EUROPEAN COMMISSION
Community research

PAMINA
Performance Assessment Methodologies in Application to Guide the Development of the Safety Case

(Contract Number: FP6-036404)

TRIAL OF FORMAL USE OF EXPERT JUDGEMENT FOR SCENARIO CONCEPTUALISATION
MILESTONE (N°: M2.2.C.3)

Author(s): **J.B. Grupa**
Nuclear Research & Consultancy Group, The Netherlands

Date of issue of this report : **24/09/2009**

Start date of project : **01/10/2006**   Duration : 36 Months

Project co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	X
RE	Restricted to a group specified by the partners of the [PAMINA] project	
CO	Confidential, only for partners of the [PAMINA] project	

Foreword

The work presented in this report was developed within the Integrated Project PAMINA: **P**erformance **A**ssessment **M**ethodologies **IN** **A**pplication to Guide the Development of the Safety Case. This project is part of the Sixth Framework Programme of the European Commission. It brings together 25 organisations from ten European countries and one EC Joint Research Centre in order to improve and harmonise methodologies and tools for demonstrating the safety of deep geological disposal of long-lived radioactive waste for different waste types, repository designs and geological environments. The results will be of interest to national waste management organisations, regulators and lay stakeholders.

The work is organised in four Research and Technology Development Components (RTDCs) and one additional component dealing with knowledge management and dissemination of knowledge:

- In RTDC 1 the aim is to evaluate the state of the art of methodologies and approaches needed for assessing the safety of deep geological disposal, on the basis of comprehensive review of international practice. This work includes the identification of any deficiencies in methods and tools.

- In RTDC 2 the aim is to establish a framework and methodology for the treatment of uncertainty during PA and safety case development. Guidance on, and examples of, good practice will be provided on the communication and treatment of different types of uncertainty, spatial variability, the development of probabilistic safety assessment tools, and techniques for sensitivity and uncertainty analysis.

- In RTDC 3 the aim is to develop methodologies and tools for integrated PA for various geological disposal concepts. This work includes the development of PA scenarios, of the PA approach to gas migration processes, of the PA approach to radionuclide source term modelling, and of safety and performance indicators.

- In RTDC 4 the aim is to conduct several benchmark exercises on specific processes, in which quantitative comparisons are made between approaches that rely on simplifying assumptions and models, and those that rely on complex models that take into account a more complete process conceptualization in space and time.

The work presented in this report was performed in the scope of RTDC 2.

All PAMINA reports can be downloaded from http://www.ip-pamina.eu.

Trial of formal Use of Expert Judgement for Scenario Conceptualisation

PAMINA RTDC 2 - M2.2.C.3

Under the contract of EC, VROM

Author(s):	J.B. Grupa	reviewed:	A.D. Poley
name:	97222jg 170909 DEF	approved:	R. Huiskamp
Reference:	NRG-21952/09.97222		
97 pages	24 September 2009		

Foreword

This work is performed as part of the PAMINA project that is part of the European Commission 6th Framework Program for Nuclear Research and Training Activities. The main objective of PAMINA is to improve and harmonise integrated performance assessment (PA) methodologies and tools for various disposal concepts of long-lived radioactive waste and spent nuclear fuel in different deep geological environments. PAMINA aims at providing a sound methodological and scientific basis for demonstrating the safety of deep geological disposal of such wastes, that will be of value to all national radioactive waste management programmes, regardless of waste type, repository design, and stage, that has been reached in PA and safety case development.

This report follows from the work done in RTDC-2 'Treatment of uncertainty during safety case development', Task 2.2.C 'Scenario Uncertainty', Topic 3 'Trial of formal use of expert judgement for scenario conceptualisation'.

Contents

Summary

Trial of formal use of expert judgement for scenario conceptualisation.

Scenarios are sometimes defined as a way to handle uncertainties that otherwise cannot be narrowed down / quantified. NRG is undertaking a trial of formal use of expert judgement to assess the possibility of improving the basis for conceptualisation of stylized scenarios. This exercise focuses on the 'abandonment scenario'. Experts have been interviewed by NRG in a predefined procedure to identify agreements and differences in their judgements for selected scenarios. Agreements might then be used to improve the basis for a given scenario, while differences might be resolved either by widening the uncertainty related to the scenario (to cover different views of the experts), or by iterative steps in the interview procedure of the experts. The experts might include individuals with regulatory experience.

Expert	Affiliation
Dominique Ngan-Tillard	Assistant professor Faculty of Civil Engineering and Geosciences Department of Geotechnology Geo-engineering section (TU Delft - NL)
André Vervoort	Professor at the Department of Civil and Mining Engineering of the Katholieke Universiteit Leuven (Belgium)
Ton Wildenborg	Senior Researcher, TNO Built Environment and Geosciences (NL)
Janos Urai	Professor, RWTH Aachen University
Toon Leijnse	Private consultant

1 Introduction

The safety of deep underground repositories for radioactive waste is commonly addressed by studying many ‘scenarios’ that describe various potential future evolutions of the repository system. This report deals with the so-called ‘abandonment scenario’, a scenario in which it is assumed that a deep underground waste repository is abandoned without proper closure.

In the present PAMINA WP 2.2.C expert judgment is used to evaluate the possible consequences of the abandonment of a geological repository without proper closure. Expert judgement is a valuable tool in this respect since experiments and/or measurements, although these may be theoretically possible, are not feasible in practice for many reasons. Such experiments are ´out of scale´ financially, morally, or physically in terms of time, energy, or distance.

The protocol for the expert judgement (also addressed as expert elicitation) is taken from the *Procedures guide for structured expert judgment* [1].

This work is performed in the framework of the PAMINA Integrated Project and is part of the EC sixth Framework Program. The project is a ‘shared cost project’, i.e. the contributions of each partner to the project are financed partly by the EC and partly by the partner or a third party. This contribution to PAMINA was financed by the EC and counter-financed by the Dutch government. For the PAMINA project the added value of the work is mainly found in the test of the formal expert elicitation procedure for scenario development and the lessons learned on procedural level, while for the Dutch research program ([2]) the experts’ findings with respect to the abandonment scenario (the ‘technical findings’) are also of interest.

2 Background of the Abandonment Scenario

Radioactive waste originates in various industrial processes, such as the medical industry and nuclear power plants. Management and disposal of this type of waste requires specific precautions due to its potentially dangerous nature. Most radioactive waste worldwide is temporarily stored in interim facilities, since solutions for high-level waste are still in an experimental stage. Several disposal concepts exist, among which underground disposal, for which extensive research has been performed. A small number of deep underground disposal facilities are presently in operation or have been operated: These facilities only accept low level and some intermediate level wastes. The high level wastes (spent fuel and vitrified high level waste) are presently kept in interim storage facilities.

The deep geological repository concept involves the encapsulation of spent nuclear fuel and high-level wastes in long-lived engineered casks which are then placed and sealed within excavated rooms in a naturally occurring geological formation at a design depth of 200 to 1000 metres below ground surface. It involves the construction of vaults within stable, low permeability bedrock using conventional mining methods. The bedrock and other engineered barriers would provide a high level of long-term safety.

Many countries, such as Belgium, Canada, Finland, France, Germany, Sweden, Switzerland, the United Kingdom and the United States have performed detailed studies, or characterizations, drilling numerous boreholes and exploratory shafts and ramps in underground research laboratories. All these data will be useful in determining the predicted safety performance of future nuclear waste repository sites.

Common elements of potential repository systems include the radioactive waste, the containers enclosing the waste, the tunnels housing the containers, and the geologic makeup, or type of rock, of the surrounding area. Some countries are developing their own repository systems; others are working in collaboration with other nations to develop shared technologies.

2.1 Long Term Safety

Long-term safety studies provide estimates of potential dose rates and the associated risks as a consequence of radioactive material that might escape from the repository. For most repository designs there is a non-negligible probability that a small amount of radioactive material will be able to escape from the waste container, move through the remains of the underground facility, and enter a deep aquifer. Eventually some of this material may reach the surface groundwater and enter the food chain. If the radioactive material is ingested by humans, the radiation from the radioactive material may potentially cause a biological effect and health damage. This is quantified by the effective dose rate. For a properly designed repository, the long term safety studies show that this effective dose rate is orders of magnitude smaller then the normal (unavoidable) background dose rate resulting from natural background radiation. The dose rates and risks reported in safety studies are within legal limits and are considered to be safe.

The exposure pathway described above is schematically shown in Figure 1.

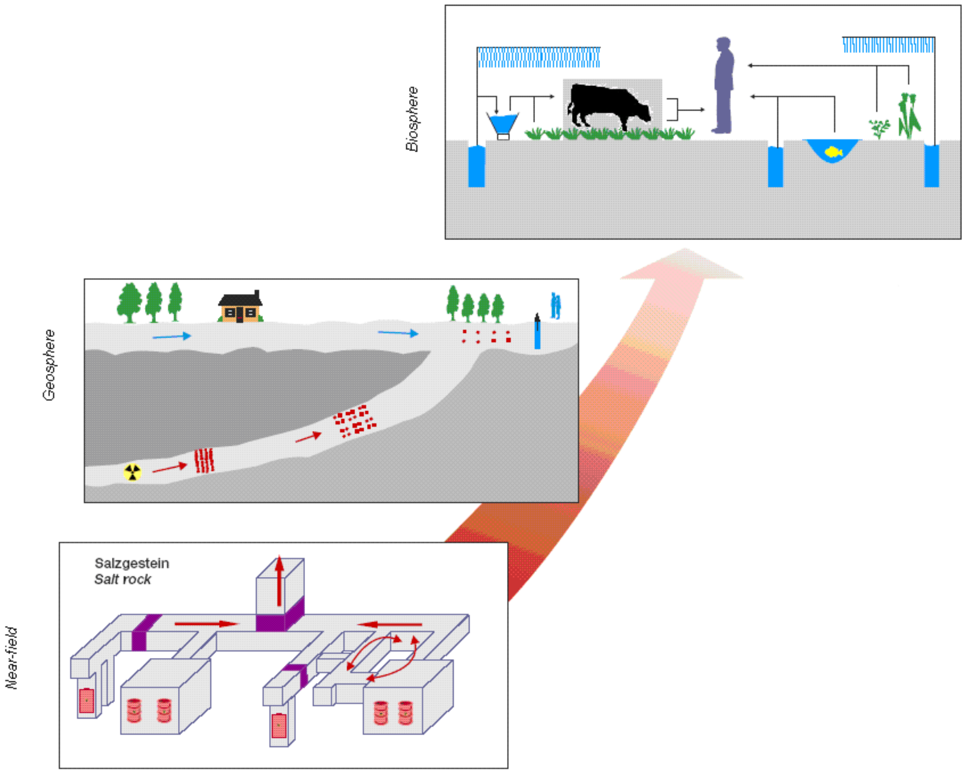

Figure 1 Schematic drawing of different parts of a repository system and the potential exposure pathway. Source: GRS

The repository system contains a sequence of engineered barriers: the first engineered barrier that prevents the waste from escaping is the waste form itself. Long-lived radioactive waste is typically 'immobilised' (stabilized) with cement or glass. Spent fuel is already immobilised; it consists of a stable uranium matrix surrounded by a metal shell (the cladding). The second barrier keeping waste inside the repository is the waste container, typically made of cement, concrete, steel, or copper. The next barrier is formed by the backfill and buffer materials, which seal the disposal cells and galleries and provide both a physical and chemical barrier against transport of the waste products. The last engineered barriers are the plugs emplaced in the access tunnels to block any potential movement of water through the disposal cells and galleries.

The waste that leaks out when the engineered barriers have degraded faces a second set of barriers, the natural barriers. The first is the geological formation in which the repository is built. This is a very stable rock, such as old clay, salt and granite formations. These rock formations retain the waste for many thousands of years, so that almost all radionuclides decay within this period of time resulting in considerable decrease of radioactivity. Moreover, clay and salt are plastic, 'self-healing' rocks, which means that any cracks or open spaces around the waste are closed through the high pressure at repository depth. As a result, in the course of time, complete isolation of the waste is obtained. The next natural barriers, the rock cover and the biosphere, ensure further retention and dispersion of released radionuclides.

2.2 Scenarios

Scenario development is the identification, broad description, and selection of alternative futures relevant to a reliable assessment of radioactive waste repository safety. Scenarios are primarily seen as a method of dealing with uncertainty about the possible future evolution of the repository. A single scenario specifies one possible set of events and processes and provides a broad-brush description of their characteristics and sequencing. The range of the uncertainty about the future evolution of the repository is expressed in a set of different scenarios. Some scenarios of this set are described below.

The sequence of events described in the previous section is normally referred to as the 'normal evolution scenario'. Safety studies also address the effect of unlikely events that can disturb the future evolution of the repository. Most of these events do not change the evolution of the repository to the extent that results obtained for the normal evolution scenario are not applicable. In other words, most of these unlikely events are actually covered by the description of the normal evolution scenario.

However, some events are judged to disturb the evolution of the repository significantly. In safety studies these are addressed by 'altered evolution scenarios'. Examples of 'altered evolution scenarios' are:

- Brine intrusion scenario for a repository in rocksalt: groundwater penetrates into the repository as a result of, for example, unexpected fracturing or an undetected water-permeable inclusion in the rock salt. Radionuclides and salt dissolve in this water. Subsequently, convergence of the disposal chambers in the salt can force the brine, contaminated with radionuclides, out of the salt formation into the groundwater. The radionuclides then may enter the biosphere via the groundwater.
- Poor sealing scenario for a repository in clay: This scenario treats the unlikely case where at least one disposal gallery and an access shaft have been poorly sealed during closure of the facility.
- Human intrusion scenarios: Various forms of mining engineering activities (exploratory drilling, construction of a mine) may bring future generations into involuntary contact with the waste.

The subject of the present study is the so-called “abandonment” scenario, which is described in the following section.

2.3 Description of the scenario that is the subject of this expert judgement exercise

From a safety perspective it is required that the repository is fail-safe during all steps of the disposal process, including the operational phase, the closure phase, and the post-closure phase. This means that even in case of abandonment of the repository without proper closure, the waste must not become a threat to our environment.

Given that a repository will be in operation for about 50 to 100 years, events of concern are:

- Economic distortion
- War, national disaster
- Mining disaster

These events could lead to abandonment of the repository without proper closure. This event was considered in a few desk studies (e.g. [2]), where it was assumed that abandonment would lead to the following chain of events:

1) Flooding of unsealed galleries
2) Soluble parts of the waste dissolve in the water
3) Advective flow and diffusion through the remains of the underground infrastructure
4) Radioactive material reaches aquifer and biosphere
5) Exposure of humans to radioactive material

These desk studies have shown that the impact of this scenario is very similar to the ‘brine intrusion scenario’ and the ‘poor sealing scenario’ mentioned in the previous section. However, in these scoping analyses not much attention was given to the credibility of the assumed sequence of events, and it has not been attempted to obtain further insights from mining technology and (hydro-) geology that are relevant to the scenario.

The objective of the present expert judgement exercise is to obtain a credible description of the abandonment scenario, to obtain one or more representative timelines of events that can serve as a basis for the dose calculations, to obtain a description of the water flows into and out of the facility, and to obtain quantitative information about the groundwater movements through the facility and the exchange of water with the aquifer system.

3 Elicitation Procedure

The staring point for the protocol is taken from the *Procedures guide for structured expert judgment* [1]. This protocol consists of 15 steps, as shown in Table 1. Although this protocol originally is focused on obtaining quantitative values for uncertainty bandwidths, it is also useful for obtaining the more qualitative information needed for the scenario conceptualisation.

Table 1 Protocol for expert elicitation

Step	Description	Comment
1	Definition of case structure	The case structure provides the frame for the panel of experts specifying all issues taken into consideration.
2	Identification of target variables	All model parameters to be assessed by experts are identified and listed. A formal procedure will be used to select the most important ones for expert elicitation.
3	Identification of query variables	The target variables as defined under step 2 may not be appropriate for direct elicitation. The questions must be formulated consistent with the way in which an expert represents the relevant information in his/her knowledge base.
4	Identification of performance variables	Performance variables are supported with evidence unknown to the experts.
5	Identification of experts	An expert is regarded by others as being knowledgeable about the subject.
6	Selection of experts	The selection of experts may take place through a formal procedure with a selection (or nomination) committee, or by the project staff.
7	Definition of elicitation document	This document contains the following information: - exact description of the questions - necessary explanation of each question - additional remarks on what is to be included or excluded - the format in which the assessments need be provided by the experts.
8	Dry run exercise	One or two persons (not the selected experts) experienced in the field of interest should be asked to provide comments on the case structure and the elicitation document.

Step	Description	Comment
9	Expert training session	The experts may need to be trained in understanding the issues and in providing the answered in the requested format.
10	Expert elicitation session	Each expert is interviewed individually. In such sessions a 'substantive' expert, who is experienced in the expert's field of interest, is present as well.
11	Combination of expert assessments	The results will be treated anonymously. The responses of the experts must be combined in a way that agreement between the responses and conflicts or discrepancies can be identified.
12	Discrepancy and robustness analysis	Discrepancies in the responses must be reviewed in order to find the reason for the discrepancy.
13	Feed back	The results will be treated anonymously, and the experts name will only be used in passages such as the composition of the panel, if the experts agree. Each expert must have access to his/her assessment and to the way the responses have been combined.
14	Post-processing analyses	The aggregated results need to be post-processed if the target variable differs from the query variable.
15	Documentation	All relevant information and data, to be presented to the PA-community and to the experts, will be documented in a formal report.

In the procedure, various roles can be distinguished:

Elicitors: the persons that guide the elication process, decide on how the steps in the scheme above have to be performed (Jacques Grupa - NRG, Benno Haverkate - NRG)

Substantive-experts: the persons that decide what the target variables are, and prepare the elicitation document (PA team of NRG)

Normative experts: if the aim is to develop statistical distributions, the normative experts will perform the statistical operations to obtain these from the expert's responses (none)

Experts: the persons that have been selected to provide the expert judgements (see Section 4.4).

The steps in Table 1 have been dealt with as follows:

a) Steps 1, 2, 3 and 7 are treated in the next chapter.

b) Step 5 (expert identification) has been performed by the elicitors by using work contacts who provided lists of potential experts. These potential experts have been contacted and asked if they were interested in cooperating in this project and if they knew other potential experts.

c) Step 6 (expert nomination) was done by the elicitators. There was no formal nomination procedure or a nomination committee. The nomination was based on the recommendation that identified the expert (in step 5) and on the field of expertise of the expert. The following fields of expertise are considered relevant: (1) mining engineering, (2) general geology, and (3) hydrogeology. Also knowledge of potential host rocks (but limited to clay or rock salt) is required. Once the panel of nominated experts covered these fields of expertise, the nomination procedure was stopped.

d) Step 8 (dry run) was performed by a panel of Substantive experts. As a result of this session the questions in the draft elicitation document have been changed substantially. For the final version, a complete dry run has not been performed, although the questions have been reviewed by the panel of Substantive experts.

e) Step 9 (expert training) was skipped, partly due to budget and time constraints, but also because this training in the original scheme mainly consisted of a training in statistical techniques to express numerical uncertainties, which was not an issue in this exercise.

f) Step 10, the expert elicitation session, was formally not effectuated. Due to limited resources, no substantive expert was present during the ‘elicitation session’. Instead, the experts have been sent the elicitation document by e-mail. The result of step 10 is found in Appendix A of this document

g) Step 11 and 12 were performed by drafting this document.

h) Step 13 was performed by giving the experts the opportunity to comment and correct the draft of this document

i) The present document is the result of step 15.

4 Summary of the Expert Elicitation Method for the Abandonment Scenario

4.1 Identification of the target variables

The initial list of target variables that needed further explanation and judgment by the experts has been identified as follows:

- Generic description of the expected sequence of events
- Probabilities and timeline(s) of the events
- Identification of groundwater flow pathways between the (remains of the) repository and the aquifer
- Best estimates and upper and lower boundaries for the time it takes until the abandoned repository is flooded.
- Best estimates and upper and lower boundaries of water flow rates during and after the flooding.

Note that the experts have been interviewed through explicit questions that will be listed in the next sections

4.2 Identification of query variables

The target variables as defined under step 2 may not be appropriate for direct elicitation. The questions must be formulated consistent with the way in which an expert represents the relevant information in his/her knowledge base.

To provide a framework for the questions and the answers in the 'elicitation document', a reference design of the repository and the local geology has been adopted. This reference design is based on reference designs used in previous EC projects. Actually it turned out that the EC PAGIS project [3] contained descriptions of the reference designs that were expected to be suitable for the experts.

In the initial draft of the elicitation document the query variables were almost directly related to the target variables. During the dry run session with the Substantive-experts (i.e. the experts that were involved in developing the elicitation document, which consisted of the NRG PA-team) a question strategy was developed:

- The experts should not have to reproduce knowledge that is already known to the substantive-experts. So questions like "How does xxx depend on yyy?" were replaced by "Do you agree that xxx depends on yyy as follows: (...)?"
- The experts don't have to perform calculations if they can provide sufficient information for the substantive-experts to do the calculations. So questions like "How long does it take for xxx to move from yyy to zzz?" were replaced by "Which processes and phenomena determine the speed at which xxx can move?".

In a few iterations the questions evolved into their final shape as indicated in Table 2.

Table 2 List of questions for elicitation

Question 1	Which events or processes could lead to a situation where a flooded underground disposal facility (flooded due to e.g. abandonment or a mining accident) cannot be recovered?
Question 2	Do you think that the broad description of the abandonment scenario given in Section 2.5 (summarised below* in the paragraph 'background') is correct?
Question 3	Which processes can lead to flooding of the facility after abandonment of the facility?
Question 4	Which processes and mechanisms control the future evolution of flooded galleries?
Question 5	Which are the main potential pathways to the biosphere for radioactive contaminants that may escape from the sealed waste package?

* In the elicitation document each question is accompanied by some text providing the background for the question. The full elicitation document is included in Appendix A.

Scenario development is an important issue in PA, see e.g. the review in PAMINA D1.1.1 [4]. In Section 4 of Part 2 of D1.1.1 the following is stated:

*The procedure (*of scenario development*) itself has also some components, which are widely used in the respective methodologies. These components are:*

- *Collection of FEPs*[1]
- *Screening of FEPs*

---

[1] FEP = Features, Events and Processes, which are commonly recorded in a FEP catalogue

- *Combination of FEPs to scenarios or grouping of phenomenological situations based on repository evolution towards a normal evolution scenario (in that case, checking of results to FEPs database)*
- *Grouping of scenarios to representative scenarios*

Although this seems a logical sequence of steps to develop scenarios, in practise the process of developing scenarios is iterative. E.g. screening of the FEPs requires some knowledge of the central evolution scenario, and will also depend on identified altered evolution scenarios.

One of the objectives of the work done by the experts is that, based on their responses, additional or refined FEPs will be established and recorded in the FEP catalogues. The various FEP screening procedures applied for scenario development should identify the relevance of these FEPs and initiate additions to the PA-models. This is actually a more formal approach to what is described above as “The experts don’t have to do calculations if they can provide sufficient information for the Substantive-experts to do the calculations.”

4.3 Identification of performance variables

In [1] ‘performance variables’ are introduced to give a statistical weight to the probability functions provided by the experts and to resolve conflicts. The values that have to be attributed to the performance variables are supported with evidence unknown to the experts. In one example the experts were asked to estimate the outcome of an empirical study that was at that time not finished, i.e. the actual results would be published in a few years time.

The background of this ingredient of expert elicitation is found in the application of expert judgement to obtain statistical distribution functions. It was observed that the aggregated confidence bandwidth of the elicited parameter grows with the number of experts in the panel. An important ingredient of the growth is that some experts provide distributions that conflict with the data provided by other experts. In larger expert panels these conflicts occur more often. A consequence of such conflict is that the aggregated distribution is much broader than any of the distributions provided by the individual experts.

The assumption is that if two experts provide conflicting data, one of them is wrong. Performance variables will enable the elicitator to identify the better expert, and the data provided by the ‘lesser’ expert will be given less weight. In effect, the bandwidth of the aggregated results will decrease using this procedure. If there are more than two experts, the procedure can be subtler. Nevertheless, the application of this procedure is still under discussion. Moreover, it is very difficult to find relevant performance variables.

The main difference with the present study is that the statistical distributions obtained with the formal expert judgement in practice are used blindly by the substantive experts. For the present study concerning scenario development, it was already pointed out that the information obtained from the experts can be recorded in a FEP database. In contrast with statistical distributions, FEPs are not applied blindly by substantive experts. The importance of the FEPs for scenarios will be screened and evaluated at various steps in the analysis schemes. This requires knowledgeable application of the FEPs.

The conclusion is that for this study no performance variables are needed.

4.4 Experts Required for the Elicitation Process

As already explained, step 5 (expert identification - see Table 1) has been performed by the elicitors by using work contacts who provided lists of potential experts. These potential experts have been contacted and asked if they were interested in cooperating in this project and if they knew other potential experts. Step 6 (expert nomination) was done by the elicitators. There was no formal nomination procedure or a nomination committee. The nomination was based on the recommendation that identified the expert (in step 5) and on the field of expertise of the expert.

Table 3 shows the fields of expertise that are relevant and their relation to the target variables.

Table 3 Relation in broad lines between the target variables and the expertise required

Target variable*	**Mining engineering**	**General geology**	**Hydro-geology**
Generic description of the expected sequence of events	x	x	
Probabilities and timeline(s) of the events	x	x	
Identification of groundwater flow pathways between the (remains of the) repository and the aquifer		x	x
Best estimates and upper and lower boundaries for the time it takes until the abandoned repository is flooded.	x		x
Best estimates and upper and lower boundaries of ground water flow rates during and after the flooding.	x		x

*Additionally different potential host rock types have been considered; here it is restricted to clay and rock salt.

Table 4 Nominated expert and their expertise

Expert	Affiliation	Expertise	*)
Dominique Ngan-Tillard	Assistant professor Faculty of Civil Engineering and Geosciences Department of Geotechnology Geo-engineering section (TU Delft - NL)	Integration of geo-engineering information, such as geological, geophysical and geotechnical data Degradation of geomaterials	(1),2
André Vervoort	Professor at the Department of Civil and Mining Engineering of the Katholieke Universiteit Leuven (Belgium)	Technical evaluation of future or current mining or civil engineering projects, ore reserve estimations and environmental problems, but also general technical expertise.	1
Ton Wildenborg	Senior Researcher, TNO Built Environment and Geosciences (NL)	Research on (radioactive) waste disposal and geological risk assessment	2,(3)
Janos Urai	Professor, RWTH Aachen University	Structural Geology-Tectonics-Geomechanics	2
Toon Leijnse	Private consultant	Soil Physics, Ecohydrology and Groundwater Management	3

*) 1: Mining engineering; 2: General geology; 3: Hydro-geology

4.5 Expert Elicitation

Following the elicitation procedure described in Table 1 in Section 3, the experts would be involved in step 9 (Expert training), step 10 (Expert elicitation) and Step 13 (Feed back).

Step 9 (expert training) was skipped, partly due to budget and time constraints, but also because this training in the original scheme mainly consisted of a training in statistical techniques to express numerical uncertainties, which was not an issue in this present exercise.

For step 10 the elicitators developed the elicitation document, which is included in Appendix A. This has been sent by mail to the experts, and the experts returned the answers. The answers are included in Appendix A.

Step 13 (Feed Back) was performed by giving the experts the opportunity to comment and correct the draft of this document.

5 Results and Analyses

In this chapter the results of the expert judgement exercise are presented. First a summary of the responses is given. In addition, Section 5.2 gives a list of system modifications that the experts have suggested to improve the disposal system design. In Section 5.3 the answers provided by the experts plus their argumentation are analysed in more detail to obtain answers to the target variables defined in 4.1.

5.1 Aggregated responses

The following tables show for each question the aggregated responses of the five experts, here anonymously represented as numbers 1 to 5. In some cases the complete answers were too comprehensive to be contained in a table without loosing the overview. These answers have been shortened. The complete answers to the questionnaire can be found in Appendix A.

Q1	***Which events or processes could lead to a situation where a flooded underground disposal facility (flooded due to e.g. abandonment or a mining accident) cannot be recovered?***
1	1) Flooding of water by failure of shaft lining, due to e.g. poor maintenance, combined with insufficient pumping capacity, poor maintenance of pumping equipment and/or insufficient means, expertise or interest to re-open. 2) Flooding of water and soil or rock material by failure of shaft lining, resulting in a difficult situation to re-open (stopping the flow, pumping the water away and excavating the loose material) I foresee a bigger problem, if the failure is due to poor maintenance of the shaft infrastructure. In such a situation, there is a chance that also the maintenance of e.g. the underground pumps is poorly done. Or in other words, if the underground facility and shaft infrastructure is not maintained, as it should during the disposal and closure phase, the underground facility can be flooded and if there is a lack of funding, expertise or interest this could lead to a complete abandonment.
2	The control of a partially flooded facility depends on the flooding rate and sequence of flooding.
3	Assuming that there is an institutional system for control and recovery in place the conclusion is that temporary situations of no exertion of control can exist due to a number of causes: Internal:

	o Defect in the shaft short-circuiting the shallower aquifers with the disposal horizon o Accident with waste containers leading to contamination in the access tunnels or in the galleries so that workers have to leave the area o Defect with the pumps External: o Flooding with seawater o Flooding with river water A combination of internal and external causes No situations have been identified that could lead to long periods of flooding with a duration of decades or more.
4	Only catastrophic events such as earthquakes or volcanic activity could lead to a situation where the disposed material cannot be recovered
5	If the facility is insufficiently characterized and validated, flooding may lead to large deformations and changes in geometry which in turn can create pathways to an aquifer that allow groundwater fluxes so large that are uncontrollable using present day technology, within the 100 years to be addressed here.

Q 2	***Do you think that the broad description of the abandonment scenario given (summarised below* in the paragraph 'background') is correct?***
1	Looking at the chain of the 6 events described in the Background, I have no direct criticism or remark on the succession of these events. However, I would like to formulate some comments on event N° 4, being Advective flow and diffusion through the remains of the underground infrastructure. (...)
2	The proposed description of the abandonment scenario is realistic but incomplete. One should also research the possibility of steam formation due to the high temperature gradient around the canisters, upward turbulent steam flow and mixing with the atmosphere.
3	The description of the abandonment scenario in Section 2.5 of the elicitation document is largely correct provided that the causes of flooding are specified and the relevant mine compartments which can be flooded, is completed.
4	Yes, under the given assumptions, the description of the abandonment scenario as given is correct.
5	The scenario is correct but incomplete. Possible additional processes such as the generation of a gas phase around the waste canisters and the creation of lithostatic fluid pressures must be included in the model scenarios.

* In the elicitation document each question is accompanied by some text providing the background for the question.

Q 3	***Which processes can lead to flooding of the facility after abandonment of the facility?***
1	This is a more difficult question to answer in a generic way, as it depends on a specific location and on a specific design and working procedure. E.g. presence of aquifer and way of backfilling the galleries (retreating the support, backfilling by sand or by clay, different compartments within the underground facility, etc). The failure of the lining at the intersection with the aquifers remains the critical or weakest link.
2	Flooding of the facility can occur either by: 1. accidental ground water leakage through the shaft supported by a concrete lining in the permeable (sand) layers above the repository 2. ground water leakage through an unexpected fault in the clay layer which is connected to aquifers and through the concrete lining and the backfilling of the disposal galleries 3. connection between the upper aquifer and the facility via an exploration borehole not well sealed

	4. mining activities/ underground storage (in salt) interfering with the repository 5. fault reactivation in permeable layers under the repository and fault propagation to the repository and above induced by human activities (CO2 sequestration, geothermal activity) 6. sea water ingress via the shaft in case of rupture of sea water defences during a large storm event or 7. meteorological precipitations ingress via the shaft under current or future extreme climatic conditions. Considering the current annual precipitations and the volume of the facility, flooding by ingress of meteorological water into the shaft will be slow and controllable.
3	Several internal or external causes (see also answers to Questions 1 and 2) could lead to the flooding of the repository: - Flooding by seawater if access to repository is at or below sea level - Sabotage/destruction of the mine shafts and pumps - Flooding by a river if repository access is in floodplain - Lake discharging in the repository - Failure of shaft isolation in shallow aquifer zone - Technical pump failure - Leakage along fractures/fault in clay repository - Leakage along anhydrite layer in rock salt
4	Flooding of the facility could be caused by leakage of the seals, dissolution of salt seams in rock salt, cracks or fractures developing due to mechanical failure of the formation in combination with pressure gradients.
5	In this answer I consider only the 100 year timescale and not discuss longer term geologic processes. The processes form a continuum with those during operation, but now there is no new galleries and boreholes created but time available is longer.

Q4	***Which processes and mechanisms control the future evolution of flooded galleries?***
1	I limit my answer to the reference design in clay. So, in general, I would conclude that even after flooding there will not be major collapses of the lining. In other words, in my opinion one should consider the case during 100's or 1000's of years that the access tunnels remain open. In case, that there would be a large collapse, I am not convinced that the tunnel will close quickly due to plastic deformation; or in other words, that one can calculate transport phenomena with the clay characteristics instead of these of open paths.
2	Micro-biological, thermal, hydraulic, mechanical and chemical processes and their interactions control the future evolution of the flooded repository. The following issues are not problematic - Flooding of a repository in a swelling clay. The addition of water accelerates sealing, swelling pressures increasing the plastic deformation of the clay.
3	When the repository is flooded, fluid migration in the salt repository is influenced by the dissolution of rock salt in the under saturated water and the heat production by the HLW, which results in density changes of the fluid. Furthermore, if water would permeate the salt, its mechanical properties would change. Due to sustained convergence of the access tunnels and the shafts fluids would be expelled from the mining area and fluid pockets might get enclosed in the rock salt. If the disposal boreholes are under pressured with respect to the water filled drifts and tunnels and the seal would have some defects, fluids might migrate into the disposal bore hole and mobilize part of the dissolvable radioactive material, which subsequently could be expelled due to ongoing convergence of the borehole. As a consequence contaminated fluids could migrate from the boreholes to the drifts and tunnels.
4	The future evolution will be controlled by the mechanical properties and processes of the host rock and of the seals of the disposal cells.
5	The combined processes of deformation, fluid flow, reactions and dissolution will be all present. The stated assumptions consider a hydrostatic fluid pressure regime. Prediction of these processes and their consequences will be much improved if the design is based on state of the art characterization of the underground structure, material properties.

Q5	***Which are the main potential pathways to the biosphere for radioactive contaminants that may escape from the sealed waste package?***
1	As I consider the weakest link and the most probable cause of flooding (see answers on previous questions and in particular on Question 1), the failure of the shaft lining at the intersection with the aquifers, it is logic that I consider this location as the blind spot. Geological faults could, I assume, occur, but first it will be location dependent and second I don't feel knowledgeable enough to comment on these aspects of structural geology.
2	Main concern is steam production and fast migration to the atmosphere, convection through the structure and slow flow through confining layers.
3	The shortest most direct pathway in the salt repository is via the drift, tunnels to the shaft and surface water or soil. The other pathway might be through the drift, tunnels, shaft and via a defect in the shaft mantle to the shallow aquifer. A less probable pathway might be via an anhydrite layer, which is in contact with the mine drift, tunnel or shaft, to the shallow aquifer.
4	The main potential migration pathway to the biosphere is through advection and diffusion in the shaft that connects the facility directly to the biosphere, or by advection and diffusion in the water in the different geological formations.
5	At the 100 years time scale considered here the most likely transport of radioactive contaminants is via advective flow of groundwater. Transfer of the radionuclides from the "salt dome" volume to the "overburden" volume can occur via the access shaft – gallery system or via a dissolution channel to a previously unknown aquifer which was created by the flooding event.

5.2 Proposed System improvements

The experts have been encouraged to make suggestions (at any point in the answers) that can result in improvement of the design of the repository and/or the selection of the site where a repository may be built.

The following suggestions have been made (citations):

1) "Another relevant question would be: "Can one design the shaft in such a way, that failure or leakage will never occur?" The answer is probably no; there is always the possibility that it will occur, certainly concerning leakage. But probably once leakage occurs over a long time period, a proper failure will happen too."
2) "I am convinced that if state of the art methods and the best available characterization is used during site selection (a suitable site may not be present in the Netherlands), design and construction, based on open discussion that leads to acceptance of the design by the scientific and engineering community, the occurrence of unrecoverable flooding can be made so unlikely that the risk is acceptable for the community."

5.3 Analyses of the responses of the experts

Here we discuss the results from the perspective of the target variables as given in Section 4.1.

5.3.1 Generic description of the expected sequence of events

As discussed earlier, it was decided to present the experts a description of the scenario and ask them for confirmation or disapproval. In this way it is avoided that the experts have to go through the whole sequence of scenario development (such as starting with normal evolution scenarios, etc.), which has already been done in various PA studies. Moreover, defining a hypothetical scenario and then testing it by means of FEPs, or, as in this exercise, by experts, is a valid approach in scenario development.

The scenario that has been proposed to the experts consists of six steps:

1) Abandonment of the facility
2) Flooding of unsealed galleries
3) Soluble parts of the waste dissolve in the water
4) Advective flow and diffusion through the remains of the underground infrastructure
5) Radioactive material reaches aquifer and biosphere
6) Exposure of humans to radioactive material

All experts accept this generic description in broad lines. However, various remarks were made:

- One can indeed design an underground facility to be operated for 50 to 100 years. However, such a facility will only remain safe and operational when one does the necessary maintenance over the entire time period.
- The effects of local high temperatures (heat generating wastes) and temperature gradients have to be considered.
- If small amounts of water enter a high temperature area (near the canisters), and if the temperature is above the boiling point, the pressure may rise due to steam generation. The background is, that due to the seal of the disposal cell, it will take some time before the water reaches the hydrostatic pressure level.
- The scenario is correct but incomplete:
  - Add between 2 and 3: “Creation of dissolution cavities and associated deformation”
  - Add ‘thermal convection’ to 4
  - Add between 4 and 5: “Deformation of the subsurface, with possible changes in permeability.” and “Creation of cells with different pressure regimes and fluid contents. Reactive transport processes.”
- Special attention should be given to (accidental) human intrusion (such as exploration drillings) in this scenario.

5.3.2 Probabilities and timeline(s) of the events

As discussed before, probabilities and timelines can be determined in a PA study if the experts have identified the relevant processes and events. However, some of the experts argued that the reference case description (Appendix A) contains an amount of uncertainty, which is fully unacceptable for such a reference case, i.e. also formations not suitable to host a facility comply with the information provided. Therefore, the prerequisites that the experts have used are: (1) that state of the art methods and the best available characterization is used during site selection and: (2) that acceptance of the disposal plan is based on open discussions (assuming that these will lead to design improvements and acceptance).

Abandonment of the facility

The overall probability of an uncontrolled flooding event has been discussed in the answers to Q1. It is pointed out that attempts to recover the mine are likely to be successful (some experts claim that such attempt will be successful), so there must be an external reason for not attempting to recover the facility. This event is termed ‘loss of institutional control’. It is difficult to determine a probability for this, and it could be argued whether a numerical value is useful. Under circumstances the event of 'loss of institutional control' can be considered safety relevant.

In D3.1.1 [5] a scenario related to the development of a society is classified as stylized scenario. The reason for separating stylized scenarios from the common normal evolution and altered evolution is that there is little consensus on the role of stylized scenarios in a safety case, and national authorities have different views on how to deal with stylized scenarios. Sometimes a stylized scenario is regarded as one of the altered evolution scenarios; in other cases the same scenario is considered a special case.

Flooding of unsealed galleries

A generic estimate for the rate at which a facility would be flooded after abandonment is not provided, since this depends on site specific and technical issues (e.g. method used for lining the shafts, the type of aquifers that the shafts cross). However, most experts point out that a combination of abandonment and shaft failure can occur, leading to fast flooding of the facility in weeks to months.

For rock salt, it was pointed out that salt domes are complex, 3D structures consisting of severely deformed layers of various evaporites - according to some experts, the list given in the reference case is incomplete. Shafts and galleries have to penetrate these to connect to the volumes of sufficiently homogeneous (halite) rock salt where the waste can be disposed. At these contacts with the non-halite salts, dilatant deformation, dissolution channels and connections of permeable inclusions can develop. For a well designed facility the consequences of these processes may be marginal, but adequate characterization is required: modern high resolution 3D seismic techniques, several boreholes which are extensively studied, numerical simulation of the geologic evolution of the salt body will result in an accurate characterization with well constrained uncertainties.

For clay, it was pointed out that the water flooding the disposal facility might have a different chemical composition than the ambient water in the geological formation. For clay this may very well influence both the mechanical as the geochemical properties, and therefore also the adsorption properties and the mechanical properties of the formation.

Soluble parts of the waste dissolve in the water

For this scenario there was no specific need to have the experts look in depth into this item, since this is relevant to almost all scenarios (including the normal evolution). Therefore, the questions suggest that it can be assumed that "disposal cells (galleries or boreholes that contain the waste canisters) are all backfilled and sealed." It was rightfully commented by the experts that an incident could also occur during one or more emplacement operations. One expert noted that the backfilling and the sealing of disposal cells seem to be the weakest points. These will be constructed while the facility is in operation, and are as yet not fully proven to be "fail-safe" for a period of 50 years or more.

Advective flow and diffusion through the remains of the underground infrastructure

This is governed by the processes and mechanisms that control the future evolution of flooded galleries (question 4). The general opinion is that tunnels tend to close because of the swelling of the clay and convergence of openings in rock salt, but on the other had it is pointed out that one should not be too optimistic, by assuming that the tunnels will collapse and seal off due to creep (salt) or plastic deformation (clay).

Thermal convection and gas generation can drive transport through the flooded underground infrastructure and should be taken into account, likewise creation of cells with different pressure regimes and fluid contents, and reactive transport processes.

If the facility is abandoned, differential stresses in the host rock remain, the waste generates heat, and pathways for fluids, which were initially very limited, can become amplified.

Local heterogeneities in the properties of the formations surrounding the facility will play a major role in determining the occurrence of preferential flow paths.

Local mechanical weaknesses in the surrounding formation may cause more of a problem. If these exist, pressure gradients may cause cracks to develop, both in rock salt as in clay.

Radioactive material reaches aquifer and biosphere

The shortest and most direct pathway in the repository is via the drift, tunnels to the shaft and surface water or soil. The other pathway might be through the drift, tunnels, shaft and via a defect in the shaft mantle to the shallow aquifer. A less probable pathway might be via an anhydrite layer (salt) or a geological fault (clay), which is in contact with the mine drift, tunnel or shaft, to a shallow aquifer (through a channel that may be created by the flooding event).

Exposure of humans to radioactive material

Also this step is not unique for the abandonment scenario, so this has not been addressed. Biosphere is also treated in WP1.1 [6].

In conclusion, the information provided by the experts gives sufficient basis for further development of the abandonment scenario. However, a prerequisite to the scenario is a loss of institutional control. There is at this time no consensus on how to treat this in a safety study [5].

If it is decided to deal with the scenario, some variants of the scenario could be developed (e.g. ‘natural flooding’ as a variant and ‘human errors related shaft failure’ as a variant). The different variants may be combined into one main scenario by a probabilistic process. Also uncertainties with respect to the long-term evolution of the underground remains of the repository have to be considered. Although these analyses would require a considerable amount of work for the PA-experts, this is not essentially different from the work done for e.g. the normal evolution scenario.

5.3.3 Identification of groundwater flow pathways between the (remains of the) repository and the aquifer

Since this is also relevant to the ‘probabilities and timelines’ of the events, the issue was already addressed: the shortest and most direct pathway in the salt repository is via the drift, tunnels to the shaft and surface water or soil. The other pathway might be through the drift, tunnels, shaft and via a defect in the shaft mantle to the shallow aquifer. A less probable pathway might be via an anhydrite layer (salt) or a geological fault (clay), which is in contact with the mine drift, tunnel or shaft, to a shallow aquifer.

5.3.4 Best estimates and upper and lower boundaries for the time it takes until the abandoned repository is flooded.

In normal conditions this cannot be determined in a generic way: if the circumstances are unfavourable flooding would take a few years after closure, but if the circumstances are more positive, it could also take decades before the repository will be flooded. Failure of a shaft lining is the most probable cause for a fast flooding of the underground facility. Once this failure has occurred the complete flooding of the underground facility can be very fast, ranging from some hours to some months or even years depending on the flow rate. If the failure is broad, it will be no more than a few hours. In other cases, one is rather talking about leakages of the shaft lining.

5.3.5 Best estimates and upper and lower boundaries of water flow rates during and after the flooding.

The answer to this question depends mainly on the processes and mechanisms that control the future evolution of flooded galleries (question 4). As stated before, the general opinion is that tunnels tend to close because of the swelling of the clay and convergence of openings in rock salt, but on the other had it is pointed out that one should not be too optimistic, by assuming that the tunnels will collapse and seal off due to creep (salt) or plastic deformation (clay).

The answer to this requires additional efforts in the field of hydro-mechanical modelling, which is already being addressed in the work performed for the post closure flooding scenarios (clay: poor sealing; salt: anhydrite vein).

5.4 Feedback from the experts

Feedback from the experts (step 13 of the elicitation procedure) was obtained by giving the experts the opportunity to comment and correct the draft of this document. The responses are presented in Table 5.

Table 5 Feedback from the experts on the draft report

	Feedback from the experts
1	I have read the complete (draft) report and paid special attention to chapter 5. I assume that it is not the intention to comment to the contributions or opinions of the other experts. This may be useful, but should be organised in a structured discussion (a suggestion for future work). I think that Chapter 5 objectively presents, compares and synthesises the various opinions. Therefore I have no comments. I appreciated to have had the opportunity to read the draft report, and recommend maintaining this in future studies.
2	I have read the 30 July draft of the NRG report and found no points that require feedback. I feel our comments are included in a clear manner. The only point that could be made on the general report is that sec. 5.3.2. /Exposure of humans to radioactive material/ is very short and it is unclear if deliberate or unforeseen opening of the facility (terrorism or salt mining activities as respective examples) is covered in this section. The mining option has been mentioned in the answers by experts, but I see no reference in sec. 5.3.2.
3	Overall the draft report well reflects my contribution to the elicitation exercise. Below is a list of some minor comments to the report. ➢ Section 4.1: Looking at the ‘variables’ I think the term ‘Characteristics’ better fits the contents. ➢ Section 4.1: The last two bullet points relate to quantification of the properties. The 5 questions do not or hardly do address the quantification of the scenario properties. So in my view this seems no to be consistent. ➢ Table 3: For future exercises input from rock mechanical/geochemical experts could have added value. ➢ Section 5.3.1: an additional bullet point with an additional event: 'degradation of the

	engineered barrier(s)'. ➢ Section 6.2, 2nd par: 'For the quantitative target…'. As I mentioned before the questions do not reflect a quantitative target. ➢ In various places in the text, the explanation and wording can be improved. Details have been send to the author.
4	I have read the report, I have no comments. It seems to me that the information provided by the experts is correctly summarised and represented.
5	Thank you for the draft report. It is interesting to see the wide range of opinions. I hope that I contributed a little to finding a good solution for our radioactive waste. I find it difficult to provide more feedback because I don't have a clear idea where this process is going. My impression is that this was more an exercise in the process than a serious technical discussion.

If the feedbacks are split into technical feedback and procedural feedback, the following conclusions can be drawn from the feedback provided. For some technical feedback items, a response on behalf of the substantive-experts (the persons that defined the target variables are, and prepared the elicitation document, abbreviated to SE) has been added between brackets.

Technical feedback

- Most experts explicitly state that the information they provided is represented correctly, some do not give a feedback with respect to this issue.
- One experts remarks that the 'target variables' have not been resolved completely: no quantitative results have been obtained. (SE: This observation is correct: after the definition of the target variables it was decided not to elicitate on quantitative aspects. So, to keep consistency the target variables should be modified. However, the inconsistency was maintained to show a 'lesson learned'.)
- Deliberate or unforeseen opening of the facility should be addressed. (SE: In a safety study this is commonly addressed as one of the human intrusion scenarios)
- For future exercises input from rock mechanical/geochemical experts could have added value (SE: the present team of experts covers this expertise, but it is not explicitly listed in the respective table).
- One expert states that a more serious technical discussion is required; this was also stated in the respective response to the elicitation document.

Procedural feedback

- There are no negative comments with respect to the procedural steps where the experts were involved.
- The experts seem to appreciate the opportunity to provide feedback to the report.
- One expert suggests that it will be useful to organise an expert discussion, maybe as part of the feedback)
- It was unclear to the experts how the information provided would be processed.

6 Conclusions

6.1 Information provided by the experts

The description in broad lines of the abandonment scenario was accepted by all experts.

It was pointed out that loss of institutional control is a prerequisite to the scenario. If there is institutional control, an attempt to recover the facility will be undertaken, and it is believed that such an attempt is likely to be successful. In case of ongoing institutional control the abandonment scenario is very unlikely.

Two variants of the scenario can be distinguished.

1) One variant is that the facility will gradually flood because of the normal inflow of water (because the underground pumps are not working). Depending on the local site characteristics and the design of the facility, it can take years or decades for the facility to become completely flooded.
2) In the other variant it is assumed that the shaft lining will fail. In that case the facility can become completely flooded in a very short time, i.e. days to weeks. This scenario is likely if the actual loss of institutional control is preceded by a period of insufficient institutional control during which the maintenance of the facility is poor.

It was also pointed out that if the abandonment is unprepared and occurs during the period in which waste is emplaced in the facility, it is likely that one or more disposal cells with waste canisters are not completely sealed, i.e. they can be in various stages of the sealing operation.

The shortest potential pathway from the underground facility to the biosphere is via the drift, tunnels to the shaft and surface water or soil. Another pathway might be through the drift, tunnels, shaft and via a defect in the shaft mantle to a shallow aquifer.

With respect to the information provided by the experts, it is concluded that the way forward is to include the information in a FEP database. This database is used for systematic approach to scenario development. Updating of the FEP database was not foreseen in the PAMINA project.

Inclusion of the information provided by the experts will also lead to a more serious technical treatment of the issues brought up by the experts.

6.2 Elicitation procedure

The elicitation procedure developed for obtaining statistical distributions for quantitative target variables through expert judgement is also useful for qualitative target variables, as has been demonstrated in this trial.

For the quantitative target variables the steps to aggregate the results of the experts are straightforward (although this can be mathematically complicated). For qualitative target variables, aggregation of the results is less straightforward. Also the experts reported in their feedback that it was unclear what would be done with the information they have provided. During the analyses of the results, the idea came forward to record the responses of the experts in FEPs (it was also recommended by one of the experts). This was not foreseen at the start of this work, and is therefore out of the present scope. For future expert judgement studies for scenario development it is recommended to add to the procedure that the responses of the experts will be recorded in FEPs.

The advantage of using FEPs is that there is no need to measure the performance of the experts (i.e. by using ‘performance variables’) to be able to resolve conflicts in the responses. The information in the FEPs will anyhow be re-evaluated when the FEPs are used in the scenario development approach, and it is expected that at that time it can be decided which expert’s view is most applicable to the scenario(s) under consideration.

It is recommended that for quantitative target variables, a scheme is developed that also ensures that the qualitative argumentations of the experts are available when the results are used. This may be a better approach then weighting the experts view beforehand with a weighting scheme that may not be appropriate to the situation where the quantitative results are eventually used. This is actually one of the main arguments against the application of performance variables.

One of the experts reported in his feedback that it should be considered to give the experts the opportunity to discuss their contributions and opinions. This will probably improve the quality of the individual contributions. However, this could also lead to ‘group thinking’ and/or anchoring. Moreover, if the contributions of the experts are put in FEPs, these will anyhow be reviewed at a later stage.

Acknowledgements

The author likes to thank the experts for there willingness to contribute to this study, and for their patience during the long time it took to develop the elicitation document. Also I want to thank Jan Prij, who has volunteered to help developing the elicitation questions and whose comments have been very useful.

List of tables

List of figures

Appendix A Elicitation document

A.1 Summary

Trial of formal use of expert judgement for scenario conceptualisation

Scenarios are sometimes defined as a way to handle uncertainties that otherwise cannot be narrowed down / quantified. NRG is undertaking a trial of formal use of expert judgement to assess the possibility of improving the basis for conceptualisation of stylized scenarios. This exercise will focus on the “abandonment scenario”. Experts will be interviewed by NRG in a predefined procedure to identify agreements and differences in their judgements for selected scenarios. Agreements might then be used to improve the basis for a given scenario, while differences might be resolved either by widening the uncertainty related to the scenario (to cover different views of the experts), or by iterative steps in the interview procedure of the experts. The experts might include individuals with regulatory experience.

This appendix contains the following information:

- description of the “abandonment scenario” in relation to the safety of a geological repository
- questions
- explanatory notes for each question
- additional remarks on what is to be included or excluded in the answers
- the format in which the answers need be provided by the experts.

A.2 Introduction

The safety of deep underground repositories for radioactive waste is commonly addressed by studying many ‘scenarios’ that describe various potential future evolutions of the repository system. This report deals with the so-called ‘abandonment scenario’, a scenario in which it is assumed that a deep underground waste repository is abandoned before proper closure.

In the present PAMINA WP 2.2.C expert judgment is used to evaluate the possible consequences of the abandonment of a geological repository prior to its proper closure. Expert judgement is a valuable tool in this respect since experiments and/or measurements, although these may be theoretically possible, are not feasible in practice for many reasons. Such experiments are ´out of scale´ financially, morally, or physically in terms of time, energy, distance, etc.

The protocol for the expert judgement (also addressed as expert elicitation) is taken from the *Procedures guide for structured expert judgment*[2]. This protocol consists of 15 steps - this report is actually step 7 in this protocol: 'Definition of elicitation document'. The elicitation document contains the following information:

- background information (reference repository system; scenario description)
- exact description of the questions
- necessary explanation of each question
- additional remarks on what is to be included or excluded
- the format in which the assessments need be provided by the experts.

This is addressed as follows: the next chapter gives general information on geological disposal, safety issues and scenarios; in Chapter A.4 the questions are given; Chapter A.4.6 gives the format in which the experts provide their answers.

[2] R. M. Cooke, L. J. H. Goossens Procedures guide for structured expert judgment EUR 18820 EN

A.3 Description of the case

A.3.1 Introduction

Radioactive waste originates from various industrial processes, such as the pharmaceutical industry and nuclear power plants. Management and disposal of this type of waste requires specific precautions due to its hazardous nature. At the moment, most radioactive waste worldwide is temporarily stored in interim facilities, since concepts for the long-term disposal of high-level waste[3] are still in an experimental stage. Several principal concepts for the long-term disposal of radioactive waste exist, among which the deep underground disposal, for which extensive research has been performed. Only a small number of deep underground disposal and research facilities are presently in operation or have been operated: These facilities are designed only for low level and some intermediate level wastes. All high level wastes are presently retained in interim surface storage facilities.

The present concepts of deep geological repositories of high level waste make use of a multi-barrier-concept: the spent nuclear fuel will be encapsulated in long-living engineered casks, which then will be placed and sealed in excavated chambers in a naturally occurring geological formation. The geological formation that will host the repository consists of a stable, low permeability bedrock at a depth of 200 to 1000 metres below ground surface. The bedrock together with the engineered barriers will provide a high level of long-term safety.

There is a strong consensus among all countries with a large nuclear program that the disposal of high level waste in a suitable deep geological formation has the potential to permanently isolate the nuclear waste, and this option is being studied extensively. Many countries are currently exploring the possibility of a permanent disposal of highly radioactive solid wastes deep underground in purpose built, engineered repositories. Some countries are developing their own repository designs, while others are working in collaboration with other nations to develop shared technologies.

---

[3] High level waste (HLW) is a type of nuclear waste that arises from the use of uranium fuel in a nuclear reactor and nuclear weapons processing. It contains the fission products and transuranic elements generated in the reactor core. HLW accounts for over 95% of the total radioactivity produced in the process of nuclear electricity generation. It is the most dangerous type of nuclear waste.

Most countries producing relevant fractions of their electricity by nuclear energy, such as Belgium, Canada, Finland, France, Germany, Sweden, Switzerland, the United Kingdom and the USA have performed detailed studies on deep geological disposal, including geological surveys of the deep subsurface and exploratory shafts and ramps in underground research laboratories. The information resulting from these studies can be used to determine the evolution and safety performance of future nuclear waste repository concepts.

A.3.2 Geological disposal of nuclear waste

A deep geological disposal facility for high level waste will be located in a mine to be specially built for the disposal. Common elements of potential repository systems include the radioactive waste, the containers enclosing the waste, the disposal cells housing the containers, the physico-chemical properties of the host rock and the geology of the surrounding area.
An artist impression of the general layout of a disposal facility for high level wastes is given in Figure 2.

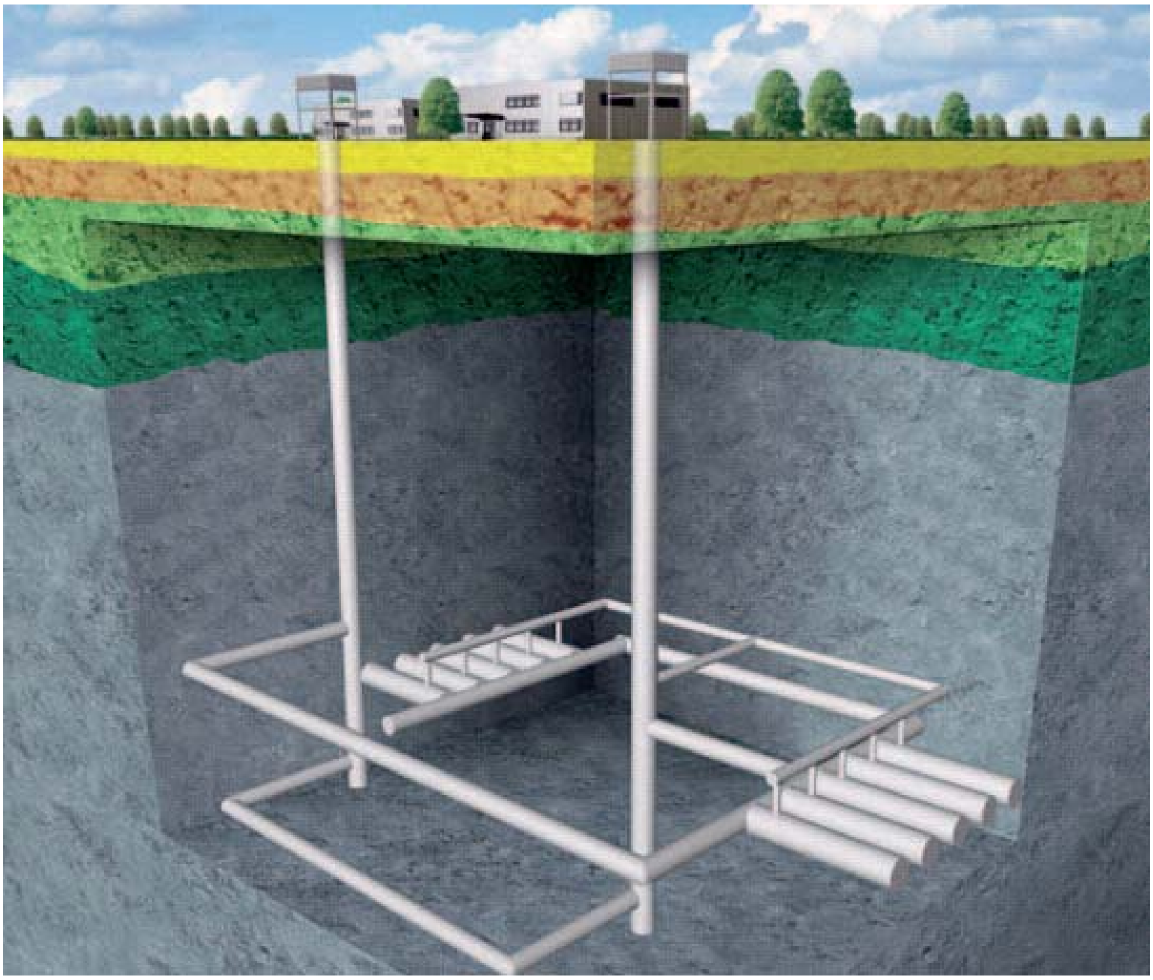

Figure 2 Artist impression of a disposal facility for high level waste (from the brochure of 'Reposafe 2007')

Although the various national designs differ in layout and size, in general three areas can be distinguished in a disposal facility:

1) Disposal cells or disposal galleries: these are, depending on the design, either galleries or boreholes (horizontal and vertical) where the waste canisters are emplaced.
2) Access tunnels: the tunnel-system that give access to the various disposal cells/galleries.
3) Shafts: access to the deep underground infrastructure. Some designs include an access via a spiral ramp.

The geological formations that are suitable for a disposal facility are stable formations that contain very little or no (moving) groundwater, e.g. clay, salt or granite rocks. These formations can retain the waste for many hundred thousands of years, in which the major part of the radioactive material is decayed, resulting in considerable decrease of radioactivity. While granite is a hard and resistant rock, clay and salt are plastic, 'self-healing' materials. This means that any cracks or open spaces around the waste will be closed because of the high rock pressure at repository depth. As a result, in the course of time, complete isolation of the waste is obtained.

With respect to the long-term isolation of the waste, the three major functions of the repository and the host rock are:

1) Limiting the release of radioactive elements and immobilising them in the repository - solubility limits.
2) Delaying and reducing the migration of radioactive elements beyond the repository – adsorption.
3) Preventing water circulation (which can degrade the waste packages and favour the migration of the radioactive material contained therein).

The host rock itself has a very important role in achieving the required long-term isolation.

Rock salt (halite) formations may be a suitable host for disposal, because:

- many deposits of salt can be found in stable geological areas with very little earthquake activity, assuring the stability of a waste repository.
- salt deposits are often found in areas with hydro-geological limited movement of water through the subsurface and thus a slow potential transport of contaminants from the waste to the surface (water, if it had been or were present in the past, would have dissolved the salt).
- salt is relatively easy to mine.
- salt formations will slowly and progressively close open spaces and fractures in mined areas and thus effectively seal the radioactive waste from the environment.

Clay (argillaceous) rocks have the following favourable characteristics:

- large-scale homogeneity,
- no advective flow through the clay due low permeability and osmotic forces,
- Stable geochemical environment,
- self-healing of cracks through plastic deformation,
- strong retention of radionuclide migration by large sorption capacity.

Granite[4] as a host rock incorporates the following suitable characteristics to host a geological repository:

- large and stable granite rock intrusions can be found in all continents,
- permeability is low, if the rock is not exceedingly fissured,
- most fissures and fractures at repository depth are closed by lithostatic pressure, or are filled with highly absorbing minerals,
- granite can be found on locations with very small hydraulic gradients (e.g. in coastal areas),
- granite can be found close to the sea, where the difference in density between saline water and fresh water provides an additional barrier against the migration of radioactive material.

Specific local conditions can make also other geological formations suitable as a repository: e.g. the Yucca Mountain Repository (Nevada, USA) is composed of volcanic material (mostly tuff) ejected from a now extinct large volcano. The proposed repository can be constructed far above the water table.

A.3.3 Long-term safety

Long-term safety studies give estimates of potential risks as a consequence of migration of radionuclides out of the repository under different circumstances. For most repository designs there is a probability that a small amount of radionuclides will be released from the waste container, move through the remains of the underground facility, and reach the overlying aquifer. If some of this material reaches shallow groundwater it may enter the food chain. If the radionuclides get ingested by humans, their radiation can cause biological effects that potentially can harm the human health.
A measure to quantify the hazard of radioactive material is the *effective dose rate*. For a properly designed repository, long-term safety studies show that under normal conditions the expected effective dose rate or other risk are far below the legal limits. When the calculated dose rates are orders of magnitude smaller than the average dose rate every human receives from natural background radiation, a repository concept may considered to be safe. Figure 3 illustrates the potential exposure pathway.

[4] Granite is an important option in many countries. Nevertheless, the present is elicition is limited to rock salt and clay

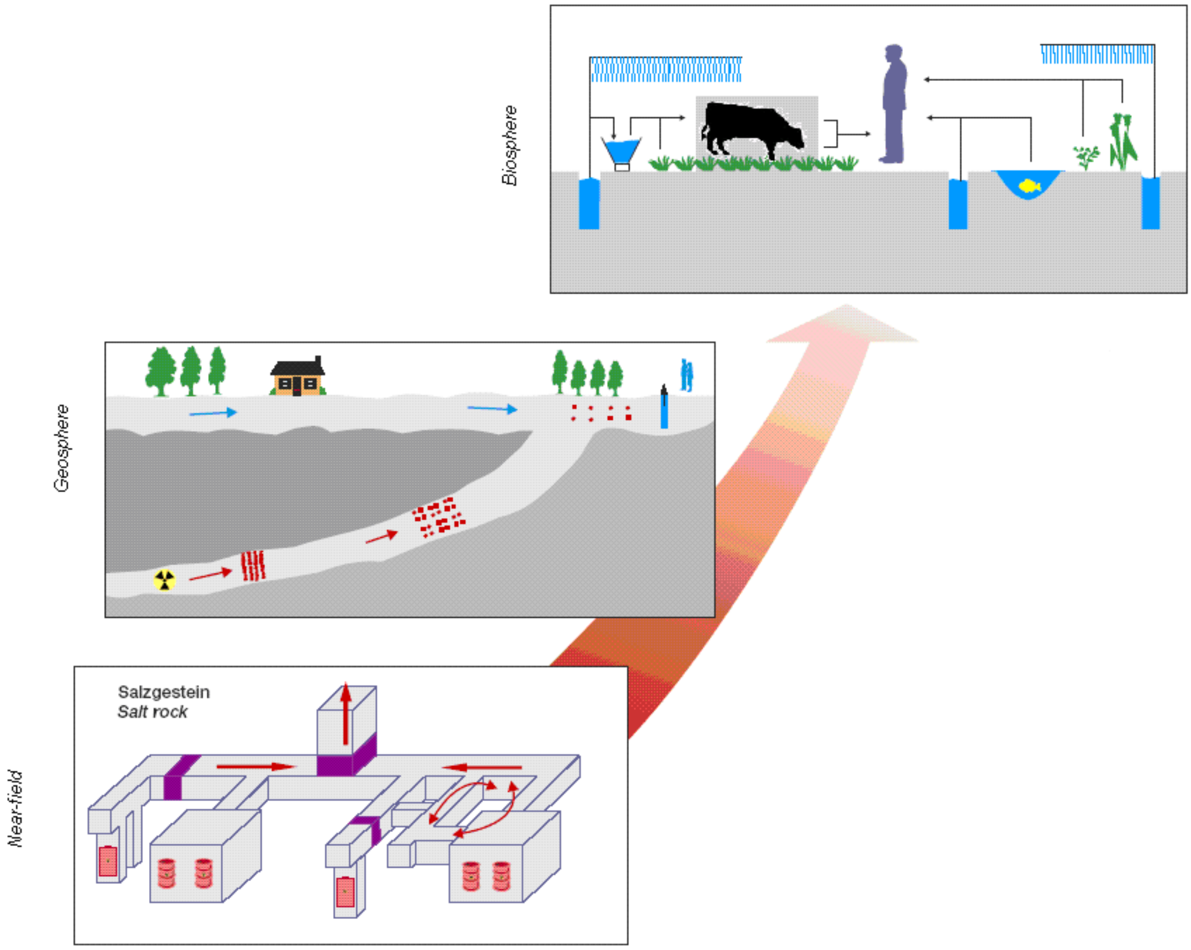

Figure 3 Schematic drawing of different parts of a repository system and the exposure pathway. Source: GRS

The repository system consists of a number of engineered and natural barriers. The first engineered barrier is the waste matrix: Reprocessed high level radioactive waste is typically ‘immobilised’ in a matrix or glass. Spent fuel elements that are stored without reprocessing immobilizes radionuclides in a matrix of stable uranium surrounded by a metal shell (the cladding). The second barrier is the waste container, typically made of cement, concrete, stainless steel, or copper. The next barrier is formed by the backfill and buffer materials that surround the waste container and fill the disposal cells or disposal galleries, and a plug that seals the disposal cells or galleries. The backfill or buffer can provide both a physical and chemical barrier against migration of radionuclides out of the waste containers. The last engineered barriers are the plugs emplaced in the access tunnels to block any potential movement of water through the disposal cells and galleries.

Radionuclides that may leak out after the engineered barriers have degraded face a second set of barriers, the natural barriers. The first is the geological formation in which the repository is built. This is a large and very stable formation, that delays the transport of radionuclides for many thousands of years, so that the larger part of radioactivity is decayed before radionuclides may reach the borders of the formation. The large distance to the biosphere and favourable hydro-geological conditions ensure further retention and dispersion for any fraction of the waste that may be released from the host rock. Figure 4 gives a schematic presentation of the barriers.

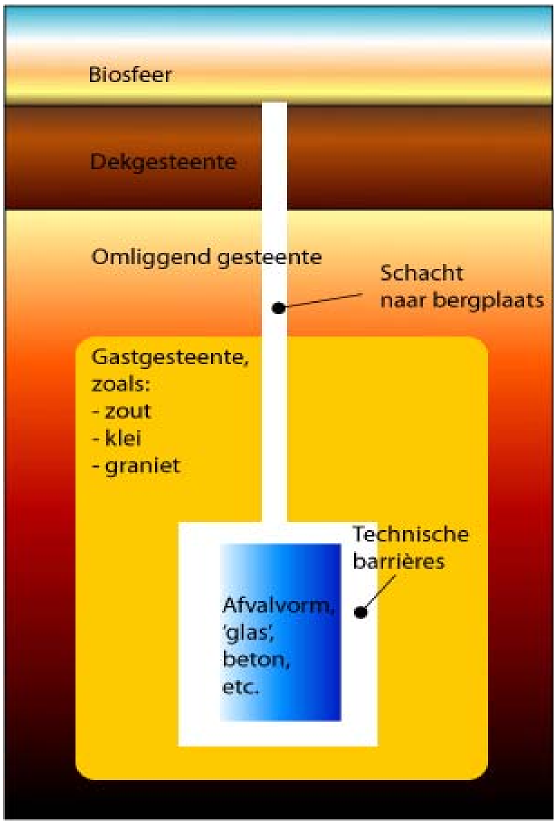

Figure 4 Schematic presentation of the multi barrier system (waste = blue, engineered barriers are white, host rock is yellow, other formations are orange/brown)

A.3.4 Scenarios

Scenario development is the identification, broad description, and selection of different evolutions relevant to a comprehensive assessment of radioactive waste repository safety. Scenarios are primarily seen as a method of dealing with uncertainty about the possible future evolution of the repository. A single scenario specifies one possible set of events and processes and provides a general description of their characteristics and sequencing. The range of uncertainty about the future evolution of the repository is expressed in a set of different scenarios. Some scenarios of this set are described below.

The sequence of events outlined in the previous section, where the engineered and natural barriers will behave as designed is referred to as the ‘normal evolution scenario’. Safety studies also have to address the effects of altered evolutions or unlikely events that may disturb the normal evolution of the repository. Most of these events do not change the evolution of the repository to the extent that results are relevantly different from the results obtained for the normal evolution scenario. However, some events may significantly disturb the normal evolution of the repository. In safety analysis these events are addressed as ‘altered evolution scenarios’. Examples of ‘altered evolution scenarios’ are:

- Brine intrusion scenario for a repository in rocksalt: groundwater penetrates into the repository, for example, as a result of unexpected fracturing or an undetected water-permeable inclusion in the rock salt. Radionuclides get dissolved and convergence of the rock salt formation forces the contaminated brine out of the disposal chambers through the salt formation into the groundwater. The radionuclides then may enter the biosphere via the groundwater.
- Poor sealing scenario for a repository in clay: This scenario treats the case where at least one disposal gallery and an access shaft have been poorly sealed during closure of the facility. In addition, a severe climate change is assumed to occur, which change the present hydraulic gradient such that the hydraulic potential over the clay formation is maximal.
- Human intrusion scenarios: Various forms of mining engineering activities (exploratory drilling, construction of a mine) may bring future generations into involuntary contact with the waste.

For risk assessment, it is important to cover all these altered events, independent of their likelyhood.. The subject of the present study is the so-called “abandonment” scenario, which is described in the following section.

A.3.5 Description of the scenario for this expert judgement exercise

For the design of a repository it is required that the repository is fail-safe not only in the long term, but also during the time the repository is open. This means that even in case of an abandonment of the repository before galleries and shafts are proper sealed, the radioactive waste must be enclosed in a sufficient way that no hazardous material is released to the environment.

Given that a repository will be in operation for about 50 to 100 years, economic crisis, public disturbance, (civil) war and/or mining accidents may lead to a situation where shafts and galleries are not properly closed, and intruding water is not pumped out of the mine anymore. The abandonment of a mine was considered in a few desk studies, where it was assumed that abandonment would lead to the following chain of events:

1) Flooding of unsealed galleries.
2) Dissolution of soluble waste fractions in the intruding water.
3) Transport of contaminated water through the remains of the underground infrastructure by advective flow and diffusion.
4) Transport of radionuclides into overlying aquifers and further into the biosphere.
5) Exposure of humans to radionuclides.

However, in these desk studies not much attention was given to the credibility of the assumed sequence of events, since it has not been attempted to perform a detailed analysis of the likelihood of the proposed events from the mining technology or hydro-geological point of view. E.g., waste canisters were assumed to be destructed immediately, disposal cells are assumed to be flooded instantaneously and intruding water originates from an undefined source.

The objective of this expert judgement exercise is to obtain a more credible description of the abandonment scenario that can be used to establish one or more representative timelines of events. The results can serve as a basis for a better estimation of the water flows into and out of the facility, the groundwater movements through the facility and the exchange of water with the aquifer system in case of abandonment of the facility.

A.3.6 Reference disposal systems

This section provides generic information about two reference disposal systems (one in clay and one in rock salt) that forms the basis for the experts to develop their thoughts on the qualitative (and to a limited extend quantitative) aspects of the given scenario. The descriptions are taken from the EC PAGIS[5] study.

Reference Salt dome - Geologic setting and stability (taken from PAGIS)

The reference system is located in a salt diapir that originally developed about 200 million years ago. The uplift, which took place during later periods, was a slow process with an average postdiapiric uplift rate of 0.02 mm/y due to the available salt supply. This uplift value is conservatively assumed to be still occurring. The diapir appears to have pierced the surface and overturned about 100 million years ago and

---

[5] Performance Assessment of Geological Isolation Systems for Radioactive Waste, 1988

must have undergone extensive subrosion by surface or subglacial waters before being covered by surface deposits.

The geological cross-section through the salt is displayed in Figure 5. It shows that the oldest and most favourable layers of rock salt have risen in the middle with the younger layers following on both sides. This uplift was connected with intensive folding. These folds seem to have only horizontal axes. The covering anhydrite and salt clay may have broken into plates, due to its stiffness. These may have been dragged away from each other so that there are regions where the anhydrite vein is likely to be interrupted.

Glaciers have twice covered the salt dome. About 500 thousand years ago the sediments, which originally formed an impermeable layer over the salt, were eroded down to approximately 300 m below the current surface by subglacial waters. The channel formed has been filled with later sediments. Figure 5 shows the present structure of the layers above the salt dome, along the axis of this channel.

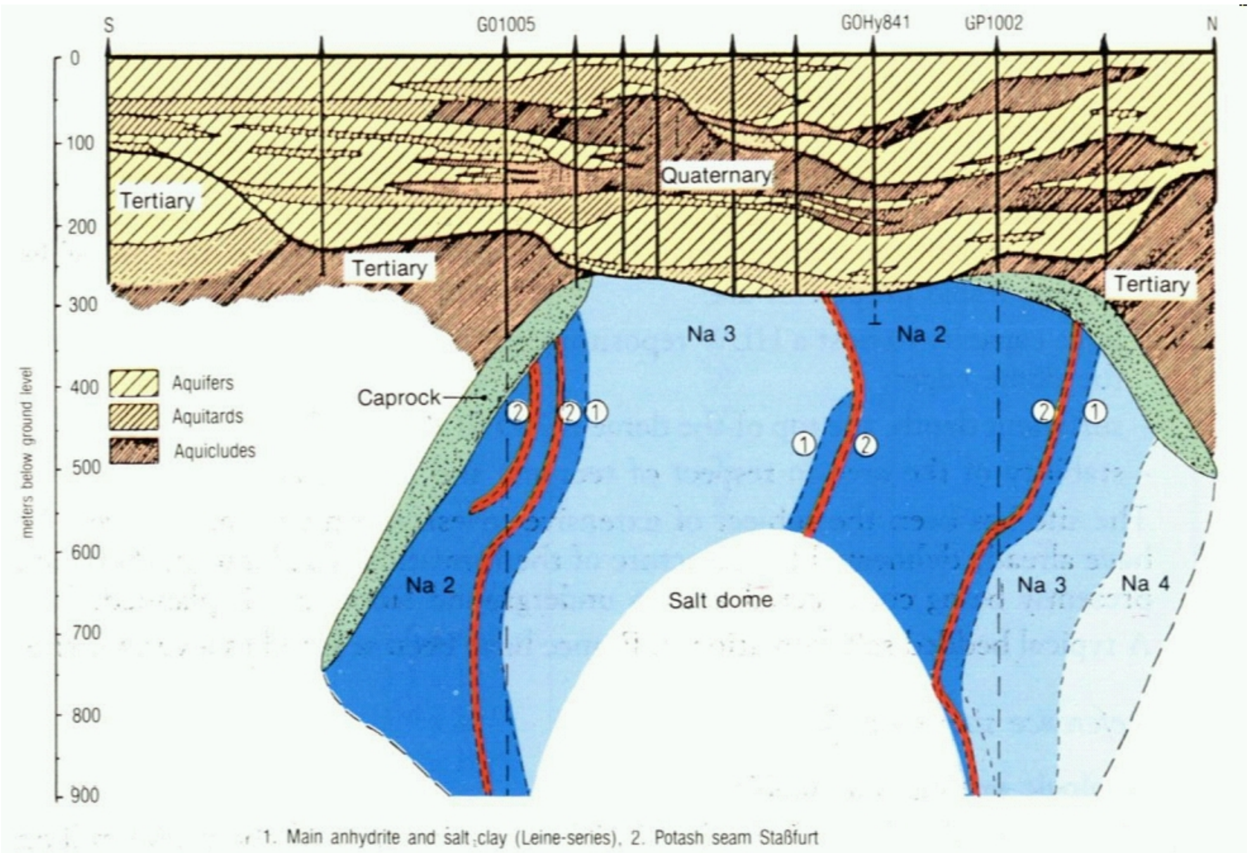

Figure 5 Geological Cross Section and Conceptual Hydrological Regime (disposal in rock salt)

Rock characteristics

The main constituent of the salt dome is halite (common salt). The mineralogical composition and characteristics of the dome are shown in Table 6. Water or moisture is almost absent in salt. A few brine inclusions i.e. small volumes of salt solution are found in the dome, mainly near the anhydrite vein at depths in the range of 400 to 1500 m. The composition of the brines indicates that they are not originating from the overlying groundwater but must have migrated from other parts of the salt dome into their present positions. The sediments overlying the rock salt are made up mainly of gravel, sand, boulder marl, silt and clay.

Table 6 Characteristics and Physical Properties of the Rock Salt

Composition	
Halite (NaCl)	87%
Anhydrite ($CaSO_4$)	7%
Salt clay	4%
Carnallite ($KMgCl_3.6H_2O$)	2%
Volumetric parameters	
Density at T_o = 20°C	2.16 t m^{-3}
Porosity	<0.04
Thermodynamic parameters	
Dilatation coefficient (volumetric)	4 x 10^{-5} °C^{-1}
Specific heat at T_o	880 J kg^{-1} °C^{-1}
Heat conductivity	6.1 W m^{-1} °C^{-1}
Release temperature for water of crystallisation of Carnallite	145 °C (at 10 MPa)
Hydraulic parameters	
Permeability (at 14 MPa)	<6 x 10^{-18} m^2
Mechanical parameters	
Young's modulus (static, dynamic)	<25 GPa, 35 GPa
Poisson's number (static, dynamic)	0.15, 0.27
Compressive strength	25 MPa
Shear modulus	12 GPa

Hydrogeologic aspects

The groundwater recharge area is located to the south of the salt dome. Due to the hydraulic gradient the groundwater flows to the west and north, and down towards the top of the salt dome. The hydraulic conductivity of the overlying sediments assumed for the calculations in the horizontal direction ranges up to 10^{-3} m/s. Conductivity in the vertical direction is assumed to be smaller by one order of magnitude.

Repository design - borehole emplacement concept

The reference repository design is considered suitable for any salt deposit of sufficient vertical and horizontal extent. The reference repository design used in PAGIS is shown in Figure 6. In the reference design HLW canisters are disposed in unlined boreholes drilled vertically downwards from the disposal level. The stacking height of HLW canisters is limited to 300 m. The boreholes will be closed with a plug of about 10 m height which consists of compacted crushed salt or salt concrete.

The capacity of the repository is designed to accommodate approximately 9 000 m^3 of high-level (vitrified) waste expected to arise from the reprocessing of fuel from 50 years operation of an installed nuclear capacity of 50 GWe. This will be disposed of in about 60 000 canisters, each containing 150 litres (about 410 kg) of vitrified waste.

The facility will have a lateral safety distance to the flanks of the salt dome of 200 m and a vertical safety zone beneath salt top of 300 m. Additionally a safety area (pillar) of 300 m will remain around each shaft which should not be used for disposal purposes. The mining procedure and exact repository layout will be dependent on the structure of the salt dome chosen for the disposal.

The major effect of the repository on the salt rock is due to the heat generation of the high level waste. This will lead to an increase of the compressive stresses conditions in the salt layers surrounding the repository which will be released only slowly and will result in an expansion of the salt dome. The borehole depth and spacing is arranged in a way that the temperature increase in the salt layers surrounding the waste is low enough to prevent the release of crystallisation water of from the rock salt.

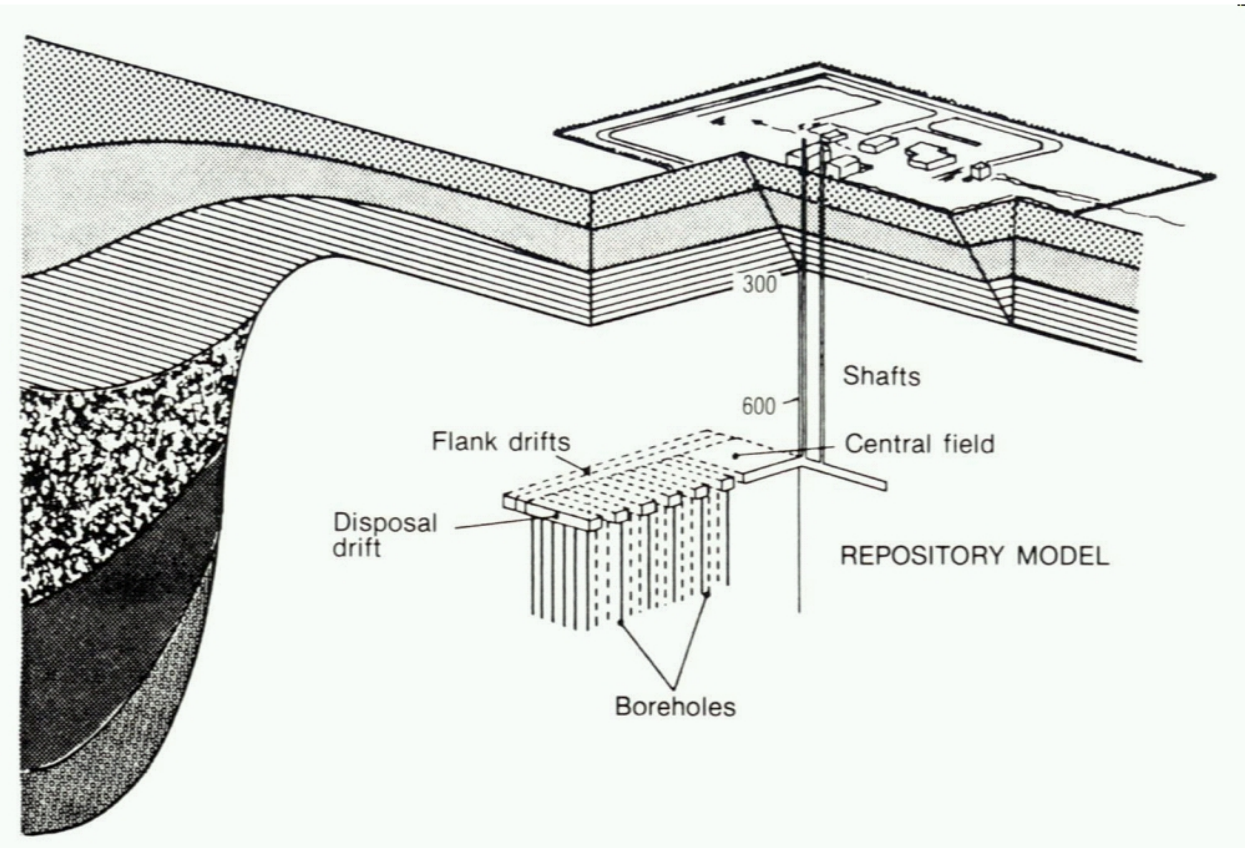

Figure 6 Reference Repository Design in Rock Salt

The time necessary for the operation of a repository is assumed to be about 50 to 100 years. After all waste has been brought into the disposal, the disposal fields or disposal levels will be sealed by dams. The exact structure, position and composition of the dams is yet unknown. After all operations are completed the shafts will be backfilled and sealed. The permeability of the filled shafts will be at least as low as the surrounding geological formation.

The main characteristics of the repository are summarised in Table 7.

Table 7 Main Characteristics of the Reference Repository in Salt

Capacity		
Volume of vitrified HLW	9 000	m^3
Equivalent to reprocessing	70 000	tHM
From power production of	2 500	GW(e)y
Number of HLW canisters	60 000	
Repository		
Volume of the central field	100 000	m^3
Length of disposal field	2 000	m
Depth of disposal floor (below shaft entrance)	840	m
Flank drifts		
Height	4	m
Width	7	m
Length	1 460	m
Initial porosity of backfill (crushed salt)	0.3	
Length of dam	50	m
Disposal drifts		
Height	6	m
Width	6.6	m
Length	650	m
Initial porosity of backfill	0.3	
Length of sealing	20	m
Boreholes		
Number	264	
Depth	310	m
Diameter	0.55	m
Height of borehole plug	10	m

Repository design - drift emplacement concept (post PAGIS)

The PAGIS reference disposal system only considers vitrified high level waste (i.e. waste that remains after reprocessing of the spent fuel). The drift disposal concept (Figure 7) has been developed for the direct disposal of spent fuel after completion of the PAGIS project. The waste package is a Pollux-8-Cask, filled with the disassembled rods of eight fuel elements. This thick-walled cask is expected to confine the waste for at minimum 500 years.

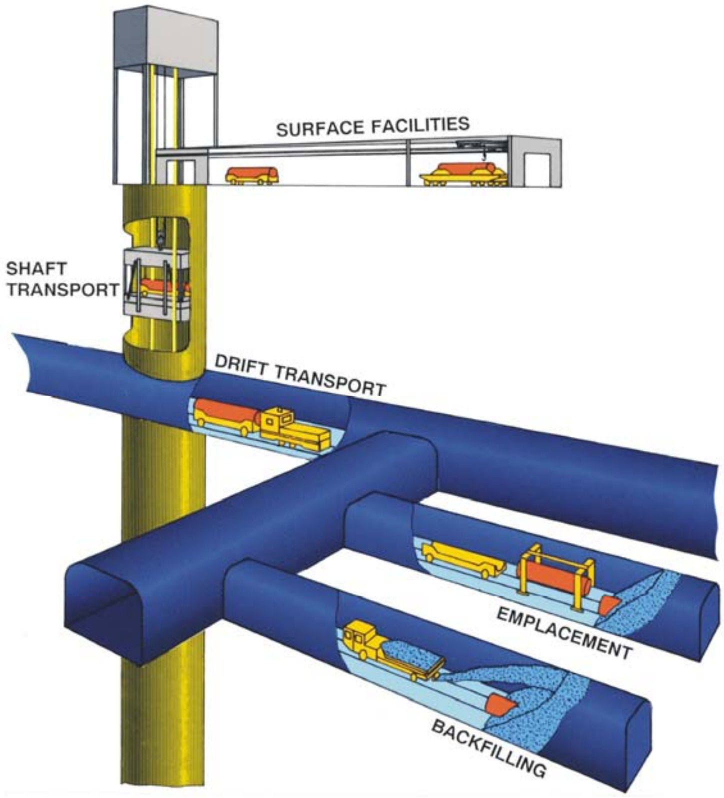

Figure 7 Layout of the drift disposal concept (rock salt)

Temperature development

The decay of the short-living nuclides in the high level waste produces considerable amounts of heat. This leads to an increase of the temperature nearby the high-level waste containers. The heat production of the high level waste decreases considerably when the short-living fraction of the waste is decayed (a few hundreds of years). Usually, some decades after disposal of the waste the maximum temperature is reached, and the repository will cool down. Figure 8 shows an example for the temperature development for different disposal configurations.

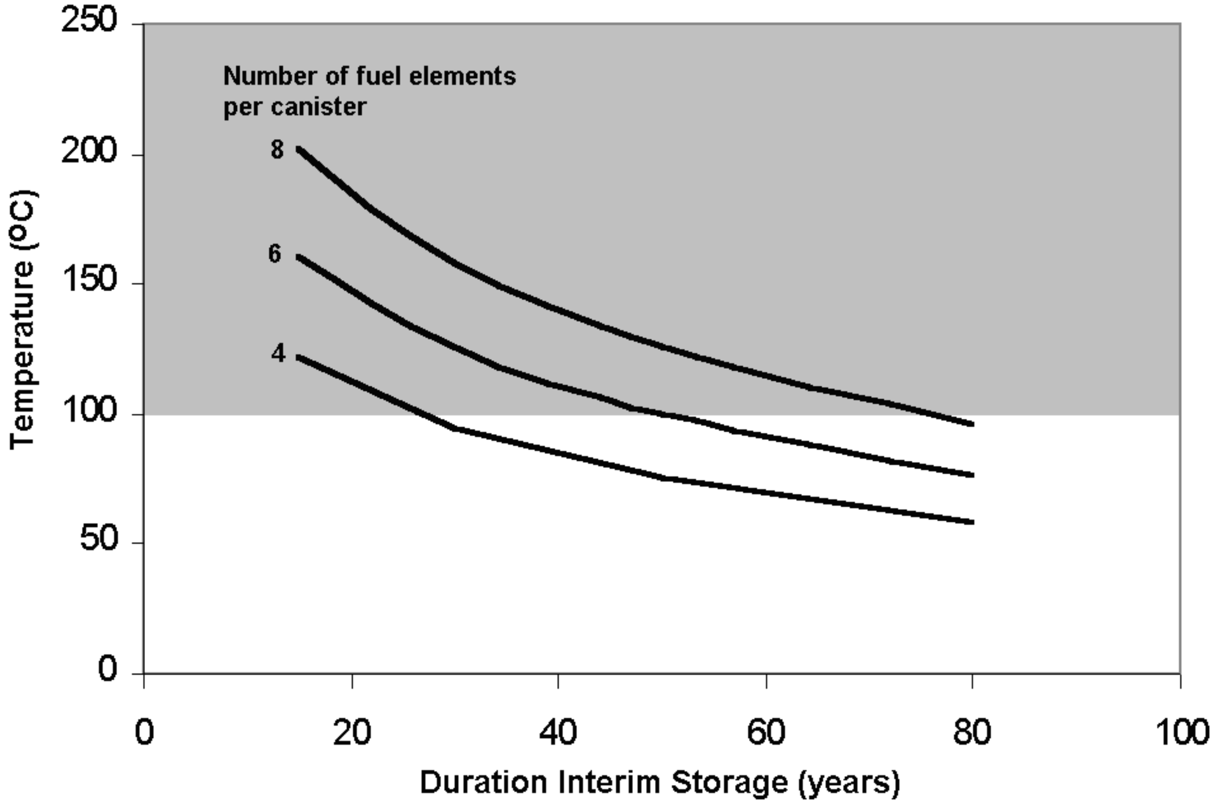

Figure 8 Maximum temperature in the disposal field for different disposal strategies (rock salt)

Reference Clay Formation - Geologic setting and stability (taken from PAGIS)

The formation selected as a potential host rock for a repository is the Boom clay, which is the uppermost clay formation of an alternating sequence of clays and sands deposited about 30 million years ago. The general geologic structure of the Mol area and the position of the Boom clay together with a general stratigraphic log is given in Figure 9 only to serve as a reference (as it was in PAGIS), and without the intend to suggest that a repository will be built at the Mol site.

In the last 70 million years, the margin between land and sea has been moving continuously due to the combined action of continental mass movements, sea-level changes and faulting. All these processes, as inferred from the geological evolution, are so slow that, assuming the same intensities and rates for the future, a repository in the midplane of the Boom clay (at 220 m selected depth) will not be disturbed within a time span of some ten million years.

The maximum subsidence rate in the Mol region is presently about 0.5 mm per year. The zone is characterised by very low tectonic and seismic activity. Faulting activity has not been observed since the last ice age. The known faults and linear features are oriented NNW-SSE and NE-SW.

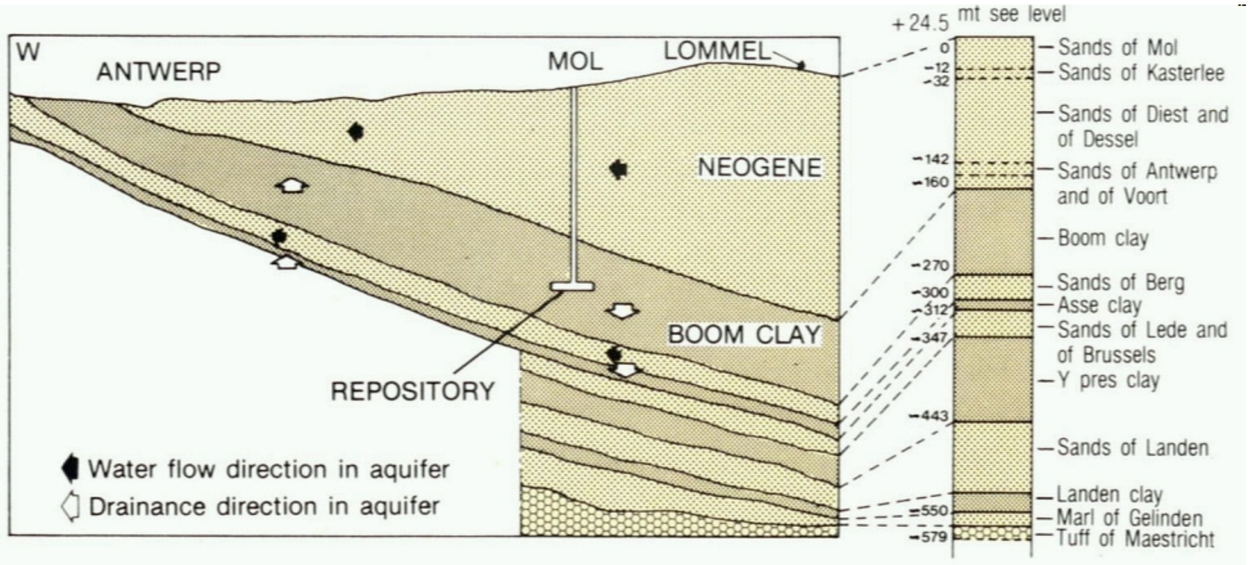

Figure 9 Geological Cross-Section and Conceptual Hydrological Regime (disposal in a clay formation)

Rock characteristics

The grain size distribution of the sediments in the layers between 150 and 270 m depth, including the Boom clay, is characterised by a small fraction (typically 5 %) of coarse material. The mineralogical, chemical and physical properties of the clay at the Mol site have been extensively investigated. The main characteristics are compiled in Table 8.

Hydrogeologic aspects

Observations on the aquifers over- and underlying the Boom clay indicate a general groundwater flow from east to west. At Mol, a gradient between the aquifer above and the aquifer beneath the Boom clay also exists and is about 1 to 2 m per 100 m, so that downward seepage through the clay must be considered. The gradient between the overlying and underlying aquifers of the Asse clay (the clay layer below the Boom clay in Figure 9) is approximately 2 m at Mol, also resulting in a downward seepage. The conceptual hydro-geological system is shown in Figure 9.

Table 8 Characteristics and Physical Properties of the Host Clay

	Mol site (Boom clay)	
Composition	Vermiculite	38%
	Smectite	24%
	Illite	23%
	Chlorite	15%
Volumetric parameters		
Bulk density (wet)	1.9 to 2.1 t m^{-3}	
Dry density	1.68 to 1.80 t m^{-3}	
Water content	15 to 22 wt%	
Thermodynamic parameters		
Specific heat	1.4×10^3 J kg^{-1} $°C^{-1}$	
Thermal conductivity	1.69 W m^{-1} $°C^{-1}$	
Thermal diffusivity	18.8 m^2 y^{-1}	
Mechanical parameters		
Atterberg limits:		
plastic limit	26%	
liquid limit	77%	
plasticity index	51%	
Elasticity modulus	100 to 350 MPa	
Shear strenght (unconfined, undrained)	0.6 MPa	
Hydraulic parameters		
Hydraulic conductivity	1×10^{-10} m s^{-1}	
Diffusion coefficient	3×10^{-10} m^2 s^{-1}	
Porosity	0.33	

Repository design

The capacity for the reference design of the repository in clay is derived from a postulated nuclear installed capacity of 10 GW(e). The corresponding amount of vitrified high level waste for a period of 30 years is about 900 m^3. The repository is designed to receive cladding and alpha waste as well as vitrified HLW. In the reference layout, the different types of waste are emplaced in separate sectors of the repository.

Geological aspects refer to the minimum depth of the clay formation and to its thickness. A depth of the repository of 200 m depth and a compact clay buffer of 50 m above and beneath the repository is expected to provide a safe containment. These figures are satisfied at the Mol site where the subhorizontal clay formation, 110 m thick, is covered by at least 160 m of sediments. The geometric characteristics of the formation mean that the repository needs to be limited to a single layer for emplacement of waste. Generic data are given in Table 9.

The repository concept for a disposal in clay (Figure 10) consists of a main gallery that leads to the disposal galleries. Due to the mechanical properties of the clay, all galleries are supported by concrete liners. Similar to the repository design in salt, all galleries will be backfilled after disposal of the waste.

Table 9 Main Characteristics of the Reference Repository in clay.

Capacity			
Volume of vitrified HLW		900	m^3
Equivalent to reprocessing		8 200	t HM
From power production of		300	GW(e)y
Number of HLW canisters		6 000	
Repository details			
Main gallery:	diameter	4.5	m
	length	550	m
Secondary galleries:	number	3	
	diameter	3.5	m
	length	2 500	m
Repository area (HLW)		1	km^2

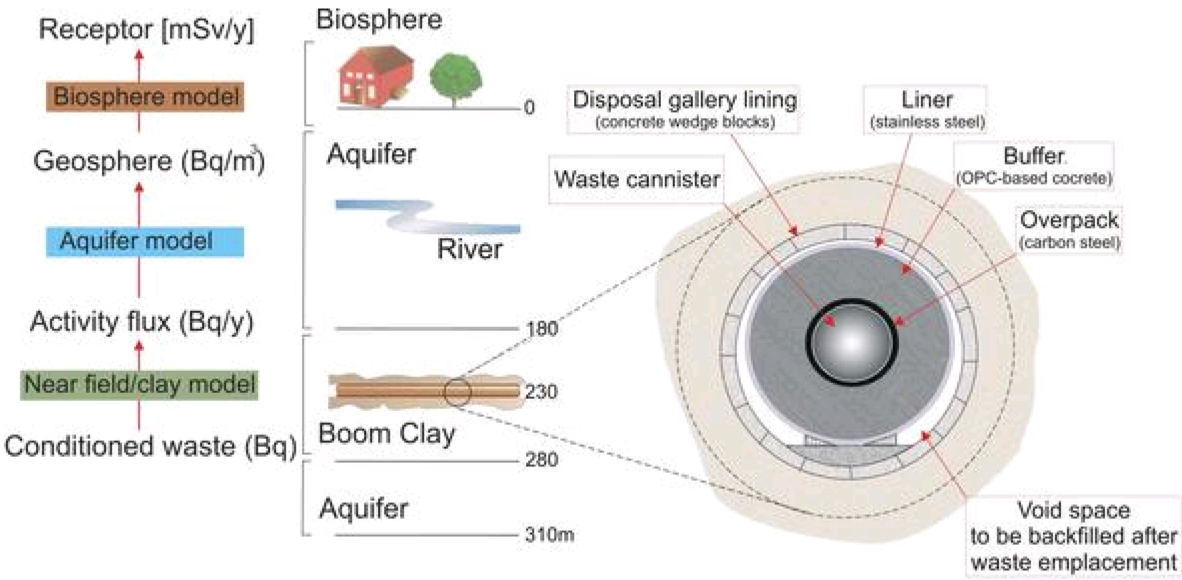

Figure 10 Schematic overview of the disposal system in clay (graphics taken from SCK·CEN's website)

Concrete will be used for the shaft walls, which will be isolated from the aquifer with impermeable layers, and the galleries will be lined. At the end of the operational phase of the repository the shafts will be filled with sand in the uppermost part (aquifers), and sealed with clay in the lower part. Galleries will be filled with cement/clay mixtures. Clay or cementitious grouts will provide additional backfilling in the disposal galleries.

Temperature development

The decay of the short-living nuclides in the high level waste produces considerable amounts of heat. This leads to an increase of the temperature. The heat production of the high level waste decreases considerably when the short-living fraction of the waste is decayed (a few hundreds of years). Usually, some decades after disposal of the waste the maximum temperature is reached, and the repository will cool down. Figure 11 shows the temperature at various distances from the waste.

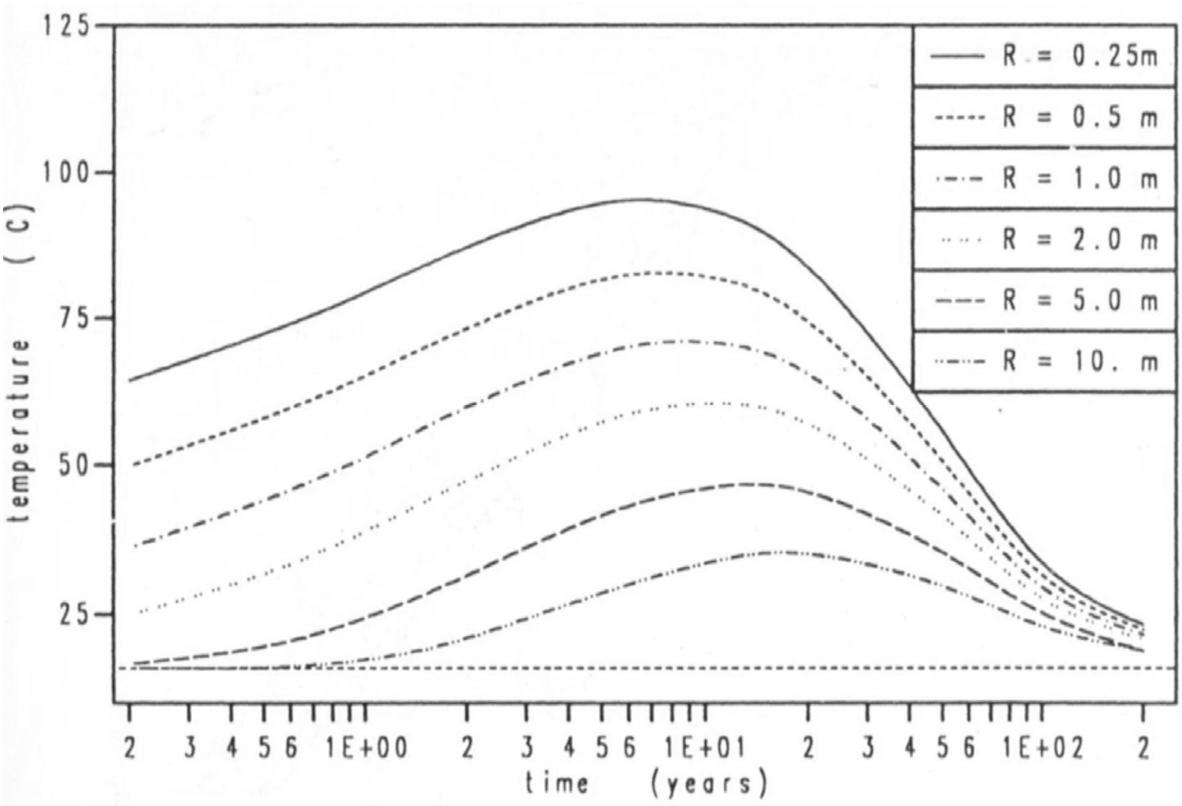

Figure 11 Temperature for various distances from the central axis of the disposal gallery for vitrified waste in clay (PAGIS)

A.4 The Questions

The strategy to identify altered evolution scenarios is to start with an existing description of a scenario and confront this scenario with our present knowledge. This confrontation will lead to confirmation of the existing description or modifications of the description, and sometimes to the identification of a new scenario. The questions presented in this section use the existing description of the abandonment scenario, and ask for confirmation or broadening of this description.

A.4.1 Question 1

Which events or processes could lead to a situation where a flooded underground disposal facility (flooded due to e.g. abandonment or a mining accident) cannot be recovered?

Assume that the:

1) The facility is designed to be in operation for 50 to 100 years.

2) The facility is (partly) flooded due to e.g. abandonment or an accident.

3) Present day means common for western countries are available for recovering the facility.

Background

This questions aims at obtaining a basis for evaluating the likelihood of a scenario in which the facility moves into an uncontrollable situation. It also presents a starting point for the sequence of events that follows after losing control of the facility. This sequence of events is the subject of the next question.

A.4.2 Question 2

Do you think that the broad description of the abandonment scenario given in Section A.3.5 (summarised below in the paragraph 'background') is correct?

Assume that:

1) Disposal cells (galleries or boreholes that contain the waste canisters) are all backfilled and sealed.

2) The facility is designed to be in operation for 50 to 100 years.

You can limit your answer to one of the two reference designs or discuss both reference designs.

Background

In the risk studies, it is assumed that abandonment would lead to the following chain of events:

1) Abandonment of the facility
2) Flooding of unsealed galleries
3) Soluble parts of the waste dissolve in the water
4) Advective flow and diffusion through the remains of the underground infrastructure
5) Radioactive material reaches aquifer and biosphere
6) Exposure of humans to radioactive material

This is considered to be the only way for the radioactive content of the waste to migrate from the waste package to the biosphere. The driving process is the intrusion of water into the system, and the outflow of water carrying radioactive contaminants.

Although a disposal facility may be irreversible flooded as a result of other events then abandonment, in previous studies the abandonment scenario was chosen as a representative scenario. It was assumed that the consequences of abandonment are representative for the consequences of other flooding scenarios.

A.4.3 Question 3

Which processes can lead to flooding of the facility after abandonment of the facility?

Assume that:

1) Disposal cells (galleries or boreholes that contain the waste canisters) are all backfilled and sealed.
2) The facility is designed to be in operation for more than 50 years.

You can limit your answer to one of the two reference designs or discuss both reference designs.

If possible, provide a ranking of the processes with respect to the speed of flooding the facility.

Background

The timing of events is important. In most risk studies it is assumed that there is a small probability that some of the seals that isolate the waste packages may fail once a full hydrostatic pressure has developed in the flooded access gallery. Moreover, in the calculations it is assumed that the flooding is fully established directly after abandonment.

The answer to this question may result in better estimates of the timing of events in future studies.

A.4.4 Question 4

Which processes and mechanisms control the future evolution of flooded galleries?

Assume that:

1) The maintenance and operation of the facility stops while the access galleries and shafts have not been filled and sealed.
2) The host rock formation (clay or rock salt) can undergo plastic deformation.
3) The open access galleries in the reference design for clay are supported by a concrete liner that provides a safe working environment during the operation of the facility. In rock salt the access galleries are unsupported.

You can limit your answer to one of the two reference designs or discuss both reference designs.

Background

For the description of the scenario it is needed to picture the situation at the end of the scenario. Understanding of the processes and mechanism that drive the evolution of the underground infrastructure will help to improve this. In past studies concerning disposal in clay it was assumed that after a long time the remains of the galleries are large fragments of clay, where the volumes between the concrete are filled with clay from the host rock and some void (water filled) volumes. For rock salt it is assumed that, due to creep of the rock salt, the seals of the disposal cells have been compacted to an impermeable state, and that all open volumes such as access galleries have converged completely.

A.4.5 Question 5

Which are the main potential pathways to the biosphere for radioactive contaminants that may escape from the sealed waste package?

Assume that:

1) The maintenance and operation of the facility stops while the access galleries and shafts have not been filled and sealed.
2) Disposal cells (galleries or boreholes that contain the waste canisters) are all backfilled and sealed, but in one or more of the seals radionuclides can leak out of the disposal cell.

You can limit your answer to one of the two reference designs or discuss both reference designs.

Background

The main issue is what happens to the radioactive contaminants that leave the host rock (i.e. the clay layer or the rock salt). In past studies it was assumed that the radioactive contaminants leave the host rock through the water in the flooded shafts and enter an underground aquifer. From that point on a generic aquifer model has been applied. The blind spot in this migration pathway are the mechanism and processes that control the transfer of the contaminants from the water in the flooded facility to the water in the aquifer.

A.4.6 Format in which the assessments need be provided by the experts

The experts will provide written answers to each question. We envisage that one or two pages is needed for each answer, but the expert is free to decide how much is needed or how little is enough.

Each answer must consist of four sections:

1) Question
   (Literal quote of the question for administrative purposes)
2) Short answer
   (The answer without argumentation, if possible in one line or one paragraph.)
3) Argumentation
   (Rationale of the answer)
4) Background and comments
   (This section is optional. Here you can give more background, discuss the issue in a broader sense, or even challenge the question.)

Note that:

- The answers provided will be reported in a public report, and will be anonymous (i.e. will be attributed to Expert 1, Expert 2, etc.
- The public report will give a list of names of the experts that contributed.
- The expert can use any convenient layout for the written answers.
- The text provided by the experts will be reformatted to a uniform format that fits in the report.
- Each expert will have the opportunity to review the draft of the public report, and is entitled to make changes to his contribution and/or to the conclusions drawn from these.

Please feel free (at any point in your answers) to make suggestions that can result in improvement of the design of the repository and/or the selection of the site where a repository may be build.

Appendix B Responses of the experts

The nominated experts are shown in the table below.

Expert	Affiliation
Dominique Ngan-Tillard	Assistant professor Faculty of Civil Engineering and Geosciences Department of Geotechnology Geo-engineering section (TU Delft - NL)
André Vervoort	Professor at the Department of Civil and Mining Engineering of the Katholieke Universiteit Leuven (Belgium)
Ton Wildenborg	Senior Researcher, TNO Built Environment and Geosciences (NL)
Janos Urai	Professor, RWTH Aachen University
Toon Leijnse	Private consultant

It has been agreed that the results will be treated anonymously, and the experts name will only be used in passages such as the composition of the panel, if the experts agree. Therefore, in the following sections the experts are represented by the numbers 1 to 5.

B.1 Response of expert 1

Question 1 ***Which events or processes could lead to a situation where a flooded underground disposal facility (flooded due to e.g. abandonment or a mining accident) cannot be recovered?***

I consider here the case, whereby during the operational phase of 50 to 100 years an incident occurs prior to the proper sealing and/or closure of the underground facility. Such an incident could be the failure of the shaft lining, due to e.g. poor design or execution, or poor maintenance; by such a failure, the water of one of the groundwater tables flows straight into the shaft at a possibly large rate. In older mines, where one indeed does not do the proper maintenance, this phenomenon is not unusual. So, this scenario cannot be considered to be unlikely (of course linked to poor maintenance). Another incident could be the flooding of the surface area itself, resulting in a flooding of the underground facility.

Other reasons for flooding an underground disposal facility are more difficult to visualize. In normal mining operations, caving is sometimes part of the mining part (e.g. for the longwall and sub level caving methods) or large collapses occur, resulting in the occurrence of fractures between the caved zone or the collapsed area and the groundwater tables or surface water, resulting in the flooding of the mine. During mining operations, such events do occur, however the required conditions for this should not be present in a well-designed underground waste disposal facility: one is talking for the latter about small openings and not about caving methods, and if larger openings are foreseen (e.g. disposal in salt) they should remain stable during long time periods.

If we come back to the failure of the shaft lining, one should make a difference between the situation, whereby there is only a flow of water into the shaft, and the situation whereby there is a flow of water and sand or parts of the rock mass.

In case of only water flowing into the shaft, the pumping capacity of the underground facility should be large enough to overcome this problem. Of course, if this is considered as a realistic scenario (i.e. flooding of the mine), one should foresee sufficient pumping capacity (which is maybe more easily said than done). However, the problem becomes more dangerous if the cause of the failure of the lining is poor maintenance, instead of bad design or execution. In the latter situation (i.e. bad design or execution), the pending problem should be observed at an early stage, by large deformation, excessive leakage, etc., and there is no reason to assume that even after failure the normal operational capacity is not working properly (e.g. underground pumps are working). I foresee a bigger problem, if the failure is due to poor maintenance of the shaft infrastructure. In such a situation, there is a chance that also the maintenance of e.g. the underground pumps is poorly done. Or in other words, if the underground facility and shaft infrastructure is not maintained as it should during the disposal and closure phase, the underground facility can be flooded and if there is a lack of funding, expertise or interest this could lead to a complete abandonment.

In case that the shaft is immersed by water and sand or parts of the rock mass, one would have a serious problem. It won’t be that easy to re-open the facility. On the one hand one should stop the flow and on the other hand one has to pump the water and excavate the loose material. This will certainly imply a large cost and several years to re-open the facility. There will also be extensive damage to lining, support, equipment, etc.

If during the normal operational time of 50 to 100 years, flooding would occur as described above without immediate action to re-open the facility, one should take into account that this situation remains as such for a very long time period, even forever.

One should also not underestimate the amount of water that can be accumulated underground and that, depending on regulations, has to be treated after pumping up. So, it does not seem to be unrealistic that one would decide at such a moment to leave the water underground.

In summary: “Which events or processes could lead to a situation where a flooded underground disposal facility (flooded due to e.g. abandonment or a mining accident) cannot be recovered?”

1) Flooding of water by failure of shaft lining, due to e.g. poor maintenance, combined with insufficient pumping capacity, poor maintenance of pumping equipment and/or insufficient means, expertise or interest to re-open.
2) Flooding of water and soil or rock material by failure of shaft lining, resulting in a difficult situation to re-open (stopping the flow, pumping the water away and excavating the loose material).

Question 2 Do you think that the broad description of the abandonment scenario given in Section A.3.5 (summarised below in the paragraph ‘background’) is correct?

Maybe, first a remark on the first assumption. One could question, if all disposal cells are backfilled and sealed, at the moment that an incident (e.g. flooding due to the failure of the shaft lining) occurs. One must assume that an incident occurs at a moment that one does not expect it; else, one would/should have taken the cause away. Of course, one can impose as good rule of practice that one places a canister cell per cell and that prior to going to the next cell, one backfills and seals the disposal cell. Although on paper, this rule sounds good, I have my doubt if in a production phase, one will work that way. It is probably more realistic that one works with a number of disposal cells at the same time. Question remains how many would be realistic, i.e. a good compromise between safety on the one hand, and time and cost on the other hand.
In this regard, one should not forget that one is talking about a large number of canisters and large volumes of e.g. clay excavated and of backfill. Probably, the backfill material will be different from the excavated clay material (if talking about clay as host rock). For salt, it could be that the same excavated material is used. If one goes for the procedure of one cell at a time (disposal, backfill and sealing), one is talking about several years or tens of years to finish the active phase of the disposal process. Or, one opts for working in badges due to practical reasons (first preparing a certain area, followed by the placement of all canisters in that area, next the backfill of all cells and finally the sealing).

About the second assumption, I would like to add that one can indeed design an underground facility to be operated for 50 to 100 years. However, such a facility will only remain safe and operational, when one does the necessary maintenance over the entire time period. I have seen mines and accesses to mines in third world countries, where indeed due to political instability, lack of financing, etc., the necessary maintenance was not done during e.g. 10 years, resulting in unsafe conditions, failure and no proper operation anymore.

Looking at the chain of the 6 events described in the Background, I have no direct criticism or remark on the succession of these events. However, I would like to formulate some comments on event N° 4, being Advective flow and diffusion through the remains of the underground infrastructure. Even when it is not specified in paragraph A.3.5, one has to be very careful in making assumptions about the cause of the advective flow and about the hydrological characteristics of the tunnels, which are abandoned prior to backfilling. In one way, I assume it is valid for clay and salt, although I am more familiar with clay.
Cause of advective flow: probably a lot will depend on the final design of the underground facility, but one can assume that for clay as host rock material the total area of the underground facility covers several square kilometres. Assuming that there is one access at one side of this area and another at the other side (or at 1 or 2 km's) and assuming that the mine is flooded by the water of groundwater table(s), I think that the flow within the underground tunnels can be quite large and be in the same order as the flow in the above aquifers. And this, independent of the warming up of the water due to the radioactive source nearby. In case, that the accesses are situated more closely together the flow related to the flow within the aquifer is probably smaller.
Hydrogeological characteristics of the tunnels: One extreme is considering that the tunnels do not collapse and remain completely open. This means that the water can flow without much obstruction. One can argue how long this situation remains. Anyway, before the entire tunnel network has collapsed, one has probably to consider several years, even decades. Local collapses can occur relatively fast after flooding. However, one should not be too optimistic, by assuming that the tunnels will collapse and seal off due to creep (salt) or plastic deformation (clay). It has been observed that small openings, e.g. boreholes, close completely, but these were unsupported or only partially supported. For tunnels, one talks about large openings and for clay completely supported (and probably heavily supported, e.g. concrete lining). So, probably a collapse has first to occur, resulting in clay and concrete blocks present. In such a situation it will take a long time before all openings have been closed by the plastic deformation of the surrounding clay mass. So, I will always consider openings with a large permeability, allowing an advective flow.

As answer to the question if these events are the only way for radioactive content of the waste to migrate from the waste package to our biosphere, one could say that this is the only way in case that there is no intrusion by human activities. I do not think that one will ever start digging for clay at large depth, but for salt it is more than realistic and one can also assume that one start drilling, as a water well or as prospection. In such a situation, other events can accelerate the transport of radioactive material to the biosphere.

Question 3 Which processes can lead to flooding of the facility after abandonment of the facility?

This is a more difficult question to answer in a generic way, as it depends on a specific location and on a specific design and working procedure. E.g. presence of aquifer and way of backfilling the galleries (retreating the support, backfilling by sand or by clay, different compartments within the underground facility, etc).

Anyway, as the shafts or other access roads are intersecting the aquifers, I consider this as the weakest link, or in other words the failure of the lining as the most probable cause for a fast flooding of the underground facility. Once this failure has occurred the complete flooding of the underground facility can be very fast, from some hours to some months or years depending on the rate. If it is real failure, it will be indeed a few hours. In other cases, one is rather talking about leakages. When such a failure occurs cannot be determined in a generic way; if the circumstances are “right” this can be a few years after closure, but if the circumstances are more positive, it could also take decades before it happens.

Another relevant question would be: ‘Can one design the shaft in such a way, that failure or leakage will never occur ?”. To this question the answer is probably no; there is always the possibility that it will occur, certainly for the leakage. But probably once you have leakage over a long time period, a proper failure will happen too.

As mentioned in my answer to Question 1, flooding of the surface area is also a possible cause. But I assume, that the required pre-cautions are taken that in such an event and after closure of the facility, the water cannot flow directly into the underground workings by a barrier constructed after closure. Also, assuming that the surface flooding lasts only a short period (days or weeks), this barrier should be effective enough. In other words, the failure of the lining at the intersection with the aquifers remains the critical or weakest link.

Question 4 Which processes and mechanisms control the future evolution of flooded galleries?

I limit my answer to the reference design in clay. The issue in this question is already partly discussed in Question 2.

In normal operational conditions in an underground environment, it is already difficult to predict failure or collapses. Seldom, one works with zero risk or 100% certainty. In other words, locally a collapse may always occur, while certain openings can remain stable for long time periods, even if the safety factor is smaller than 1. In this study, one adds the aspect of time to it without knowing properly the boundary conditions.

So, the scenario as I understand it is as follows: the main access tunnels have been excavated about 50 years ago, the lining which is correctly designed and installed just after excavation is still in good shape, as one has done regular inspection and maintenance if needed, this lining is not recovered or weakened prior to closure, and shortly after closure the underground facility is flooded.

If one first looks at a scenario without flooding. Probably the main difference after closure and during the normal operational phase prior to closure is that the ventilation fans are switched off. And then there are two possibilities: either the shafts remain open, allowing a natural ventilation direction (at a smaller flow rate of the air than with fans operating), or they are closed. In the last situation the underground environment evolves towards an equilibrium (i.e. nearly constant) in temperature and humidity, except if the radioactive waste produces still a lot of heat. Then, the air temperature can increase systematically as a function of time over a long time period. In case that the shafts remain open, the increase of temperature due to the radioactive waste will be smaller or the average temperature and humidity will be smaller and fluctuating with the seasons.

Now I would say as long as the temperature would remain normal (i.e. less than 40 or 50° C), I do not see the lining collapsing soon. Always assuming that the lining has not been weakened prior to closure or was already in bad shape at that time. Of course, locally one could get a small collapse, but this would not result in a closure of the section. In these circumstances, I would say that such openings could remain intact for 10’s of years, 100’s of years even 1000’s of years. I would say, no-one can really predict this.

If the temperature would become quite high (100° C and more), then all will depends on the type of material is being used for the lining (probably concrete ?). I would then assume that the lining would get damaged much sooner, but this will be in first instance mainly small fracturing of the lining and not large collapses. In this situation and in comparison to the colder one, I would say that more frequent and sooner local collapses will occur. But in general, the openings remain accessible and open for similar time periods as mentioned above.

Now going back to the real scenario, whereby the main access tunnels are flooded. Does this make a big difference ? There are probably three points that can be different:

1. Temperature: It depends again if there is a significant flow within the water or not. If there is, the temperature does not increase that much. If there is no flow, one should have a look at the maximum temperature that the water can reach in a specific design.
2. Pore pressure and pressure on the lining (outside diameter). All depends probably also if the lining is permeable or not. But once flooded, one can assume that the pore pressure becomes equal to the hydrostatic pressure inside the tunnel. From a point of view of loading of the lining, this could even be positive.
3. Degradation of the lining linked to the composition of the water. Certain water types could accelerate the degradation of the concrete or of the filling material between the lining blocks.

So, in general, I would conclude that even after flooding there will not be major collapses of the lining. In other words, in my opinion one should consider the case that the access tunnels remain open during 100's or 1000's of years.

In case, that there would be a large collapse, I am not convinced that the tunnel will close quickly due to plastic deformation; or in other words, that one can calculate transport phenomena with the clay characteristics instead of these of open paths. One should not be too optimistic, by assuming that the tunnels will collapse and seal off due to plastic deformation of the clay. It has been observed indeed that small openings, e.g. boreholes, close completely, but these were unsupported or only partially supported. For tunnels, one talks about large openings and completely supported tunnels. In such a situation it will not only take a long time before a collapse takes place and, once it happens, the collapsed material is a combination of clay material and concrete blocks. In such a situation it will take a long time before all openings have been closed by the plastic deformation of the surrounding clay mass.

Question 5 Which are the main potential pathways to the biosphere for radioactive contaminants that may escape from the sealed waste package?

Again, I limit myself to the reference design for the clay host rock.

As I consider the weakest link and the most probable cause of flooding (see answers to previous questions and in particular to Question 1), the failure of the shaft lining at the intersection with the aquifers, it is logical that I consider this location as the blind spot. Other scenarios, apart from human intrusion, are in my opinion much more difficult to visualize. I do not see it as realistic that the water in the horizontal tunnels will migrate back through the clay layer to the biosphere. As also explained in my answer to

Question 1, the clay package will not be fractured over its entire height, as no caving methods are applied and relatively small openings are excavated, which are on top of their scale heavily supported. Geological faults could, I assume, occur, but first it will be location dependent and second I don't feel knowledgeable enough to comment on these aspects of structural geology.

So, this means that I do not see many possibilities or different scenarios. Of course, other scenarios involve human activities: pumping the flooded mine, drilling boreholes for water wells or as part of an exploration, but I assume such scenarios do not have to be considered in answering this question.

B.2 Response of expert 2

Question 1 ***Which events or processes could lead to a situation where a flooded underground disposal facility (flooded due to e.g. abandonment or a mining accident) cannot be recovered?***

Short answer

The control of a partially flooded facility depends on the flooding rate and sequence of flooding.

Argumentation

As long as the flooding rate is low in a repository in clay and the structure of the galleries remain stable, the situation is controllable; there is sufficient time available to pump water out the facility and recover the facility. One assumes that means exist to decontaminate large quantities of polluted water.

If the flooding rate is high and the facility becomes quickly fully filled in with water, the galleries are at hydrostatic pressure, seals around the canisters fail; the situation becomes uncontrollable for a period of time.

If the facility is affected by a large scale collapse (due to fire, terrorist attack or hydrological instability) before being invaded by water, the recovery of canisters without damage to the canisters is compromised. Current technology does allow the repair of local collapses by grouting, freezing, etc…

Question 2 ***Do you think that the broad description of the abandonment scenario given in Section A.3.5 (summarised below in the paragraph 'background') is correct?***

Short answer

The proposed description of the abandonment scenario is realistic but incomplete.

Argumentation

One should also research the possibility of steam formation due to the high temperature gradient around the canisters, upward turbulent steam flow and mixing with the atmosphere.

Question 3 Which processes can lead to flooding of the facility after abandonment of the facility?

Short answer and argumentation

One assumes that that disposal cells are backfilled and sealed.

Flooding of the facility can occur either by:

1. accidental ground water leakage through the shaft supported by a concrete lining in the permeable (sand) layers above the repository
2. ground water leakage through an unexpected fault in the clay layer which is connected to aquifers and through the concrete lining and the backfilling of the disposal galleries
3. connection between the upper aquifer and the facility via an exploration borehole not well sealed
4. mining activities/ underground storage (in salt) interfering with the repository
5. fault reactivation in permeable layers under the repository and fault propagation to the repository and above induced by human activities (CO_2 sequestration, geothermal activity)
6. sea water ingress via the shaft in case of rupture of sea water defences during a large storm event

or

7. meteorological precipitations ingress via the shaft under current or future extreme climatic conditions.

Considering the current annual precipitations and the volume of the facility, flooding by ingress of meteorological water into the shaft will be slow and controllable.

Question 4 Which processes and mechanisms control the future evolution of flooded galleries?

Short answer

Micro-biological, thermal, hydraulic, mechanical and chemical processes and their interactions control the future evolution of the flooded repository.

Argumentation

Some issues deserve a special attention:

- Anisotropic loading due to heterogeneous radioactive waste storage in the canister leads to gradients, which result in enhanced transportation in water.

- Thermal effects affect the hydraulic conductivity and diffusivity coefficient of sealed micro-fissures.
- Dissolution potential of the confining salt layers by fresh water has to be quantified. As fresh water becomes saturated by dissolved salt in the fully flooded gallery, brine is formed. Brine is denser than fresh water, fresh water floats on brine. Salt dissolution progresses upwards as more fresh water penetrates into the storage.
- Application of hydrostatic pressure to the wall of the gallery leads to a decrease of the compressive tangential stress around the gallery in partially saturated (and therefore less plastic) clay and causes the reopening of cracks in the EDZ.
- Presence of organic matter in clay causes the formation complexes which increase solubility.
- Thermodynamical gradients, i.e., electrochemical and osmosis effects influences transport in water.

The following issues are not problematic
- Flooding of a repository in a swelling clay. The addition of water accelerates sealing, swelling pressures increasing the plastic deformation of the clay.

Question 5 ***Which are the main potential pathways to the biosphere for radioactive contaminants that may escape from the sealed waste package?***

<u>Short answer and argumentation</u>

Main concern is steam production and fast migration to the atmosphere, convection through the structure and slow flow through confining layers.

B.3 Response of expert 3

Question 1 ***Which events or processes could lead to a situation where a flooded underground disposal facility (flooded due to e.g. abandonment or a mining accident) cannot be recovered?***

<u>Short answer</u>

Assuming that there is an institutional system for control and recovery in place, the conclusion is that temporary situations of no exertion of control can exist due to a number of causes:
- Internal:
    - o Defect in the shaft short-circuiting the shallower aquifers with the disposal horizon
    - o Accident with waste containers leading to contamination in the access tunnels or in the

galleries so that workers have to leave the area
    - Defect with the pumps
- External:
    - Flooding with seawater
    - Flooding with river water
- A combination of internal and external causes

The duration of periods of ‘no exertion of control’ is estimated at weeks (pump defect) to years (repairing a leaking shaft). In the meantime the water in the flooded mine could get contaminated if the 2nd engineered barrier would not function properly. It is doubted however that this engineered barrier would fail already within several years. The very unlikely combination of an accident with containers and a simultaneous flooding could lead to contamination of the flooded mining area. Particular attention should be directed to drying any non-closed disposal bore holes in the salt repository after a flooding event and the convergence rate of these flooded bore holes during periods of several years. The convergence might complicate the access of the bore hole after the water in the access tunnels and drifts has been removed (and remediated).

<u>Argumentation</u>

No situations have been identified that could lead to long periods of flooding with a duration of decades or more. Individual not properly closed disposal bore holes could in a very extreme case become inaccessible during a flooding period.

The external causes relate strongly to the geographical setting and the climate conditions. Due to global climate change the risk of flooding might increase in lowland areas near the sea and areas in floodplains. If the disposal site is well above +6 m above mean sea level and is not located in a river flood plain, the risk however is negligible.

<u>Background and comments</u>

The question of ‘the likelihood that the repository moves into an uncontrollable situation’ implies that, although there is a control system in place, the repository can physically not be controlled. Otherwise the question would refer to ‘the likelihood that the repository moves into an uncontrolled situation’ implying that there is no control system in place (e.g. by loss of institutional control and neglect). My interpretation of the 3rd assumption (Section A.4.1) is that we are dealing with the first option of an ‘uncontrollable situation’ and abandonment is not caused by mere neglect.

Question 2 ***Do you think that the broad description of the abandonment scenario given in Section A.3.5 (summarised below in the paragraph 'background') is correct?***

Short answer

The description of the abandonment scenario in Section A.3.5 is largely correct provided that the causes of flooding are specified and the relevant mine compartments which can be flooded, is completed.

Argumentation

The 2nd paragraph in Section A.3.5 suggests that a situation where institutional control is absent (economic crisis etc.) for some time (years to decades) or maybe has disappeared altogether. The assumption under Question 1 however is that institutional control is still in place. Summarizing, three groups of flooding could be discerned:

1. Institutional control in place: flooding periods of weeks to years during which recovery actions are technically not possible
2. Institutional control is absent for years to decades during which the repository might be flooded
3. Institutional control and documentation of repository has disappeared and repository might be flooded for a long period (note that is in contradiction with the assumption under Question 1)

The first event could be expanded resulting in '1) Flooding of unsealed disposal galleries and bore holes'.

Background and comments

None

Question 3 ***Which processes can lead to flooding of the facility after abandonment of the facility?***

Short answer

Several internal or external causes (see also answers to Questions 1 and 2) could lead to the flooding of the repository:

- Flooding by seawater if access to repository is at or below sea level
- Sabotage/destruction of the mine shafts and pumps
- Flooding by a river if repository access is in floodplain
- Lake discharging in the repository
- Failure of shaft isolation in shallow aquifer zone
- Technical pump failure
- Leakage along fractures/fault in clay repository
- Leakage along anhydrite layer in rock salt

Argumentation

The flooding rates for fractures/faults and anhydrite are expected to be lower than for flooding of the mine access zone with seawater, rivers or lakes or flooding by failure of the shaft islolation. It is however much more difficult to provide corrective measures for the first group compared with the second group.

Background and comments

None

Question 4 Which processes and mechanisms control the future evolution of flooded galleries?

Short answer and argumentation

Assumption 1) (Section A.4.4) suggests that we have a situation comparable to category 3: Long period of flooding.

When the repository is flooded, fluid migration in the salt repository is influenced by the dissolution of rock salt in the undersaturated water and the heat production by the HLW, which results in density changes of the fluid. Furthermore, if water would permeate the salt, its mechanical properties would change. Due to sustained convergence of the access tunnels and the shafts fluids would be expelled from the mining area and fluid pockets might get enclosed in the rock salt.

If the disposal boreholes are underpressured with respect to the water filled drifts and tunnels and the seal would have some defects, fluids might migrate into the disposal bore hole and mobilize part of the dissolvable radioactive material, which subsequently could be expelled due to ongoing convergence of the borehole. As a consequence contaminated fluids could migrate from the boreholes to the drifts and tunnels.

Background and comments

None

Question 5 Which are the main potential pathways to the biosphere for radioactive contaminants that may escape from the sealed waste package?

Short answer

The shortest most direct pathway in the salt repository is via the drift, tunnels to the shaft and surface water or soil. The other pathway might be through the drift, tunnels, shaft and via a defect in the shaft mantle to the shallow aquifer. A less probable pathway might be via an anhydrite layer, which is in contact with the mine drift, tunnel or shaft, to the shallow aquifer.

Argumentation

The permeability of the anhydrite layer is probably too small to create a preferential pathway for contaminated fluids.

Background and comments

None

B.4 Response of expert 4

General

In the framework of geologic sequestration of CO_2, it is these days common practice to use a methodology for scenario analysis that is based on a comprehensive inventory of risk factors, so called FEP's (Features, Events and Processes) and subsequent selection of the most critical ones. There is an amount of software available that allows for a consistent treatment of these FEP's. A comprehensive description of such an approach is a.o. given in:

Overview of the FEP Analysis Approach to Model Development
NIREX Science Report no. S/98/009, United Kingdom

Modelling Requirements for Future Assessment Based on FEP Analysis
NIREX Science Report no. S/98/012, United Kingdom

Although this method is probably also well known in the world of safety assessment and scenario analysis for nuclear waste repositories, I have not found that clearly in the document. For that reason I wanted to mention it here. Of course, such an approach still requires expert judgement in order to identify the relevant Features, Events and Processes in the different stages of the storage of nuclear waste, and their relative importance.

Question 1 ***Which events or processes could lead to a situation where a flooded underground disposal facility (flooded due to e.g. abandonment or a mining accident) cannot be recovered?***

Answer: In my opinion only catastrophic events such as earthquakes or volcanic activity could lead to a situation where the disposed material cannot be recovered.

Argumentation: All other processes other than the catastrophic ones are relatively slow processes. In order for the material in the facility to become non-recoverable, it has to move to a position that is either not known or not accessible. It seems to me that that cannot be accomplished by “normal” mechanical movement in either rock salt or clay.

Comments: Since repositories are in general positioned in areas of no or extremely little geological activity, the main reason for “catastrophic” movement of the facility would be human activity. That would lead to the option that such an event could happen due to the construction of the facility, and that seems highly unlikely. Even the “earthquakes” that are a result of gas production from a large subsurface gas reservoir would not lead to a situation where large movements of the underground facility would occur. And these cover a much larger area than the disposal facility.

Question 2 Do you think that the broad description of the abandonment scenario given in Section A.3.5 (summarised below in the paragraph ‘background’) is correct?

Answer : yes, under the given assumptions, I think that the description of the abandonment scenario as given is correct.

Argumentation: I cannot imagine any other pathway for the radioactive material to be transported to the biosphere, again given the prevailing assumptions.

Comments: The basic assumption in this scenario is that the galleries and the boreholes that contain the canisters are properly backfilled and sealed. A much faster transport path to the biosphere could be created by leakage of the backfilling and sealing. In that case, water could bypass the near (geological) environment and the aquifer overlying the geological formation in which the facility is situated. Such a situation could develop when the pressure in the water filled galleries and boreholes increases dramatically due to the movement of the either salt or clay. Local (mechanical) heterogeneities could than cause the opening of preferential pathways, which would result in a very fast transport of the radioactive material dissolved in the water phase.

As was already stated in the question itself, the description of the abandonment scenario is very broad. Even though the pathway is clear, it is not obvious what the (total) transport rates will be, because these are very much influenced by many processes and events, and the coupling between these. For instance, local heterogeneities in the hydraulic parameters that control the transport in the different geological formations are in general not very well known. Also, pressure differences and temperature differences may have a pronounced effect on especially the geochemical properties that control the adsorption characteristics (mainly of clay) or on the mechanical properties that control the sealing capacity of the geological formation.

Regarding the temperature effect, I assume that the temperature profiles that are presented in the elicitation report are calculated from a conduction equation (that is at least what I think looking at these profiles). However, if there is for some reason substantial water flow taking place, e.g. because preferential flow paths develop, the convective transport of heat may also play a role. This may result in a larger energy transfer into the formation, and, possibly in higher temperatures in the near environment of the disposal facility. This will in turn lead to larger effects than anticipated, e.g. with regard to the release of crystalline water from the rock salt.

Finally, the water flooding the disposal facility may have a different chemical composition than the ambient water in the geological formation. For a facility in rock salt this probably does not have a large effect, because dissolution of the rock salt is only minimally influenced by that composition. However, for clay this may very well influence both the mechanical as the geochemical properties, and therefore also the adsorption properties and the strength of the formation.

Question 3 Which processes can lead to flooding of the facility after abandonment of the facility?

<u>Answer:</u> flooding of the facility could be caused by leakage of the seals, dissolution of salt seams in rock salt, cracks or fractures developing due to mechanical failure of the formation in combination with pressure gradients.

<u>Argumentation:</u> There is only a limited number of ways water can enter the facility: either through the backfilling and/or seals, or through the surrounding geological formation. Given the time frame, substantial water transport through the geological formation can only occur if preferential pathways with low resistances (high permeabilities) are present. These in turn, can only be created in rock salt by dissolution, and in both rock salt and clay due to changing pressure gradients and weak mechanical spots in the formation itself.

<u>Comments:</u> It seems to me that the backfilling and the sealing are the weakest points. These will be constructed while the facility is in operation, and are as yet not fully proven to be “fail-safe” for a period of 50 years or more.

In contrast, the geological formations, both clay and rock salt, have a visco-elastic behaviour, such that cracks and preferential flow paths will be closed due to the creep of the material. However, the latter is a very slow process, which means that preferential flow paths that are created for some reason, will close slowly, still allowing for enhanced water transport during a certain time.

Local heterogeneities in the properties of the formations surrounding the facility will play a major role in determining in the occurrence of preferential flow paths.
For rock salt these will have to do with possible layers that are easily dissolvable in water, easier than the main part of the salt. However, since dissolution is in itself a slow process as well, it is highly unlikely that this will create the possibility of enhanced water transport.

Local mechanical weaknesses in the surrounding formation may cause more of a problem. If these exist, pressure gradients may cause cracks to occur, both in rock salt as in clay. This will be a much faster process than the dissolution of salt, and will therefore not be as quickly counteracted by the visco-elastic behaviour of the surrounding formation. Pressure gradients in the water may be enhanced by the same visco-elastic behaviour.

In clay formations, the composition of the water in the facility may have a pronounced effect on the mechanical properties of the clay, and cause preferential pathways to be created.

Question 4 Which processes and mechanisms control the future evolution of flooded galleries?
Answer: The future evolution will be controlled by the mechanical properties and processes of the host rock and of the seals of the disposal cells.

Argumentation: If no catastrophic changes occur in the future, the mechanics of the system will fully control the evolution of the facility. These mechanics will be determined by the mechanical properties of the host rock, possible changes in these properties, and outside stresses on the system.

Comments: This is a little bit outside my field of experience. But it seems to me that the visco-elastic behaviour of either the rock salt or the clay is the determining factor for the future evolution. Whether the access galleries and the shafts have been filled and sealed or not does not really play a role then (it does however for the potential pathways to the biosphere (see question 5). Possible changes in the mechanical properties of the geological formation hosting the facility could occur e.g. due to temperature effects generated by the heat production in the waste.

Outside stresses on the system could change if we consider large time periods, and the effect of e.g. climate change, or, if we consider geological times, the occurrence of a new ice age. That, however, is outside the scope of this elicitation.

Question 5 Which are the main potential pathways to the biosphere for radioactive contaminants that may escape from the sealed waste package?

Answer: The main potential migration pathway to the biosphere is through advection and diffusion in the shaft that connects the facility directly to the biosphere, or by advection and diffusion in the water in the different geological formations.

Argumentation: There are only two pathways that connect the facility with the biosphere: a direct connection through the shaft that was used for access to the facility or a pathway through all geological formations surrounding and overlying the facility.

Comments: If the access galleries and the shafts have not been filled and sealed, radionuclides that leak through one or more of the seals of the disposal cells could have a direct connection to the biosphere, irrespective whether the facility is located in rock salt or in clay. This pathway provides by far the fastest transport route, even though the transport could be diffusion controlled. In the early stages, when the radioactive waste still generates heat, temperature differences might create forced convection in the shaft. In principle, the water entering the shaft from the leaking seals will have a higher temperature than the ambient water, and has therefore a lower density, creating a physical unstable situation in which convection cells might develop, enhancing the transport of radioactive contaminants to the biosphere. Given the relative large diameter of the shafts this would certainly be possible. Since the shafts are not backfilled, this is a free flow region where hardly any retardation of the contaminants will occur (only possibly at the walls of the shafts).

The pathways through the different geological formations have extensively been studied in the past. Basically, the heterogeneity of hydraulic and geochemical characteristics plays a major role, and especially the (unknown) spatial distribution of these parameters. However, it is obvious that this pathway will result in a much smaller exposure.

B.5 Response of expert 5

Question 1 ***Which events or processes could lead to a situation where a flooded underground disposal facility (flooded due to e.g. abandonment or a mining accident) cannot be recovered?***

Short answer

If the facility is insufficiently characterized and validated, flooding may lead to large deformations and changes in geometry which in turn can create pathways to an aquifer that allow groundwater fluxes so large that are uncontrollable using present day technology, within the 100 years to be addressed here.

Argumentation

I was very surprised by the depth of knowledge presented in the formulation of the reference case. The way it is presented contains an amount of uncertainty which is fully unacceptable for such a reference case in my opinion.

(1) the structure of the salt body is presented as a cross section, leaving out the third dimension. Salt domes like this one are inherently 3D, complex structures. Considering this profile it is conceivable that the mining operations drill or mine into a highly unstable part of the mine, such a high pressure fluid pocket, a permeable sediment inclusion or even the country rock which is connected to a large aquifer. Adequate characterization requires modern high resolution 3D seismic, several boreholes which are extensively studied, numerical simulation of the geologic evolution of this body, resulting in an accurate characterization with well constrained uncertainties, even before starting to build the repository. During construction, extensive and systematic data collection is required, updating the models.

(2) Based on the information above, extensive simulations of the different flooding scenarios and their consequences must be conducted, to make a convincing case that an uncontrollable and unrecoverable flooding event has such a low probability that it is accepted as negligible by the responsible authorities.

(3) For such simulations, a complete characterization of the rocks involved is required. The table of properties in the reference case is very incomplete. First, it does not contain descriptions of all the rock types involved. For example, Biscofite ($MgCl_6.6H_2O$) which has a lower melting point than Carnallite and is present in the subsurface of the Netherlands in such quantities that it is being mined commercially, is not on the list. Nor is there a list of all the relevant mechanical properties of the rock salt given, such as dilatancy limits, creep parameters. These must be

defined for all the different Halite types involved and this has been done for example for the Gorleben salt dome.

(4) There is no information on the hydrogeologic regime in the rocks around the salt dome, for example on the presence of thermohaline convection cells so it is not possible to predict where the critical points are where a transport pathway from the salt dome could lead to such high fluxes of groundwater.

(5) Based on the above, the main event or process leading to an unrecoverable flooded mine is the design and construction process which is not of adequate quality.

(6) It can lead to unexpected situations where large dilatant deformation, dissolution channels and connections of permeable inclusions in the salt lead to unexpected and uncontrollable fluid fluxes in such a way that presently available technology is inadequate to recover the facility.

(7) I am convinced that if state of the art methods and the best available characterization is used during site selection (a suitable site may not be present in the Netherlands), design and construction, based on open discussion that leads to acceptance of the design by the scientific and engineering community, the occurrence of unrecoverable flooding can be made so unlikely that the risk is acceptable for the community.

Question 2 Do you think that the broad description of the abandonment scenario given in Section A.3.5 (summarised below in the paragraph 'background') is correct?

Short answer

In my opinion the scenario is correct but incomplete. Possible additional processes such as the generation of a gas phase around the waste canisters and the creation of lithostatic fluid pressures must be included in the model scenarios.

Argumentation

The abandonment scenario described is probably the one with the highest potential transport efficiency of waste into the biosphere. In my opinion it is correct but incomplete.

I would propose the following chain of events (my additions in bold)

- Abandonment of the facility
- Flooding of unsealed galleries
- **Creation of dissolution cavities and associated deformation**
- Soluble parts of the waste dissolve in the water
- Advective flow **(thermal convection?)** and diffusion through the remains of the underground infrastructure
- **Deformation of the subsurface, with possible changes in permeability.**
- **Creation of cells with different pressure regimes and fluid contents. Reactive transport processes.**
- Radioactive material reaches aquifer and biosphere
- Exposure of humans to radioactive material

Firstly, the flooding will most likely happen by salt - unsaturated brines which will dissolve the surrounding salts. This will be made much more severe if unknown K-Mg salts are present in the structure (see my answer to Question 1). This will lead to solution of the evaporates, by processes comparable to solution mining or to those related to the formation of carst cavities in salt. The extent of these processes will very strongly depend on the presence of feedback processes (fluid flow pathways will be enlarged by the dissolution process, thereby increasing the permeability). Such processes must be considered using state of the art simulations to make sure their extent is limited and risks acceptable.
Secondly, the flooding of the facilities will lead to enhanced deformations of the evaporites, especially if K-Mg salt are in contact. Deformation can lead to the creation of higher than hydrostatic pore pressures in converging cavities, which are surrounded by impermeable salt, but also to dilatancy, and creation of additional fluid pathways.
If the surroundings of the canisters also produce significant amounts of gas (there is not sufficient information provided to know if this is the case) then the fluid flow models must include migration of gas also.
The permeability of Halite is very strongly dependent on the mean effective stress, which in turn is dependent on pore pressure. This process is well known and is an issue with the abandonment of solution mining caverns. High-pressure fluids will in turn cause the surrounding salt to dilate and such fluids pockets are known to migrate through the salt. I do not know if this process, at the possible size of fluid pockets in the area considered.

Thirdly, the advecting fluids will undergo reactions with major or minor components in the salt. This can lead to major dissolution in the case of K-Mg salt, but also to the transformation of anhydrite into gypsum, or reactions which convert dissolved waste into mineral grains thus preventing further migration.

I am convinced that if state of the art methods and the best available characterization is used during site selection, design and construction, based on open discussion that leads to acceptance of the design by the scientific and engineering community, the risk can be made acceptable for the community.

Question 3 Which processes can lead to flooding of the facility after abandonment of the facility?

<u>Short answer</u>

In this answer I consider only the 100-year timescale and not discuss longer-term geologic processes. The processes form a continuum with those during operation, but now there are no new galleries and boreholes created but time available is longer.

<u>Argumentation</u>

Most of the answer to this question is the same as my answer to question 2 and I will not repeat the whole answer here. There are two main differences: firstly in this phase there are no new galleries and boreholes created but time is longer in which deformation and fluid flow can occur. Secondly, the amount of information on the subsurface is higher because (I assume) models of the evolution have been updated to include information collected during operation. Therefore the abandonment procedures can be adapted (e.g. more backfilling, different materials) to allow only predictable, acceptable processes.

If the facility is abandoned, differential stresses in salt remain, the waste generates heat, and pathways for fluids which were initially very limited can become amplified. Once the facility is flooded, all the processes I discussed in my answer to Question 2 must be considered.

Question 4 Which processes and mechanisms control the future evolution of flooded galleries?

<u>Short answer</u>

The combined processes of deformation, fluid flow, reactions and dissolution will be all present. The stated assumptions consider a hydrostatic fluid pressure regime. Prediction of these processes and their consequences will be much improved if the design is based on state of the art characterization of the underground structure, material properties.

Argumentation

The flooded galleries can be compared to a solution mine in salt. As long as state of the art design criteria are maintained these can be operated stably, but design errors can lead to unexpected migration of the caverns, subsidence at the surface and other processes. In the case considered here much of what will happen depends on the circulation pathways of groundwater which determine how much and which salt is dissolved. Associated deformations can be predicted as long as material properties are accurately known and models take into account the combined processes of deformation, fluid flow, reactions and dissolution, and the couplings between these. I have described these processes in my answers above. Another key question is the way the galleries are connected to an aquifer, here the design of access shafts and facilities has to be taken into careful consideration for the modelling.

Question 5 Which are the main potential pathways to the biosphere for radioactive contaminants that may escape from the sealed waste package?

Short answer

At the 100 years time scale considered here the most likely transport of radioactive contaminants is via advective flow of groundwater. Transfer of the radionuclides from the "salt dome" volume to the "overburden" volume can occur via the access shaft – gallery system or via a dissolution channel to a previously unknown aquifer which was created by the flooding event.

Argumentation

The mechanism and processes that control the transfer of the contaminants from the water in the flooded facility to the water in the aquifer will strongly depend on the geometry and transport properties of the flooded shaft (all the way to the surface). Based on the information provided it is very difficult to estimate the rates of transport but worst case scenarios can assume a fully open connection with advecting brines. Rates of flow calculations will have to take into account thermal gradients and convection, connection to overpressured compartments (see above) and can be modelled once the appropriate geometries and structures are known. Reactive transport, where radionuclides can be In addition, the facility can be designed to provide resistance to transport in the case of flooding.

A second potential pathway is "sideways" into the surrounding rocks in which fluid pathways, formed during flooding, are connected to deeper aquifers.

References

1 R. M. Cooke, L. J. H. Goossens *Procedures guide for structured expert judgment* EUR 18820 EN

2 Commission on Radioactive Waste Disposal (CORA) *Retrievable disposal of radioactive waste in The Netherlands* Ministry of Economic Affairs. The Hague, February 2001. downlaod at http://www.nrg-nl.com/product/re/radwaste/policy/index.html

3 N. Cadelli, G. Cottone, S. Orlowski, G. Bertozzi *PAGIS Performance Assessment of Geological Isolation Systems for Radioactive Waste*, EUR 11775, 1988

4 Jan Marivoet, Thomas Beuth, Jesús Alonso, Dirk-Alexander Becker *Task reports for the first group of topics: Safety Functions, Definition and Assessment of Scenarios, Uncertainty Management and Uncertainty Analysis, Safety Indicators and Performance/Function Indicators* PAMINA D 1.1.1 March 2008, download at http://www.ip-pamina.eu/publications/reports/index.html

5 Jan Marivoet, Thomas Beuth *General outlines for the development of stylized scenarios.*PAMINA internal report M3.1.19. Will be published in PAMINA D3.1.1 at http://www.ip-pamina.eu/publications/reports/index.html

6 D.A. Galson, R.A. Kłos, C. Serres, *Biosphere - WP1.1 PAMINA internal report M1.1.9*, July 2009. Will be published in PAMINA D1.1.3 at http://www.ip-pamina.eu/publications/reports/index.html