis. Another aim of the report is to carry out a sensitivity analysis. This means determining which input parameters for the different models have the strongest effect on the future exposure of human beings to radioactivity.

Only for the human intrusion scenarios some estimates are given for the probability of occurrence, because these scenarios are the only ones that are found to lead to unacceptable levels of future exposure. These probabilities are used to estimate the risks of these scenarios.

The conclusions of PROSA are that the subrosion scenarios and the flooding scenarios lead to very low to negligible radiological risks for future generations. Only the risks for human intrusion scenarios are not negligible, although they are expected to be low. For all scenarios considered the health risk is less than 10^{-6}/a. The sensitivity analysis leads to the identification of some characteristics of the repository and the geological formation that are most relevant for the safety of the system. A low internal rise rate of the salt formation and the possibility of deep disposal are the safety relevant characteristics of the salt formation. The properties of the overburden (the geological layers between the salt formation and the surface) were considered not to be safety relevant characteristics.

3. Expert opinions on the reliability of risk analysis

The interviewed experts provided valuable information about risk analysis from the viewpoint of their specific disciplines. They also expressed their (sometimes personal) opinions about geological disposal of nuclear waste or related subjects. The method to use interviews as part of the field research is more often used in the social sciences than in the natural sciences, although there are examples in the natural sciences as well. For example V.M. Chernousenko[4] makes use of interviews to analyze in detail the causes of the nuclear accident at Chernobyl in 1986. The interview method used in this paper is based on the narrative interview that is developed in psychology (see for example F. Schütze[5]). R. Franke[6] further developed this method. In the narrative interview the interviewed persons are stimulated to express their opinions and (also personal) viewpoints on the subject. In this way apart from the factual information that is obtained, the interviewer also gets an impression of the viewpoints, tensions and interests within the scientific community and greater society in relationship with the subject.

Here follows a short introduction of the interviewed experts. The names of the experts are made fictitious to give them more freedom to express their opinions. The interviews were taken in Dutch. The citations were translated and edited by the author.

The interview with Mr. A. Brouwer took place in April 1995. He is a geologist and researched on location the geological characteristics of many salt formations and mines in the world. He showed a lot of motivation to express his views about the geological side of storage of nuclear waste. Here he showed more a practical then a theoretical attitude towards the subject.

Mr. C. Van Dijk is a civil engineer. The

THEORY AND PRACTICE: THE EXAMPLE OF GORLEBEN

In 1977 the Gorleben saltdome was assigned as the location for the disposal of German high-level radioactive waste. The mine, planned to be used as a disposal site for high-level radioactive waste in a saltdome at Gorleben, is about half finished. Until now, 1.3 billion Euro is spent. It will take a few decades more before the first waste-container can be stored, unless the whole project is skipped due to ungoing scientific and popular opposition.

(687.5947) WISE Amsterdam - At 840 meters below surface there is a large space with nets under the ceiling to prevent pieces of salt from falling down. There are two shafts 400 meters from eachother. Between both shafts a system of horizontal galleries (7,5 meter wide and 5 meter high) is constructed to allow natural air circulation. It is 37 degrees Celcius and there are measuring apparatus in side-walls, floor and ceiling to measure the convergence: the movement of salt. In 3,5 years (2002-2005) the convergence was 60 centimeters. Therefore employees have to scrape the galleries to keep them at the necessary height.

In 2005 Joachim Kutowski (head of the Department Geology Gorleben of the DBE -the German Company for Contruction and Operation of Final Waste Disposal) pointed out that saltdomes are not very suitable for retrievable storage of radioactive waste, because in time the galleries will silt up. Furthermore the radioactive waste produces heat and the containers can sink away in warmer salt layers and it would then not be easy to locate them if necessary for retrieval. The highest point of the saltdome is 250 meters below the surface level.

During construction the DBE located several carnallite-layers (hydrated potassium-magnesium-chloride) which had to be sidestepped. Therefor the actual disposal will, according to Kutowski, be at a different location at the dome than originally foreseen. Because the high level waste produces heat, the casks have to be stored 50 meters from each other. Given the amount of waste, twice as much space is needed as available now. From the galleries and shafts holes have to be digged out to store the waste in.

One of the reasons for the opposition to believe the saltdome is not suitable is that it is not even meeting its own standards: there should be a layer of impermeable clay over the saltdome, but it is missing for a few square kilometers. So the question is why Gorleben was chosen in the first place? Kutowski states that the decision to see Gorleben as the prime location might not have been taken on just geological grounds but also for political reasons: unemployment, located near the East-German border (but after the reunification in 1990 is was suddenly located in the heart of Germany) Kutowski said in 2005: "So there was no pile of scientific evidence in favor of Gorleben. It was about finding a suitable location, not the best available one".

This was again confirmed in April this year when it was revealed that in de mid 1980s government geologists were bullied by top government officials to change their findings regarding the suitability of the Gorleben location.

This has been revealed by Professor Helmut Röthemeyer, pensioned former department head of the Federal Physics Technology Agency (PTB), which examined the salt deposit at Gorleben in the mid-80s. The PTB commissioned deep drilling of the salt dome and because of what they revealed it advised against using the salt as a final nuclear repository. The testdrillings hadn't delivered the hoped-for findings. It was discovered that in the Ice Age a groove was made by a runnel (a small stream) through the stone covering the salt making the stone "unable to hold back contaminations from the biosphere over time".

When a meeting was called with another federal agency to discuss the findings and the recommendation to explore other sites, Röthemeyer explaines, unexpectedly representatives of the federal chancellor's [prime minister's] office, the research and technology ministry and the interior ministry also attended. (There was no environment ministry until after the Chernobyl explosion in Ukraine.) The ministry officials demanded that the PTB change its findings. "There was nothing in writing," Röthemeyer told the newspaper, "there was no written order, but we clearly had to take that conversation as an order."

The group fighting nuclear waste dumping at Gorleben says they've twice demanded the Federal Office for Radiation Protection (BfS), which succeeded the PTB, to hand them records of the position taken by the PTB or to at least see them. "The irrelevant criteria for the 1977choice of location paired with this wrong course setting in the mid-80s led nuclear waste disposal into the next dead end," says the group's media spokesman, Wolfgang Ehmke on April 19, 2009.

In the 2000 Phase-out law, a 10-year moratorium was declared to give the then SPD/Green coalition time to renew the search for another site. Very little happened afterwards.

In September last year a damning report about nuclear waste leaking from the Asse II storage facility in Lower Saxony became known. The report said nearly 130,000 barrels of low- to medium-grade nuclear waste had been mishandled and warned that groundwater leaking from the mine was radioactive. Environment minister Gabriel said Asse-II was "the most problematic nuclear facility in Europe" -- in part because the mine stood in danger of collapse. The Asse scandal (Asse II is geologically similar to Gorleben) could derail the plans of the CDU/CSU to start drilling again at Gorleben as soon as possible in order to show the population that progress was being made on the issue of storage and to postpone the planned phaseout of nuclear power.

Sources: Press release, BI Luchow-Dannenberg, 19 April 2009 / Der Spiegel online, 4 September 2008 / Nuclear Monitor 625, 8 April 2005 interview took place in June 1995. He showed himself very engaged in the subject of nuclear waste. As a civil engineer he has a profound knowledge of the technical side of the subject, but he was also very aware of the social tensions. He knew many arguments from proponents as well as opponents of underground storage and developed his own standpoint. He showed a lot of concern for a fruitful discussion between the various groups to develop workable solutions.

The mathematician Mr. E. Froon was interviewed in August 1995. He is an expert in the field of model calculations. He showed himself to be a proponent of geological disposal of nuclear waste. He formulated clear and self-assured positions, with a somewhat detached attitude towards the subject.

Mr. I. Jacobs is a physicist and works for an international environmental organisation. He was interviewed in January 1996. He is specialised in nuclear energy and nuclear weapons. The opinions he expressed were well in accord with the standpoint of his organisation, as can be expected given his job.

The interview with Mrs. S. Terbeek took place in May 1997. She is a chemical technologist and external safety advisor at an engineering office. In the interview she showed concern for the people that might be affected in the future by radiological risks. This motivated a critical attitude towards different research projects on the subject.

Mr. U. Viehoff was interviewed in October 1997. He is a mathematician and an expert on risk evaluation for water protection systems. During the interview he was very cautious to stay within the confines of his field of water protection. What he said was relevant for storage of nuclear waste, but he could not be persuaded to express any direct opinions about this subject.

3.1. The radiological risk criterion

The PROSA report uses the radiological risk criterion to evaluate the safety of underground repositories. The use of this criterion in the OPLA program was rather new in the discussion on the theme of geological disposal in the Netherlands. Before 1984 the proposed safety requirements for possible burial sites were of a geological nature like the depth of the salt formation, the existence and thickness of a caprock, the annual rising rate of the geological formation, etc. With the initiation of the OPLA program by the Dutch government in 1984 the emphasis was put on the radiological risk criterion and the geological criteria were valued of secondary importance. It is mentioned that the initiation of the risk criterion had a profound influence on the societal discussion about geological disposal in the Netherlands that was going on from 1970 on. For example Damveld et al.[7] have accused the Dutch government that by introducing the radiological risk criterion attention was diverted from the more concrete geological requirements that were heavily under fire at that time by the environmental movement. With the shift from geological to radiological criteria the research programs and also the societal discussion had a tendency to become more abstract and general. The discussion concerned not so much the suitability of actual geological sites, but 'generic' geological formations in combination with 'disposal concepts'.

Was the introduction of the radiological criterion an escape from the problematic geological criteria, or were there definite scientific reasons for its introduction and did it lead to a more reliable analysis? I asked the mathematician Mr. E. Froon what according to his opinion was the reason why the researchers of the OPLA project started to use the radiological risk criterion.

"We consider underground disposal of nuclear waste because we presume to be able in this way to bring the danger to an acceptably low level. That is the goal of underground disposal. In the seventies we had no access to an integrated calculation model to investigate to what extent we could fulfil this demand. Therefore we used partial criteria. For each compartment of the disposal facility certain requirements were set and it was presumed that then the facility as a whole is safe enough in relation with isolating the waste from the people. But how do we weigh the relative importance of the partial criteria? It may be that we reject a site because it does not meet the requirements of one of the partial criteria. But as a whole it may be that this site has the best shielding properties. What is of more importance, the fact that the containers have a thickness of 5 mm, that there exists a caprock on top of the salt formation, that the formation is moving a little bit, or that it has certain geohydrological properties? At the moment we have the calculation tools to work with one integrated criterion we no longer need these partial criteria. It is then possible to evaluate every disposal concept in terms of future radiological exposure." (interview E.Froon)

I confronted my interview partner with the following fact. In the days of the geological criteria it was recognized that none of the geological sites considered met the requirements. They were all rejected[8]. The results of OPLA on the other hand showed that all disposal concepts that were studied fell well within the levels of acceptable risk. Can we say that now suddenly all these sites are found to be suitable after all?

"That is a little bit true, but at the same time it is not true at all. OPLA worked with very little site specific information. In fact three generic formations were studied: salt layers, salt pillows and salt pillars. These formations, when they are big enough, were found in principle to be suitable for a safe and technically possible disposal of nuclear waste. When we look in the future at specific sites it is not certain of course, that they will meet the test. It is possible that strange unexpected facts will become known. In that sense your statement is not true. But on the other hand your black and white statement has more truth than is suggested from what I just said. On the basis of the earlier geologic criteria for each site there was something wrong with one or the other of the partial criteria. But when we calculate the risk with our present models, on the basis of the same information, then we find that they all meet the test of having a very low radiological risk. Then I ask the question: on what where those earlier criteria based?" (interview E.Froon)

So in Mr. Froon's opinion the reason to use the radiological risk criterion is to have one integral measure to evaluate the safety of a disposal concept. Geological aspects of a formation are incorporated in this integral measure. But we must keep in mind that PROSA does not say anything about actual sites, it deals only with generic formations. How important is this aspect? The geologist Mr. A. Brouwer has a definite opinion about this.

"We know of the Dutch salt domes that there are large site specific differences. There are large differences in depth of the salt formation, existence and composition of caprock, lithology of the rock formations above the salt, geohydrology, tectonic and geological history. Therefore it is impossible to judge if a formation is suitable for underground disposal without doing extensive research on location for several years. In my opinion it is a weak point of the OPLA project that no site specific research is done." (interview A.Brouwer)

So it may very well be that the tendency of the discussion about geological disposal to become more abstract is not so much caused by the implementation of the risk criterion. It may be caused by the fact that the OPLA project only studied generic situations and in that way diverged from actual situations. The radiological risk criterion could also be applied to studies of actual disposal sites. It is ironic that the environmental movement itself caused the rejection of research of actual sites, as was made clear by the civil engineer Mr. C. van Dijk.

"To obtain the political 'yes' for the project the beginning should not be too threatening. Only desk studies should be done, but no field studies. Only information was used that was already publicly known. Even results from drillings of oil companies that were not publicly known because of competition were not used. In fact it was initially intended to use this information, but the environmentalists resisted strongly. They occupied drilling plants, so the exploration of oil and gas became endangered. The minister then decided that the information of oil and gas drillings should not be used. Under pressure of the environmentalists the most difficult decision, namely the carrying out of drillings, was postponed. OPLA followed the directive of the minister and did not carry out site specific research. Even non-penetrating methods like gravimetry were not used." (interview C.van Dijk)

Mr. Froon observed another problem with the radiological risk criterion.

"But now we have another problem. The risks that are calculated now are all very low, well below the standards set by the government. The result is that the risk criterion does not serve as a discriminating factor between different disposal concepts. Say the standard is 10 and we compare the results of two concepts with risks 0.9 and 1.5. There is a difference between these two figures, but compared to the standard of 10 the difference is hardly meaningful. So therefore the risk criterion does not work very well in discriminating between the two concepts. Therefore we need extra measures apart from the risk criterion. Although the risk figures indicate that the isolation is all right, many people have the feeling that it is not. There is a big difference between the results of the calculations and the feeling of the people. It is important to develop measures that relate to the reasons why people think that it is not all right. So it is possible to compare concepts that are the same in terms of risk, but not in terms of acceptance by the people. We can think of all kinds of disposal concepts, but they should be accepted. We need solutions that provide sufficient isolation and that can be carried out because they are accepted." (interview E.Froon)

What kind of extra measures do you think of? Are they different from the earlier geological criteria?

"Yes, very different. Think about retrievability, choices of host rock (salt, clay, etc.), or preliminary transmutation of the actinides, etc. Then we can say that we did our job better, we have a better option, although in terms of risk it may not be different. But we score better in connection with the question 'did we do everything possible to make it more safe?'. People fear the waste. We do not yet succeed to catch that fear in the risk criterion. Apparently the fear is based on something else. People do not trust the results of the calculations. Maybe we can meet these feelings by showing that we did all that is possible, that we used all the present possibilities of technology, to make it as safe as possible. So we must try to weigh the concepts in terms of ability to realize them." (interview E.Froon)

So we have an integrated criterion, calculated risks that are so low that we cannot compare different concepts, and even more public distrust. I asked an expert in industrial safety, the chemical technologist Mrs. S. Terbeek if the quantitative method of risk evaluation that was used in the PROSA study is a usual method in safety studies in industry.

Transmutation does not eliminate the need for a repository for high-level waste and spent fuel!

"Yes, certainly. Safety reports in industry are structured in a uniform way according to manuals made by governmental organizations. The history of these procedures goes back to 1988. In that year the Dutch government issued the Large Accidents Resolution. Companies handling hazardous materials were obliged to do a safety analysis. The analyses carried out by various different research institutions were very difficult to compare. The government felt the need to prescribe a uniform method. This method became the basis for obtaining licenses. Also various standards were set, for example the probability to die as the result of a certain industrial activity for an individual should be less than 10^{-6} per year. A probability of 10^{-8} is regarded as negligible." (interview S.Terbeek)

Is the Netherlands progressive in this approach?

"Yes, very much! The Netherlands has chosen a very quantitative approach to safety management. But remember that the meaning of the quantitative figures is the ability to compare results! If all research institutions use comparable methods, the results can be compared. But the figures themselves depend very much on the application of models, failure probabilities, etc. There are many assumptions connected with these matters. If we choose them differently, the results are different. Do not take these figures too absolutely. The point is that we want people to act as safely as possible, within the limits of technology and economics. So do not pin yourself down on such figures. The matter is to compare alternatives, not more than that. It is also interesting to see that not always the same standards are used. The figure of 10^{-6} that I mentioned earlier is a workable standard in the industry. This standard is technologically and economically realistic. For safety in transport on the road of hazardous materials this standard is not useful. The risks in traffic are found to be higher, but we accept these risks. Therefore the standards in traffic are set a factor of 10 higher. We could do something like this in the case of nuclear waste, only in the other direction. Why should we use the standards of the industry? Given the large number of uncertainties in connection with nuclear waste we could easily argue to use standards that are stronger. Standards are relative!" (interview S.Terbeek)

So in the opinion of Mrs. Terbeek one should not take the calculated risk figures too absolutely. If we change our assumptions during the calculations, the figures change. The risk figures are mere instruments to compare results. Also the standards are relative. Here we may find the solution for the problem that Mr. Froon mentioned in using the risk figures to compare disposal concepts. If we choose more stringent standards in case of geological disposal of nuclear waste it may become possible again to compare results. Setting more stringent standards is justified by the large number of uncertainties that are mentioned by Mrs. Terbeek in the case of geological disposal of nuclear waste.

In conclusion we can say in connection with the reliability of risk analysis that the introduction of the radiological risk criterion has two sides. On the one hand the criterion allows an integrated analysis that can be regarded as more reliable. On the other hand the radiological risk parameters can be interpreted as too absolute, suggesting a more reliable result than can be justified. There are reasons to limit the use of the criterion to compare the results of calculations for different disposal concepts. Also the standards are not absolute. In the case of disposal of nuclear waste there are reasons to adopt more stringent standards to account for the larger uncertainties. The reason why the discussion on disposal of nuclear waste became more abstract does not seem to have been caused by the introduction of the radiological risk criterion. Instead it is due to the choice to study generic formations and not specific sites. The criterion could also be used in site-specific studies.

'In the U.S. politics, not science, has driven the Yucca Mountain Project from the very beginning. Yucca was singled out for the country's first repository not because it had suitable geology, but rather because Nevada was seen as a politically vulnerable state. In fact, from 1987 until today, safety and environmental protection regulations have been repeatedly weakened or eliminated altogether to keep the ill-conceived, dangerous Yucca proposal afloat.'
(NIRS, March 2006)

Why is the disposal of nuclear waste thought to be connected with larger uncertainties than the more common industrial practices? We will deal with this question below.

3.2. The predictability of geological processes

To evaluate the safety of a nuclear waste repository, we have to deal with very long periods of time. The waste is dangerous for hundreds of thousands of years. These are geological time scales. To what extent is it possible to predict the development of the repository containing the waste over such long periods of time? I asked the mathematician Mr. E. Froon his opinion about the extrapolation of geological processes in the very far future.

"I am not a geologist, but I have ideas about this. Not all geologists endorse the statement anymore that one is able to predict the future on the basis of the past, one to one. I think most geologists accept that we can use the past and the present as information to know how geological processes will develop in the future. A principle that is generally accepted in physics is, that if the boundary conditions are unchanged, processes develop like they developed in the past. So with disposal concepts we must take care that in the future the conditions will not be essentially different from the geological past. So the more we take care that temperature changes are sufficiently small, the stresses are small, etc., the more exact we can say that processes like the rising of the salt formation or the progress of subrosion will be the same as in the past. One expects the geology of the future to behave the same as in the past. For example one can design a model for the process of subrosion, the dissolution of the salt in the groundwater. This model can be validated with data from the past. Then one can reasonably expect that one can use this model for the calculation of the subrosion in the future. This does not mean that the rate of subrosion will stay the same as today. In the past there were irregularities, and so one can expect this to be the case for the future. If the boundary conditions do not deviate much, one reasonably expects the same developments in the future." (interview E.Froon)

How does the geologist Mr. A. Brouwer think about the predictability of geological processes?

"Future predictions with time scales of millions of years are nonsense, then you are fooling yourself. There may be glacial ages, the sea level may rise, etc. The probability that there is ten meters of water above our head or a hundred meters of ice is larger than the probability that a salt pillar reaches the surface. It is relative. I think that future people do not care very much about radioactive waste deep under their feet when they get ten meters of water over their heads. One cannot compare these situations in terms of fears, risks, etc." (interview A.Brouwer)

He also is rather critical about the extrapolation of geological processes.

"My objection to the scenarios of the OPLA studies is that the researchers start from averaged processes. For example they speak of diapirism (upward movement of the salt dome) of 0.1 mm/year averaged over ten millions of years. If one averages over periods of millions of years one will always find values of about 0.1 mm. But that does not mean that the rising rate has always had that value. In Germany we find salt domes where the dissolution of the top of the salt formation in the ground water progresses with centimeters per year. This will not last very long (on a geological time scale) but if it lasts one thousand years, the effects are considerable and in fact more important than the effects of the smooth averaged processes of the scenarios of OPLA. No one can deny that such a process may occur in the Netherlands within five hundred years." (interview A.Brouwer)

What then in his opinion does make sense if we want to evaluate risks of underground disposal?

"I think we should consider short time scales and specific locations to get a more realistic picture. With the help of site specific research we can say a lot about the geological status and stability of a salt formation for the next two hundred years." (interview A.Brouwer)

Mr. Froon observed another problem in the case of disposal of nuclear waste. We do not have a totally undisturbed geological development.

"In connection with the waste, there are many processes that are initiated by the waste, like giving off heat and radiation. The highest intensity of these processes occurs in the first stage of the disposal period. So in the beginning is the highest disturbance of the geology. With experiments we can study these intense processes of the first stage. With experiments lasting one to three years we can obtain a lot of information necessary to validate the models describing the processes. We can also use these models for the later stages when the intensity of these processes is less. There is some discussion about the problem how to do this, but generally one agrees that the disturbances of the geology are of less importance at the later stages of the disposal period. Only for radiation damage there are some small indications (only very small) that the effects may become more important at later stages." (interview E.Froon)

For the civil engineer Mr. C. van Dijk the effect of the waste on its environment is very important.

"The interaction between the waste and the host rock should be the argument of the environmental movement, but they do not bring this point to the foreground. Our starting point is a stable underground that stays stable. That is the reason to store waste in it. We have a problem if the presence of the waste threatens the stability. Stability threatening factors are heat, radiation damage and gas production. There is still a lot unknown about these processes. This should be investigated further." (interview C.van Dijk)

How should these processes be investigated? The experts had rather different opinions about this. Mr Froon:

"The way to deal with this is by developing models on the basis of laboratory experiments and extrapolate them to the far future. There is no other way, because we can do no experiments over such long periods of time. This is the proper method, we have nothing better yet." (interview E.Froon)

Could it be useful to use the first hundred years of the disposal to do observations to validate our models for the interaction of the waste with the salt?

"No, this seems to me not the appropriate method. A measurement period of a hundred years in situ does not give more information than laboratory experiments of a few years. It is even better to validate a model in the laboratory than with in situ experiments. In the laboratory we can design intelligently chosen experiments to test a model under extreme circumstances and derive precise values for the model parameters. A model that is tested in this way is better suited to deal with very long periods." (interview E.Froon)

Mr. Van Dijk:

"The retrievable stage of the storage can be used as an extended research period. We can check if the processes involved with the waste develop as predicted. Models are not sacred with respect to reliability. They have been tested in the laboratory during only a few years. Even if the theory has small deviations from reality, long periods of time may result in considerable deviations. If we can perform in situ measurements for more than a hundred years, the predictions become more reliable. So already for reasons of research a retrievable period has great advantages. If something happens that is not desirable the waste can be recovered. The decision to store the waste permanently is then postponed one hundred to two hundred years in the future. At that time there is much more knowledge to justify such a decision than at this moment. I think it is a little arrogant to presume that our generation can say definite things about the risks of underground storage. An important, almost ethical aim is that we do not saddle up the next generations with the problem of the storage. Therefore I should say be very reserved to make a definite choice now." (interview C.van Dijk)

From the foregoing discussion it becomes clear that the interaction processes between the waste and the host rock introduce a considerable uncertainty to our predictions of the future development of an underground nuclear waste repository. This uncertainty adds up to the uncertainties of the undisturbed geological development of the site. The experts have different opinions on the question of how to obtain more knowledge of these processes, but it is clear that uncertainties will remain.

In this connection I asked the opinion of Mrs. Terbeek how in the OPLA project one dealt with the interaction processes. For example, how it is that the scenarios where radiation damage plays a dominant role are "covered" within other scenarios.

"I think that this covering of certain scenarios is very critical. Exactly those processes that are difficult to understand are covered in this way. We should be very careful. We should only cover a scenario by another scenario when we have some certainty how these processes work. If we do not have this certainty we should think of experiments to get this certainty. We are dealing after all with the fate of a lot of people. It is not necessary to know everything about such a process, but we must be sure that the effects are negligible. This we must be able to justify." (interview S.Terbeek)

Minoru Ozima[9] discusses in his book "Geohistory" the reliability of research results of these interaction processes. In his view there is a fundamental limitation for the methods of physics and chemistry when geological time scales are involved. In laboratory experiments one has to simulate the long time scale by changing parameters. In the case of radiation damage for example, one can simulate the effects of a certain radiation dose over a long period by using in the laboratory a much higher dose rate than in reality. The desired dose is then reached in a manageable time. Ozima argues that it can not be excluded that factors that are not important in the laboratory experiments become very important or even dominant on a geological time scale. These factors stay invisible in the laboratory and are therefore not incorporated in our models. The extrapolation of the model yields erroneous results. According to Ozima a reliable model for geological time scales on the basis of the traditional physical research methods is impossible. He suggests that the geological time scale necessitates a different approach.

"The significance of the geological time scale that is the most fundamental characteristic of geohistorical phenomena can hardly be overemphasized. Applying conventional approaches that have been enormously successful in physical and chemical research may not be very rewarding when dealing with geohistorical phenomena. A different approach must be sought to understand geohistorical phenomena, (otherwise) few significant results can be expected. An original method is necessary in order to understand these phenomena. This is the method of seeking in nature "fossil" records of geohistorical phenomena, and using these to throw light on these phenomena. (…) Owing to its "historical" nature, geohistorical research provides us with a very useful lead to forecasting the future of the earth. Geohistory is still a fledgling discipline, but it seems to hint at its future as a vital field in earth science."[10]

For the storage of nuclear waste we should look for a "fossil" example of a nuclear waste repository. Indeed one such example exists, namely the Oklo natural nuclear reactor. Because of the anomalous isotopic ratio of the uranium in the Oklo mine in Gabon, scientists had to conclude that nearly two thousand million years ago natural fission processes occurred in this place. Some of the resulting products of this process still can be found. In the light of our discussion it would be interesting to investigate at Oklo the interaction processes between the waste and the rock, like radiation damage. This would contribute to our knowledge of these processes, even though the host rock material in our country is very different from the minerals in the vicinity of the Oklo natural reactor.

In conclusion we have seen that the geological time scales that are inherent with geological disposal introduce serious limitations to the reliability of our predictions of future processes. Especially the interactions of the waste with the host rock are difficult to model. There is still a lot unknown about these processes and the farther in the future we try to predict, the less reliable our models are. Therefore it is no good practice to sweep these processes under the rug in our risk evaluations.

3.3. Dealing with risk in practice: failure probabilities

Talking with Mrs. Terbeek about the validation of models we came upon the subject of dealing with risk in practice. The notion of failure probability is the central issue.

"We should make a difference between the physical models and the failure probabilities of the technical systems, like waste containers, etc. Over a given period a container has a certain failure probability, a probability that the waste is released. After the release the physical models come into play to describe how the waste will spread. In my opinion the physical models are the most reliable ones. Many measurements have been done, so these models are validated rather well. The only question is connected with the use of very long periods of time, associated with underground disposal of nuclear waste. Is it possible to say anything about a period of a thousand years? Periods of fifty or a hundred years are workable. There are measurements available of such periods. For example a factory spilled waste onto the ground for a period of fifty years. We can measure what happened to the waste in these fifty years. So it is possible to validate the models. But what does this mean for a period of one thousand years? Will it behave similarly? The failure probability of technical systems is another story. These probabilities are always based on case studies, experience from the past. If we have hardly no case studies for a certain technical system, the failure probabilities are very uncertain." (interview S.Terbeek)

Can you give examples where estimates of failure probabilities were given that had to be corrected considerably after new empirical facts became known?

"Yes, this definitely happened with estimates of risk for transport of hazardous materials on the road. In 1993 a study was started to estimate the probability of an accident on the road. A number of scenarios were defined based on a probability over probability approach. What is the probability of a leak? And if there is a leak, then what is the probability that it is a big leak? And if we have a big leak, then what is the probability that this will lead to an explosion? In this way the end-probabilities for severe accidents were calculated. In the following years more research was done to find out what really happened on the Dutch roads. They started to differentiate between highways and smaller roads; they looked in more detail at the accidents that happened; they looked at what happened when explosive escapes occurred. It appeared that a number of scenarios had to be modified considerably. For example it appeared that out of ten big accidents only three led to an explosion, while at first it was supposed that all big accidents led to an explosion. So this assumption was not correct. Some failure probabilities were corrected with a factor of 15, and this happened after a period of empirical research of only four years. This means that scenarios should be tested empirically, otherwise they are very uncertain." (interview S.Terbeek)

As we see from Mrs. Terbeek's reactions the concept of failure probability is used in the discussions about technical systems. But what happens in geological systems? Are natural barriers fundamentally different from engineered barriers? According to Garrick and Kaplan[11] the only difference is the complexity. A natural barrier is more complex and therefore more difficult to "specify" (understand and model) than an engineered barrier. But a natural barrier may fail as well as an engineered barrier, so for our discussion there is not a fundamental difference.

To deepen the theme of failure probabilities, I conducted an interview with Mr. U. Viehoff, an expert on risk evaluation for flood protection systems. For centuries the Dutch population has been struggling with the risk of floods. Large parts of the country are below sea level and protected by dikes and dunes. On several occasions the sea broke through and destroyed villages and large parts of the country. This happened for the last time in 1953. Also the rivers can be dangerous. In 1995 the river Meuse flooded as a result of heavy rainfall in Western Europe. In 1996 thousands of people in the central region of the Netherlands were evacuated to safe places because the river Rhine and its tributaries were on the verge of flooding. How did the Dutch people learn to deal with the risk of flooding and what can we learn from this in connection with our subject?

Mr. Viehoff told me that after the big flood of 1953 the defence against the flooding was taken up much more systematically than ever before and risk evaluations play an important part. The area of the country that has to be protected is divided into 53 separate regions, each of which is surrounded by dunes, dikes, dams, sluices, etc. If one area is flooded, the others are still protected independently. For each region a maximum acceptable failure probability is chosen, say for example one flood per 1250 years. This figure depends on the economic importance of the region and the number of inhabitants. The failure probability is translated into heights of the dikes, strengths of the dams, etc. Statistical information about sea levels, water levels of the rivers, power of storms, etc. is incorporated in the model.

Important for our subject is that the figures are not valid from now to eternity. The expert said that every five years a new evaluation is conducted. So the data about the water levels of the last few years are also taken into account in the statistical calculations, as well as new insights about the technical characteristics of the artificial flood defence systems. This may lead to the conclusion that in maintaining the chosen failure probability in light of the new information, the dikes should be made higher. The expert made clear that this is not a simple straightforward process:

"Failure mechanisms include not only overflow as the result of a water level that is too high, but also the collapse of a dike, sinking at weak spots, the failure of hydraulic systems, the failure of the layers covering a dike. All these failure mechanisms should be taken into account in the statistical analysis. Furthermore the different failure processes are not independent. The dependencies must be specified as correlation parameters. There are rather large uncertainties in these parameters." (interview U.Viehoff)

Also the characteristics of flood defense systems are not constant over time. The degradation process is different for each system.

"The problem is that each system is unique. There exists only one 'Van Brienenoord' bridge; each dike is different. Therefore the degradation of each structure will develop differently. Therefore too little information is available to predict the future of such a structure. A purely statistical analysis therefore is often insufficient. I dealt with the question to what extent the opinions of experts can be used to compensate for the lack of statistical information. Experts are asked to give an estimate for the parameters that are relevant for the degradation of the structure. The opinions of experts give the a priori information about the structure at hand. By observing the degradation process of the structure additional information is supplied and with this the a priori information is changed with the help of Bayesian statistics." (interview U.Viehoff)

Remembering what the geologist Mr. A. Brouwer said about the large site-specific differences for possible disposal places of nuclear waste, we see that we have an analogous situation here. I asked Mr. Viehoff if it is possible to construct a dike that should last a thousand years without monitoring and repairing. He answered ironically:

"That dike should be made very high. I think that dike should be made ridiculously high…" (interview U.Viehoff)

Mr. Viehoff made clear that our knowledge of risky systems and our dealing with these systems are evolving processes where observations and the continuous increase of new empirical information is an essential part. From the start one cannot have full knowledge of the risks involved. In the course of time our experience with the actual system provides us with more information. In this process Bayesian statistics are used. One form of the equation of Bayes reads as follows:

P(An B) = P(An) [P(B An) / P(B)]

The left-hand side of the equation represents the conditional probability of an event An happening to the system, given that the empirical evidence *B* is known. *P(An B)* is called the posterior probability of *An*. The prior probability of *An* before *B* was known is represented by *P(An)*. The second factor on the right-hand side of the equation represents the relative change in the probability of *An* when *B* becomes known. The Bayes equation reflects our changing knowledge about the system. An iterative process is possible, taking into account new empirical information again and again. It is supposed that in this way our knowledge of the system, represented by the set of subjective probabilities *P(An)* becomes more and more reliable.

This process only works when the system under study is continuously monitored, like is done with the flood protection systems as Mr. Viehoff explained. For the risks of failure of a nuclear waste repository this would be the same. From the Bayesian viewpoint a repository should be monitored all the time it is functioning. During this process our knowledge of the repository gradually grows and becomes more reliable.

Discussing Bayesian statistics N.J. McCormick[12] makes an important observation. He observes that the whole analysis is subjected to the restrictions of hypotheses that are assumed for the system under study. He mentions that some authors insist to indicate the conditional character of the probabilities with respect to these hypotheses or assumptions *H* about the system. P(An) should be read as *P(An H)*, *P(An B)* as *P(An BH)*, etc.

"The use of such a convention does serve to remind the risk analyst to check that the operating environment for the device is the same as that for which the failure probability data have been generated."[13]

What kind of hypotheses does McCormick mean with the symbol *H*? He obviously does not mean statements that can easily be tested empirically, because these are covered in the empirical evidence *B*. From the citation we see that McCormick recognizes a difference between the system in reality (the operating environment) and the set of conceptual models we have made for the system (that for which the failure probability data have been generated). The hypotheses *H* concern not the system in reality, but the models.

To understand this it is important to say a few words about the role of conceptual models in natural science. In his study "The Philosophy of Physics" Roberto Torretti[14] makes clear that the history of physics has shown that the development of conceptual models is not a straightforward process. It is a feedback process. On the one hand empirical results lead to theories but on the other hand often theory is needed to design the experiments and to interpret the experimental results. He shows that for a Bayesian analysis this is true as well. The empirical evidence *B* is interpreted on the background of a set of conceptual models. To say that a growing stock of empirical evidence leads to a corresponding growing knowledge of the object is too simple a picture. It is possible that at a certain moment we conclude that our models do not give a satisfactory picture of the object and we have to change them. In other words, we have to change the hypotheses *H*. The empirical evidence *B* is then seen in a new light and another interpretation should be given.

"… the Bayesian school, for all its mathematical sophistication, remains committed to the feckless assumption that concepts and meanings are fixed and that a rational agent will not be moved by empirical evidence to see things in a fundamentally different way."[15]

Apart from a lack of empirical evidence also our conceptual models are a source of error and this aspect can easily be overlooked. Ewing et al.[16] call this second class conceptual uncertainties. The authors make a clear distinction between parametric uncertainty and model uncertainty. The determination of parameter values is more straightforward then the choice of the correct model. Both uncertainties affect the reliability of the results, but the second class of uncertainties is more difficult to grasp or to quantify. (Remember that in the introduction of this paper a report of the Dutch Health Counsel was mentioned where exactly this distinction between different uncertainties was emphasized.)

As an example in the PROSA report assumptions of both classes can be found. We already saw that assumptions are made about the effects of radiation damage on a repository. Nowadays there is evidence that these effects could very well be more severe than assumed in the PROSA report[17][18]. These assumptions are both of parametric nature and conceptual nature. The model to describe the process of radiation damage formation is still being developed[19]. An assumption of an even more conceptual nature is to view the repository as a three-barrier system, where each barrier can exist in one of two possible states, present or bypassed. This is a simplification of the real situation (although understandable from a practical point of view) with the result that the operating environment is different from that for which the calculations are performed. From the viewpoint of Torretti each model is to some extent a simplification of reality and this suggests that conceptual uncertainties cannot be avoided.[20]

All these assumptions limit the reliability of a risk assessment. With this in mind it is advisable that a risk study should contain a reliability analysis, to evaluate the effects of the assumptions (parametric and conceptual) on the final results. The PROSA report only explains how it deals with parametric uncertainties. For parameters whose values are not known probability distributions are taken. But the subject of conceptual uncertainties is not discussed at all.

In this section we saw that risk evaluations are limited in their reliability. Assumptions and uncertainties play an important role. Especially the conceptual uncertainties are difficult to grasp and often have an unknown

'REDUCING THE HAZARD'

When the phrase "reducing the hazard" is used, usually it means reprocessing and/or transmutation.
However: *Transmutation does not eliminate the need for a repository for high-level waste and spent fuel!*

(687.5948) IEER - First, no transmutation scheme is able to deal with all of the radionuclides of concern since many cannot be transmuted for practical purposes. Second, transmutation of Technetium-99 and Iodine-129 is not 100% effective, even with multiple passes through the reactor, and new long-lived fission products are created from the fission of the actinides. Third, fissioning of the actinides is not 100% effective. The composition of the residual transuranic waste would be shifted towards higher isotope actinides and the waste would thus be more radioactive. This would pose greater radiological risks and complicate disposal. Finally, since cesium-137 will be disposed of in the repository with cesium-135, the large amount of heat generated by it would mean that the space requirements for disposal could be considerable.
Transmutation, even in the context of a phase-out of nuclear power, would also require decades to implement and possibly centuries to complete. This may require institutional control over the waste for time periods much longer than is feasible or desirable.

Implications of Transmutation
Proliferation. All transmutation schemes require reprocessing of transuranic radionuclides. While these schemes may not yield materials attractive to weapons designers in nuclear weapons states, they can be used to make nuclear weapons and would pose significant proliferation risks in that non-state groups or non-weapons states might seek to acquire and use them. Even the reprocessing methods that are labeled as proliferation resistant, such as pyroprocessing, can be easily modified to allow for the extraction of plutonium pure enough to make weapons. These types of facilities may in fact increase proliferation risks due to their compact size and potential problems in developing adequate safeguards. Furthermore, promotion of transmutation as a waste management tool may result in the widespread transfer of this technology.

Environment and Health. Reprocessing, which is required by all transmutation schemes, is one the most damaging components of the fuel cycle. It results in large volumes of waste and radioactive emissions to air and water. Its health impacts on workers, off-site residents, and even far away populations are well documented. Because fuel fabrication does not involve the production of liquid waste, its effects are mainly restricted to workers and are on the same order as for workers in the reprocessing sector. The increased radiological risk of handling fuel that has been repeatedly irradiated is cause for serious concern. Finally, the increased transportation of high level waste required under a number of transmutation schemes would increase the probability of a transportation accident with its attendant effects.

Reactor Safety. Transmutation would require the development and implementation of new reactor technologies and/or the expanded use of existing reactors. Some of these new reactors have been described as "inherently safe." However, increases in certain safety features, in comparison with existing reactors, is countered by decreases in other safety features and the creation of new safety problems unique to the new reactor designs. For example, some feedback effects that help prevent a runaway reaction in existing reactors do not exist in some transmutation reactors.

Cost. The cost of transmutation, particularly for the advanced schemes that would be required in order to have significant reduction of actinides, is prohibitively expensive. Furthermore, while electricity would be produced to offset these costs, it is highly unlikely that these revenues will be sufficient. Transmutation would likely require tens of billions of dollars to develop, and additional large subsidies even during operations, when electric power sales are expected to generate some revenue.

Continuation of Nuclear Power. Transmutation is not only considered in the context of managing the waste from the current generation of nuclear reactors (i.e. as part of a phase-out of nuclear power). Most transmutation schemes, particularly in Europe and Japan, assume an indefinite continuation of nuclear power, with transmutation as one part of a new nuclear fuel cycle. By supposedly solving some of the current problems with nuclear power, transmutation is seen by some as essential to ensuring the continued growth of nuclear power.

Source: "The Nuclear Alchemy Gamble: An Assessment of Transmutation as a Nuclear Waste Management Strategy", IEER, available at: *http://www.ieer.org/reports/transm/index.html*

effect on the reliability of the results. The usual way to deal in practice with these uncertain situations is to monitor the risky system. This monitoring process improves our knowledge about the system, although complete knowledge cannot be achieved. The monitoring process makes it possible that when something goes wrong we can intervene. What does this mean for disposal of nuclear waste? Because of the many uncertainties involved it can easily be argued that we should monitor the repository as long as the waste is hazardous. But is this possible? And what can we do when something goes wrong?

In connection with these questions it is interesting to mention that in 2008 reports appeared that in the Asse II mine in Germany brine was found that was slightly contaminated with radio nuclides[21]. In this salt mine radioactive waste was stored between 1967 and 1978. Between 1995 and 2004 the caves with the waste were filled with salt and can no longer be entered. The contamination is probably caused by corrosion of the waste containers as a result of water intrusion[22]. Containers were used that were not suitable for long-term storage. This example makes clear that even very shortly after waste storage began, processes took place that were not expected.

3.4. Risk and retrievability

As a reaction to the discussion on the safety of underground disposal of hazardous waste the Dutch minister of environmental protection put forward the additional criterion of retrievability in 1993. If something goes wrong in the underground we can recover the waste. Can this criterion be an answer to the uncertainties, can it provide an extra safety margin? I presented this question to Mrs. Terbeek.

"But what then? If we make retrievability a criterion, then we must have an alternative when we get it back. Now we want to bury the waste underground, because we evaluate that it is not safe enough to store it above ground. But when we retrieve it from the underground it still is not safe enough above ground! Then we have a problem, because we have no safety margin anymore. If the risk above ground is comparable to the risk underground, it could be a safety margin, but if the risk above ground is much larger, then it is no safety margin. To make it more precisely: it is important to know what situation is acceptable. Society accepts all kinds of risks, voluntary and non-voluntary. Risk management is based on the knowledge of what risks are accepted by society. The standards are made on the basis of this knowledge. We accept a non-voluntary risk of 10^{-6} or a voluntary one of 10^{-4}. If aboveground storage of nuclear waste has a risk of 10^{-6} and underground storage a risk of 10^{-8}, then retrievability may be an alternative, because the risk is comparable to what we find acceptable. But if we know beforehand that aboveground storage has a risk that is not acceptable, it is not useful to make this proposal. Maybe it is possible to show that by taking all kinds of measures the risk can be made acceptable, but then we must carefully check the costs. If they are too high, aboveground storage is not realistic and it is not an alternative to underground storage." (interview S. Terbeek)

Are there ideas about the risk of aboveground storage? Mr. Van Dijk has a very definite opinion of this.

"For storage of nuclear waste we think of long periods, say 100.000 years. In this period many geological processes can take place on the surface of the earth. The surface is the working floor of nature. As result of glacial cycles the sea level may sink 120 meters or rise 60 meters. Ice may roll over our country leaving nothing standing upright. Those are natural forces over which we have absolutely no control. Therefore we say that this working floor of nature is not the proper place to build a storage site for nuclear waste. I do not say we should store it underground, but I like more to say that there is a scientific responsibility to investigate the possibility of underground storage. That is the way I like to look at it. Of course there are risks connected with underground storage, but aboveground storage is in all cases a catastrophic matter. Another point is that a building for aboveground storage has a lifetime of only 200 years. After every such period it should be rebuilt again. It remains to be seen if human society is able economically, politically and ethically, to build a new one. The question is when our society can no longer fulfill her duties for maintenance. This is the case when society is degenerating for whatever reason. In such a crisis situation for society it is most unfortunate when at that time these hazardous materials are released into the environment. We must prevent that this may happen in such a weak period for our society." (interview C. van Dijk)

So Mr. Van Dijk foresees two sources of risk for aboveground storage of nuclear waste. The first one is that natural processes are more intense above ground than in the deep underground. The second risk factor is the possible incapability of our society to maintain the storage building.

'Once waste is emplaced underground, it is very unlikely it would ever be removed again, not only for technical reasons, but also for political reasons'

For how long a time is it possible to retrieve the waste from underground?

"It is not possible to maintain the retrievability for the whole period that the waste exists. No sane man will claim that one can retrieve the waste after one million years. Retrievability has a time limit. This is a few hundred years. This is a fact from mining. The criteria for Isolation, Managing and Control were set up twenty years ago aimed at aboveground storage. Above ground we can manage and control, because it is always available. These criteria put the emphasis upon societal capacity. If we think about geological storage we do not think anymore in terms of societal capacity, we think in terms of geological processes and very long time scales. When we choose this way we can manage and control during a certain period, but not for the whole lifetime of the storage facility. The managing and control of man comes to an end and nature takes over." (interview C. van Dijk)

The environmentalist Mr. I. Jacobs has a different wish about the duration of retrievability.

"Retrievability is forever! All the time the waste is there we must monitor and control it. The scenario as we see it is as follows. The first hundred years the waste is stored in a building above ground. For the period hereafter underground storage seems to be the best option. Anyhow, we must account for the strangest situations. Imagine if we had had a storage facility above ground in Bosnia! For the underground period we need a building underground with all the necessary measuring instruments that have to be kept working all the time. A problem is however that measuring instruments do not work longer than a hundred years…. The best thing would be that the storage building could be accessed at all times. At this moment we do not know how and if this is possible." (interview I. Jacobs)

So we see that there are various difficulties with the retrievability concept. First of all it probably does not raise the level of safety of the disposal strategy, because recovering the waste means aboveground storage and this is seen as risky business indeed. Furthermore it is by no means clear if retrievability is realizable for very long periods of time. In the opinion of Mr. Van Dijk retrievable storage is only possible for about two hundred years. After this time the mine is closed and "nature takes over". In this conception of retrievability we are in fact talking about delayed permanent disposal.

In these interviews the reasons for retrievability are seen as the possibility to take the waste back when something goes wrong underground and also to some extent to verify our theories about the long-time behaviour of the storage location and the waste.

In the CORA report, that was published a few years after these interviews took place, some other advantages of retrievability are mentioned. One of them is to be able to get the waste back when in the future we may find ways to reduce the hazard of the waste. But in the CORA report retrievability is essentially seen as a first stage of permanent disposal. After some time (a few hundred years) the mine is closed and the waste can no longer be returned to the surface even if desired.

4. Conclusions

In this paper we have explored various aspects of the reliability of risk analysis for geologic disposal of nuclear waste. In our discussion of the radiological risk criterion we saw the danger of giving a too absolute interpretation of the risk figures. Because of the many uncertainties involved it is not possible to justify the use of the risk figures for more than comparison of the risks of different disposal concepts.

In the continuation of the paper these uncertainties were further explored. The extremely long time scales involved are an important source of uncertainty. Some authors insist that the usual research methods of natural science are not expected to give reliable results at these time scales so that new methods should be developed.

In discussing the relationship between models and empirical evidence we entered into the subject of assumptions. Two classes of assumptions were distinguished, parametrical and conceptual. Especially the second class is difficult to grasp and handle. When in a reliability analysis only the parametric assumptions are discussed, an incomplete evaluation of the reliability of the results is obtained. It is argued that the conceptual uncertainties can never be avoided completely. They are part of the process of obtaining knowledge of the external world. To deal with these uncertainties in practice, risky systems are monitored. For a nuclear waste repository however, this leads to difficulties that can probably not be overcome because of the extremely long timescales involved. Also the retrievability concept is found not to be a solution if it is only seen as a first phase of permanent disposal.

Given the results, that risk evaluations of the geologic disposal of nuclear waste have limited reliability and that monitoring of the site during a long enough period is problematic, we have to put a question mark behind the very concept of permanent disposal of nuclear waste in the deep underground.

But what are the alternatives? In my opinion the first thing to do is to stop the production of nuclear waste as soon as possible simply because we have no sound solution for it. The best thing would be to end the use of nuclear fission for the production of electricity.

If that would be done, we still have a large amount of waste to be dealt with. I think we should postpone the decision for a permanent solution because we do not yet know what the safest option is. As one of the interviewed experts said, it is too early to make a definite choice now. At this moment we can better focus on interim solutions, relatively safe storage of the waste for the next decades. In the United States environmental organisations support the concept of hardened on-site storage (HOSS)[23]. In this concept irradiated fuel is stored as safely as possible as close to the site of generation as possible. Because it is not a permanent solution the HOSS facilities should not be constructed deep underground. The facilities are monitored to detect problems as soon as possible. The waste is retrievable. In the Netherlands in fact there is also an interim storage facility near the Borssele nuclear power plant. The nuclear waste is supposed to stay there for at least hundred years.

The most ideal and safe long-term solution would be to transform the waste into non-hazardous matter. But at this moment it is not clear if this ever can be done with safe and practical methods. Some steps in the direction of 'transmutation' have been taken, but as it is seen now this technique leads to new dangers, risks of nuclear weapons proliferation and also high costs. Moreover it still requires a geological repository for the remaining wastes. In a few decades we might have a better view on the best permanent solution for the nuclear waste problem. This might be underground storage but it also might be something else. But the situation now is that we do not know a safe solution, so it is common sense to stop the production of nuclear waste to make the danger for future generations not greater than it already is.

'Illusions that someday somehow a magic solution for nuclear waste will be found, just lends support to the nuclear establishment's push to just keeping operating nuclear reactors and making more waste, regardless of the lack of radioactive waste solutions'

Source and contact: Wim Slooten. He became interested in the nuclear waste problem after his study physics. This article is the result of research in this field under supervision of prof. dr. H.W. den Hartog of the University of Groningen, the Netherlands.
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