OPERA

Description of relevant scenarios for the OPERA disposal concept

OPERA-PU-NRG7111

Radioactive substances and ionizing radiation are used in medicine, industry, agriculture, research, education and electricity production. This generates radioactive waste. In the Netherlands, this waste is collected, treated and stored by COVRA (Centrale Organisatie Voor Radioactief Afval). After interim storage for a period of at least 100 years radioactive waste is intended for disposal. There is a world-wide scientific and technical consensus that geological disposal represents the safest long-term option for radioactive waste.

Geological disposal is emplacement of radioactive waste in deep underground formations. The goal of geological disposal is long-term isolation of radioactive waste from our living environment in order to avoid exposure of future generations to ionising radiation from the waste. OPERA (OnderzoeksProgramma Eindberging Radioactief Afval) is the Dutch research programme on geological disposal of radioactive waste.

Within OPERA, researchers of different organisations in different areas of expertise will cooperate on the initial, conditional Safety Cases for the host rocks Boom Clay and Zechstein rock salt. As the radioactive waste disposal process in the Netherlands is at an early, conceptual phase and the previous research programme has ended more than a decade ago, in OPERA a first preliminary or initial safety case will be developed to structure the research necessary for the eventual development of a repository in the Netherlands. The safety case is conditional since only the long-term safety of a generic repository will be assessed. OPERA is financed by the Dutch Ministry of Economic Affairs and the public limited liability company Electriciteits-Produktiemaatschappij Zuid-Nederland (EPZ) and coordinated by COVRA. Further details on OPERA and its outcomes can be accessed at www.covra.nl.

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Contents

Summary

This report describes the scenarios and assessment cases that have been adopted for the OPERA safety assessment. For completeness checking of the list of identified scenarios and assessment cases, experts have evaluated all 366 FEPs in the OPERA FEP catalogue and identified those FEPs that may have an adverse effect on one or more of the safety functions that have been allocated to the OPERA disposal concept in Boom Clay.

Based on the evaluation, 24 assessment cases have been described, classified as assessment cases for the 1) Normal Evolution Scenario, 2) the six Altered Evolution Scenarios, and 3) so-called “What-If” cases.

The identified scenarios for a generic disposal facility in Boom Clay are adequately well established to analyse with sufficient confidence the facility’s possible future developments as a result of natural processes and events as well as human actions.

Samenvatting

Dit rapport beschrijft de scenario’s die zullen worden beschouwd bij de lange-termijn veiligheidsanalyses van het OPERA programma. Om een zo volledig mogelijk beeld te krijgen van de mogelijke toekomstige ontwikkelingen van de eindberging en haar omgeving hebben experts alle 366 FEPs in de OPERA FEP catalogus geëvalueerd. Hierbij zijn die FEPs geïdentificeerd die een invloed kunnen hebben op één of meer van de veiligheidsfuncties zoals die zijn toegekend aan het OPERA eindbergingsconcept in Boomse Klei.

Op basis van de evaluatie zijn 24 “assessment cases” beschreven, waarbij onderscheid is gemaakt tussen 1) het normale evolutie scenario, 2) een zestal alternatieve scenario’s, en 3) zogenoemde “What-If” scenario’s.

De geïdentificeerde scenario’s voor een generieke eindbergingsfaciliteit in Boomse Klei zijn in voldoende mate ontwikkeld om een integraal en betrouwbaar beeld te verkrijgen van de mogelijke toekomstige ontwikkelingen van de faciliteit ten gevolge van de inwerking van natuurlijke processen en menselijke handelingen.

1. Introduction

1.1. Background

The main objective of the OPERA research programme is to provide tools and data for the development of Safety Cases for national repository concepts for radioactive waste disposals in two host rocks present in the Netherlands, salt rock and Boom Clay (Verhoef, 2011a; p.6). Within the OPERA context, the Safety Case has been explained as a collection of arguments in support of the long-term safety of the repository (Verhoef, 2011a; p.5). A Safety Case comprises the findings of a safety assessment and a statement of confidence in these findings.

A central aspect of the Safety Case is the execution of a safety assessment. Within the OPERA research programme, a generic safety assessment is being performed that evaluates all safety relevant aspects of the disposal concept (design of repository) and will assess the long-term safety of such a facility (Verhoef, 2011a; p.5).

The execution of a safety assessment requires a sound and consistent methodology fit for purpose, a critical evaluation of assumptions used in the safety assessment calculations, the definition of evolution scenarios utilizing the identification and classification of relevant features, events, and processes (FEPs), a judgement of the impact of FEPs on safety functions, the evaluation of uncertainties, and the interpretation of the calculated results. The methodology of the OPERA safety assessment has been explained in (Grupa, 2014), "*Report on the safety assessment methodology*".

The present report is the result of the research proposed for Task 7.1.1, S*cenario development,* in the OPERA Research Plan (Verhoef, 2011a). Scenarios are possible future states of the disposal system, and can be defined as combinations of features, events and processes (FEPs) that may affect the performance of the disposal system.

Scenario outlines for a disposal in clay have already been developed since the earliest safety assessments for geological disposal, e.g. in the EC PAGIS study of 1988 (Marivoet, 1988). In the Dutch CORA programme the methodology of scenario development adopted within the PROSA project for a salt-based disposal facility (Prij, 1993) was also applied to a clay-based facility (Grupa, 2000). That exercise was also the last significant one related to the development of scenarios for clay-based repositories in the Netherlands.

At the start of OPERA it was recognized that there would be no need to start the development of scenarios for clay-based repositories from scratch. Within the Belgian SAFIR-2 study several scenarios have been proposed and analysed in more or less detail (ONDRAF/NIRAS, 2001; Section 11.5.2.2.2). These scenarios have been used as a starting point in the present OPERA safety assessment.

Since the OPERA disposal concept in clay is a generic design it is not possible to identify and develop site-specific scenarios, so for the present analysis the use of generic scenario descriptions is expected to be adequate. However, for completeness checking a FEP screening process has been undertaken in order to identify potential alternative scenarios which are additional to the above-mentioned ones. This methodology is in line with internationally accepted procedures to determine possible future evolutions of a disposal system (e.g. NEA, 2012; p.10).

1.2. Objectives

The objective of this report is to describe the scenarios and assessment cases that have been adopted for the OPERA safety assessment. In addition, the OPERA FEP database (Schelland, 2014) has been evaluated for completeness checking of the list of identified scenarios and assessment cases.

To enable the analysis of their consequences, the scenarios described in the present report have to be translated into physical and geochemical models. That is performed in OPERA Task 7.1.2.

1.3. Realization

This report presents general descriptions of all scenarios relevant for the assessment of the long-term safety of a repository in Boom Clay. The set of scenarios is based on available information from various studies, e.g. the Belgian SAFIR-2 study. Within the context of the OPERA safety concept the scenarios have been evaluated and a general outline of the features and the resulting altered evolutions of these scenarios is defined.

Each of the identified scenarios, including the Normal Evolution Scenario, is expected to include several variations. In the OPERA safety assessment these variations are denoted as “Assessment Cases”.

For completeness checking a FEP screening process has been undertaken in order to identify potential alternative scenarios which are additional to the above-mentioned ones (conform NEA, 2012; p.10-11). This screening method is based on analyses of how the safety functions of the disposal system may be affected by possible events and processes.

The FEP screening process is also applied to identify FEPs that potentially may lead to assessment cases for each of the scenarios. The present report will use these FEPs only to identify the assessment cases. The precise definition of the assessment cases is part of OPERA Task 7.1.2 *Scenario representation,* which will result in M7.1.2.1 *Report on scenario model representation* and M7.1.2.2 *Reference list of model parameter for all scenarios*.

The study and analysis presented in this report are performed by members of the OPAP-consortium, consisting of NRG, TNO, SCK·CEN and GRS. For this task NRG delivered the expertise on the Engineered Barrier System and TNO on the geological features. The FEP screening methodology is developed in a joint effort of NRG and TNO.

1.4. Explanation contents

Chapter 2 describes the methodology for the development and justification of the set of relevant scenarios.

Chapter 3 describes all scenarios in the present set, i.e. the normal evoluton scenario and the altered evolution scenarios.

Chapter 4 describes the results of the FEP screening and the resulting assessment cases for each scenario.

Chapter 5 concludes the report with an overview of the main results.

2. Methodology

2.1. The framework provided by the safety case

Assessing the post-closure radiologic impact is a key topic in the entire development of a Safety Case for deep geological disposal of radioactive waste, from preliminary design considerations to final closure. IAEA SSG-23 (IAEA, 2012; p. 45) defines the following seven critical steps in their post-closure safety assessment methodology:

1. Specification of the context for the assessment;
2. Description of the waste disposal system;
3. Development and justification of scenarios;
4. Formulation and implementation of models;
5. Performance of simulations and analysis of results, including sensitivity and uncertainty analyses;
6. Comparison with safety criteria;
7. Review and modification of the assessment, if necessary (i.e. iteration).

These steps have been described in more detail in OPERA report OPERA-PU-NRG2121 (Grupa, 2014). The present document reflects **Step 3: *Development and justification of scenarios***.

IAEA SSG-23 guidance

Chapter 5 of SSG-23 (IAEA, 2012) provides additional details for each of the above-mentioned seven steps. For development and justification of scenarios the following guidance is given:

"Scenarios are descriptions of alternative possible evolutions of the disposal system. The development of scenarios is used to identify and define 'assessment cases' that are consistent with the assessment context."

and:

"*Scenarios represent structured combinations of features, events and processes (FEPs) relevant to the performance of the disposal system*."

For implementing the above-mentioned considerations into relevant scenarios for the OPERA safety assessment two main methods have been used for constructing scenarios. One main method may be described as a 'bottom-up' method and is based on screening of features, events and processes (FEPs). An alternative ('top-down') method for developing scenarios is based on analyses of how the safety functions of the disposal system may be affected by possible events and processes (e.g. NEA, 2012; p.10).

In both cases, all features, events and processes that could significantly influence the performance of the disposal system should be addressed in the long-term safety assessment.

NEA Report 78121: The Nature and Purpose of the Post-closure Safety Cases for Geological Repositories

NEA's approach to safety assessment (NEA, 2004; p.39-40) stipulates a list of criteria that should be addressed by the safety assessment and that is related to the R&D program. The following criteria are relevant for the development and justification of scenarios:

- The approach is logical, clear and systematic;
- The assessment is conducted within an auditable framework;
- Suitable criteria have been developed for the exclusion or inclusion of features, events and processes (FEPs) from scenarios for evaluation;
- FEPs to be included in the assessment are audited against international FEP lists;
- Evidence supporting the choice of scenarios, models and data comes from a wide range of sources, including field, laboratory and theoretical studies, and multiple lines of argument are, where possible, made to support the choice of particular scenarios, model assumptions and parameter values;

As mentioned above, important topics in the development and justification of scenarios are FEPs and safety functions attributed to the disposal system. The following sections describe the FEPs and safety functions in somewhat more detail.

2.2.Features, Events, and Processes

An important requisite of the information that goes into a safety assessment is that the models and data should describe and/or take into account only the features, events, and processes (FEPs) of the disposal system that are relevant to the long-term safety of the disposal facility.

As part of OPERA project OSCAR (WP2), 366 FEPs have been identified and listed. Their relevance for OPERA has been described in OPERA-PU-TNO2123A and OPERA-PU-TNO2123B (Schelland, 2014). The following five classes of FEPs can be distinguished:

- External Factors, e.g. geological and climatic events and processes, and future human actions (excavations, drilling, mining, …);
- Waste Package Factors, e.g. waste forms and properties, thermal and chemical processes occurring in the waste;
- Repository Factors, an inventory of radiological, chemical, hydraulic, thermal, and physical/mechanical processes relevant for the evolution of the engineered barriers of the facility;
- Geosphere Factors, e.g. geochemical evolution of the geosphere, thermal and hydraulic processes, transport of contaminants;

  > ❖ In the various NEA publications relating to FEPs and FEP databases no clear definition of the term “Geosphere” is provided. The reason for the indistinctness is that the NEA FEP Database is built on information provided by several countries, each relying on their own interpretation of the extension of the geosphere.
  > ❖ Within OPERA, the geosphere (or: “far field”) comprises the host rock that is not damaged during excavating of volumes and the geological media surrounding the host rock (Verhoef, 2011a; p.8).

- Biosphere Factors, e.g. processes influencing the future radiological impact on humans and the environment

Many of the 366 FEPs will to some extent be included in the OPERA integrated safety assessment model either in the form of models or as (sets of) parameters. In the present report the FEP database has been applied to check for completeness of the proposed scenarios (see Section 2.5), in accordance with internationally accepted procedures (e.g. NEA, 2012; p.10).

2.3. The safety functions

The OPERA method of scenario development is based on the PROSA-method (Prij, 1993), that has been extended during the CORA research programme (Grupa, 2000; Ch.2), and recent developments in the project PAMINA (Beuth, 2009). The PROSA-method is iterative and makes use of a preliminary set of scenario outlines prepared in an early stage of OPERA. The PROSA method has been refined in light of the discussion in the PAMINA project regarding the role of safety functions (Bailey, 2011; p.98-113).

The safety functions play a crucial role in the FEP screening procedure. In OPERA the safety functions as defined by ONDRAF/NIRAS (ONDRAF/NIRAS, 2009; Section 3.4.1) have been adopted. Safety functions are defined as the functions that a disposal system should fulfil so as to achieve its fundamental objective of providing long-term safety through a concentration and confinement strategy, while limiting the burden placed on future generations (ONDRAF/NIRAS, 2009; p.12). Figure 2-1 gives a graphical presentation of the safety functions attributed to the disposal system in Boom Clay.

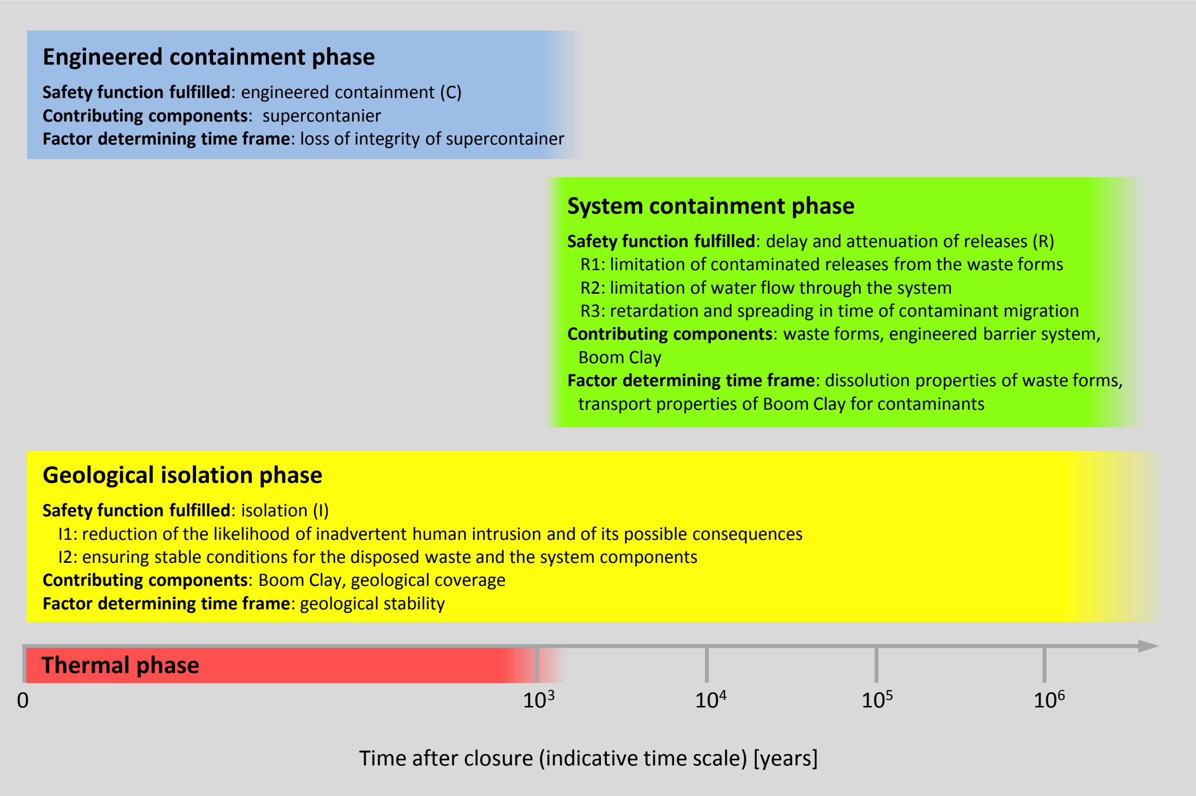

Figure 2-1 **Safety functions provided by the main components of the disposal system in Boom Clay and its geological coverage. The timescale applies to HLW.**

The following descriptions of the safety functions apply (ONDRAF/NIRAS, 2009; Annex 1):

Engineered containment (C)

The function that consists of preventing as long as required the release of contaminants from the waste container. The duration of the engineered containment function depends on the waste type. The indicative time shown in Figure 2-1 applies to HLW[1].

[1] Since in the OPERA disposal concept the ILW/LLW containers are not conditioned with additional engineered features the time scale of the engineered containment phase for these waste types may differ from those for HLW.

Delay and attenuation of the releases (R)

The function that consists of retaining the contaminants within the disposal system for as long as required, by:

- Limitation of contaminant releases from the waste forms (R1)
- Limitation of the water flow through the disposal system[2] (R2)
- Retardation of contaminant migration to the environment of the contaminants released from the waste packages (R3).

Isolation (I)

The function that consists of isolating the wastes durably from man and the environment, by:

- Reduction of the likelihood of inadvertent human intrusion (I1)
- Ensuring stable conditions for the disposed waste and the system components (I2)

2.4. Development and justification of scenarios

Scenario outlines for a disposal in clay have already been developed since the earliest safety assessments for geological disposal. For example, in the EC PAGIS study of 1988 (Marivoet, 1988), Normal Evolution Scenarios and two Altered Evolution Scenarios (climatic changes and faulting) were identified for two reference sites: in Boom clay and in Oxford clay. Since then the list of scenarios has been growing in the various national and international programmes. At the start of OPERA the following list of scenarios was already available from various studies, e.g. the Belgian SAFIR-2 study (ONDRAF/NIRAS, 2001; Section 11.5.2.2.2):

- Normal Evolution Scenario (includes the expected future climatic changes)
- Abandonment Scenario
- Poor Sealing Scenario
- Anthropogenic greenhouse scenario
- Fault Scenario
- Intensified glaciation scenario
- Human Intrusion and Human Action Scenarios

Each of these scenarios, including the Normal Evolution Scenario, is expected to include several variations. Following IAEA SSG-23, in the OPERA safety assessment these variations are denoted as “Assessment Cases” (see also Section 2.5).

Since the OPERA disposal concept in Boom Clay is a generic design (Verhoef, 2011b) it is not possible to identify and develop site-specific scenarios, so for the present analysis the use of generic scenario descriptions is expected to be adequate.

For completeness checking a FEP screening process has been undertaken in order to identify potential alternative scenarios which are additional to the above-mentioned ones. This screening method is typically a ‘top-down’ method for developing scenarios, as described in SSG-23 (IAEA, 2012; p.54). The method is based on analyses of how the safety functions of the disposal system may be affected by possible events and processes.

[2] A repository together with, in the case of geological disposal, the host formation in which it is built (ONDRAF/NIRAS, 2009; Annex 1).

This FEP screening process is also used to identify FEPs that potentially may lead to assessment cases for each of the scenarios. The present report will use these FEPs only to identify the assessment cases. The precise definition of the assessment cases is part of OPERA Task 7.1.2 *Scenario representation*, which will result in M7.1.2.1 *Report on scenario model representation* and M7.1.2.2 *Reference list of model parameter for all scenarios*.

Summarizing, the following ingredients are needed for the development and justification of scenarios:

1. Description of the scenarios
2. FEP list
3. FEP screening process
4. Reporting of the results of the screening

The description of the scenarios is provided in Chapter 3. As already noted, the OPERA FEP list has been developed in the OPERA OSCAR project and has been reported as (Schelland, 2014). The methodology of the FEP screening process is elucidated in the following Section 2.5, the results of the FEP screening are provided in Chapter 4.

2.5. The FEP screening process

The screening of the FEPs included in the OPERA FEP list is based on the methodology put forward in the CORA programme (Grupa, 2000; Ch.2) and involves an assessment of the potential impact of each FEP on the safety functions of the disposal system. The screening has been performed by experts from NRG and from TNO and is shown in the following flow chart.

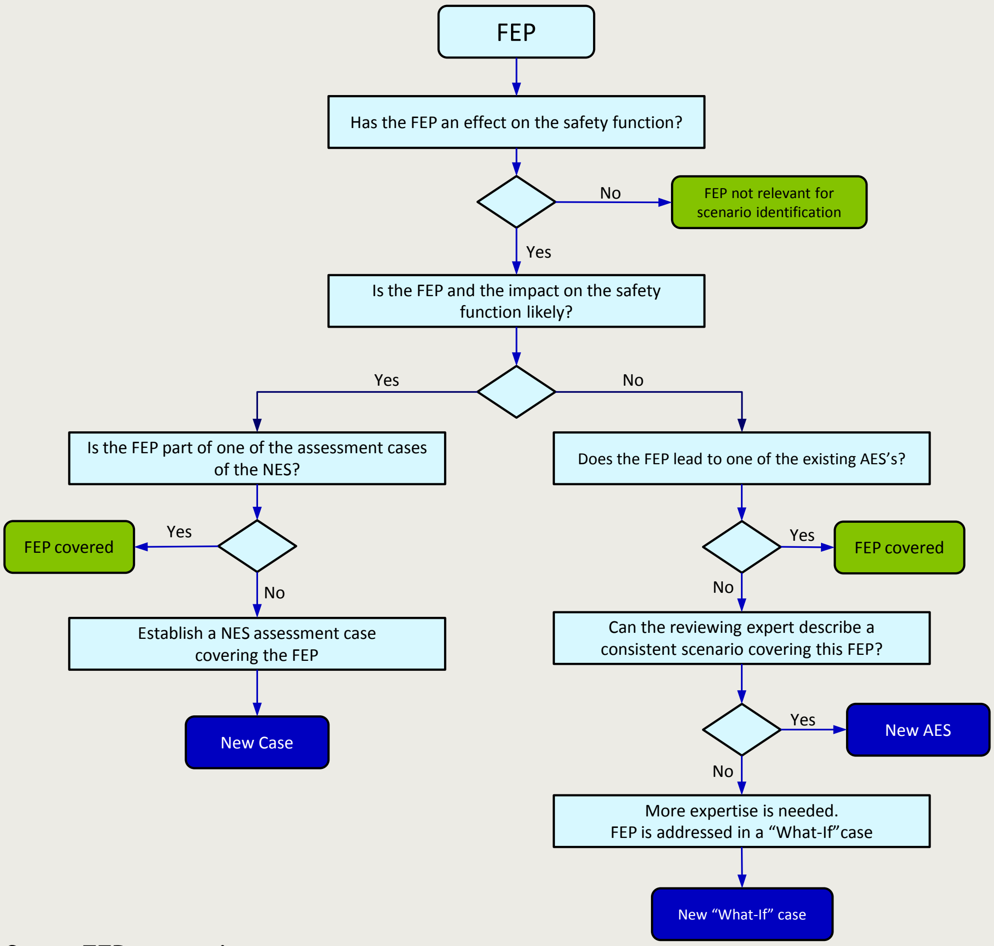

Figure 2-2 FEP screening process

Figure 2-2 shows that there are 5 possible outcomes of the screening of a single FEP:

1. The FEP is not relevant for scenario identification
2. The FEP is covered by the present set of scenario's
3. The FEP is covered by the Normal Evolution Scenario (NES), and will be addressed as an assessment case in the scenario.
4. The FEP leads the reviewing expert to a new Altered Evolution Scenario (AES).
5. The expert is in doubt to oversee the consequences of the potential impact of the FEP; the FEP has to be evaluated in a What-If case study, and from that it has to be concluded whether the FEP is covered in the existing set of scenarios, or whether a new AES is needed.

In the screening process described in Figure 2-2, only FEPs have been identified that potentially may have an adverse effect on the safety function.

The scheme of Figure 2-2 distinguishes so-called "Assessment cases" and "What-If" cases:

- Assessment cases are specific assessments of evolutions that fit in a given scenario. The FEP screening process described above led to the formulation of several additional assessment cases.
- What-If cases address phenomena that are outside the range of available scientific evidence. NAGRA's Opalinus Clay project originally introduced What-If cases as follows (NAGRA, 2002; p. VIII): "*In order to test the robustness of the repository system, a category of "what if?" cases has been introduced addressing phenomena that are outside the range of possibilities supported by scientific evidence. To limit*

the number of "what if?" cases, they are restricted to those that explore perturbations to key properties of the pillars of safety. The list of "what if?" cases is not intended to be exhaustive, but is meant to illustrate system behaviour under extreme conditions."

In the present OPERA report we introduce What-If cases initially without giving much attention to the probability or scientific reality of the FEP's impact. This can only be addressed once the What-If case has been evaluated.

The screening of FEPs to identify scenarios, assessment cases and What-If cases to be implemented in the OPERA safety assessment depends for a large part on expert judgement. As a result there is a risk that FEPs are incorrectly classified, and ultimately that important alternative scenarios or assessment cases are not identified.

The procedure can be improved if the screening is done by a larger number of experts, and by recording extensively the motivations of the experts for making their judgements.

However, such an extensive study is not in the scope of the project's budget and timeline. Moreover, it is considered that identification of additional alternative scenarios for a generic site is unlikely because scenario identification has been a continuous effort in several safety assessment studies during the last 35 years.

The benefit of the FEP screening, even if the effort is limited, is that it requires a clear description of the set of scenarios, which is sharpened by the associated primary FEPs. Also, there is a tendency that an extensive FEP evaluation results in very large, complex and, due to its complexity, unmanageable set of documents and data. In contrast, the identified primary FEPs will provide a structured and comprehensible access to the FEP database.

Note that the identification of the potential safety relevant FEPs and description of scenarios is an iterative process of updating with results from process studies, characterisation and performance assessment during the successive research phases in the preparation, site selection and implementation of a repository.

To illustrate the FEP screening procedure described above, some examples are given below.

FEP 2.3.04.04 Corrosion (waste package)

Description of the FEP

This FEP is one of the FEPs *Chemical processes (waste package)*, relating to chemical/geochemical processes that affect the wastes, containers, seals and other engineered features, and the overall chemical/geochemical evolution of near field with time. This includes the effects of chemical/geochemical influences on wastes, containers and repository components by the surrounding geology.

Has the FEP an effect on a safety function?

Yes, it can negatively affect the safety function “Engineered containment (C)”.

Is the FEP and the impact on the safety function likely?

No

Is the FEP part of the central assessment case of the NES?

No; in the Normal Evolution Scenario it is assumed that the facility is designed to cope with the anticipated, relatively slow amount of corrosion of the waste packages. In case of increased (but not excessive) corrosion rates this FEP leads to scenario N4 *Early canister failure case (normal range)*

Does the FEP lead to one of the existing AES's?

The FEP leads to the altered evolution scenario EEC1 *Excessive Early Container Failure*.

Motivation

Excessively increased corrosion rates can cause early container failures, e.g. as a result of stress-corrosion cracking. Additionally, increased corrosion rates may also increase the potential adverse effects of gas generation (see also next example).

FEP 2.3.07.07 Gas-induced failure

Description of the FEP

This class of FEPs relate to processes and events within and around the wastes, containers and engineered features resulting in the generation of gases and their subsequent effects on the repository system. Gas production may result from degradation and corrosion of various waste, container and engineered feature materials, as well as radiation effects. The effects of gas production may change local chemical and hydraulic conditions, and the mechanisms for radionuclide transport, i.e. gas-induced and gas-mediated transport. In case of excessive gas production failure of (components of) the disposal system may occur.

Has the FEP an effect on a safety function?

Yes, it can negatively affect the safety functions “Engineered containment (C)”, and “Limitation of the water flow through the disposal system (R2)”.

Is the FEP and the impact on the safety function likely?

No

Is the FEP part of the central assessment case of the NES?

No

Does the FEP lead to one of the existing AES's?

No

Can the reviewing expert describe a consistent scenario that covers this FEP?

No

More expertise is needed, FEP is addressed in a 'What-If' case

A new What-If case for excessive gas production has been recorded: *EGC1 Excessive Gas assessment case*.

Motivation

Significant amounts of gas can be produced from the corrosion of metal and chemical degradation of organic materials in the LLW and ILW sections of the disposal system. To some extent, gas can be removed from the disposal system by dissolution of the gas in the host rock pore water and subsequent diffusion through the host rock. However, amounts of gas that are not sufficiently removed by diffusion will likely lead to enhanced gas pressures in the disposal facility. If the gas pressure reaches the lithostatic pressure, the gas will be able to enter and widen pores in the clay, leading to two-phase conditions. There are observations that this so-called "slug" flow does not impair the clay permeability (ONDRAF/NIRAS, 2001; Section 13.B.11.2), i.e. the clay is able to recover from it after the gas has been removed and the pressure has decreased to ambient values. However, the observations are from relatively small scale experiments, and it is uncertain to which extent this phenomenon applies to repository conditions. Therefore, the expert judgment is to consider this FEP in a separate What-If case.

FEP 4.1.05 Undetected features (geosphere)

Description of the FEP

This class of FEPs relate to natural or man-made features within the geology that may not be detected during the site investigation. Examples of possible undetected features are fracture zones or old mine workings. Some physical features of the repository environment may remain undetected during site surveys and even during pilot tunnel excavations. The nature of the geological environment will indicate the likelihood that certain types of undetected features may be present and the site investigation may be able to place bounds on the maximum size or minimum proximity to such features.

Has the FEP an effect on a safety function?

Yes, it can negatively affect the safety functions “Limitation of the water flow through the disposal system (R2)”, and “Retardation and spreading in time of contaminant migration (R3)”.

Is the FEP and the impact on the safety function likely?

No

Is the FEP part of the central assessment case of the NES?

No

Does the FEP lead to one of the existing AES's?

The FEP leads to the altered evolution scenario "Undetected Fault Scenario" (FS1).

Motivation

Large scale discontinuities, heterogeneity and undetected features (undetected faults) may enhance water flow through the host rock, potentially leading to increased advective transport of radionuclides through the host rock. Careful site investigations reduce the potential of undetected features.

The result of the screening process of all FEPS is reported in (Schelland, 2014).

3. Scenario descriptions - narratives

Based on the combined experience of the OPAP-I partners, a preliminary list of relevant scenarios has been established:

1. Normal Evolution Scenario
2. Abandonment Scenario
3. Poor Sealing Scenario
4. Anthropogenic greenhouse scenario
5. Fault Scenario
6. Intensified glaciation scenario
7. Human Intrusion and Human Action Scenarios

The scenarios 2 to 7 comprise the Altered Evolution Scenarios. The following paragraphs describe the scenarios in more detail.

3.1. Normal Evolution Scenario

The Normal Evolution Scenario (NES) is the most likely scenario. The NES assumes normally progressing and undisturbed construction, operation, "passive" operation, and closure of the facility. However, natural processes affect the facility's engineered barriers in the long term.

For example, due to the water content of the clay rock (e.g. ONDRAF/NIRAS, 2001; Table 13-3: water content 30-40%), the facility's engineered barriers will slowly degrade as a result of corrosion and leaching processes. Soluble radionuclides will ultimately be released from the repository, and will migrate by diffusion through water present in the pore network in the clay. Diffusion is the dominant process driving nuclide migration through the clay rock. Advective transport is minor, because of the low permeability and the small pressure gradient over the clay rock.

For the OPERA disposal design these processes are considered inevitable, and therefore are part of the Normal Evolution Scenario.

The Normal Evolution Scenario can be described broadly by the following sequential steps (see also Figure 3-1):

1) The repository is being constructed: shafts and galleries are excavated and consequently the surrounding rock is disturbed to some extent, the so-called "Excavation Disturbed Zone" (EDZ).

   The waste packages are emplaced in the disposal galleries. The lining and the installed sealing plugs are assumed to be intact upon their emplacement, and therefore the inside of the disposal galleries is initially dry.

2) The gallery internals will become saturated relatively fast, i.e. presumably within several decades, with pore water from the surrounding Boom Clay. Eventually, all sections of the disposal facility will be saturated with pore water.

   For ILW and LLW, no additional engineered containment is foreseen and the waste may start to corrode and leach (slowly) relatively soon after closure. For the HLW, the steel canisters and concrete overpacks are more resistant to corrosion and leaching and will likely fail only after some thousands of years as a result of corrosion processes, and soluble species (some containing radionuclides) will start to leach from the HLW.

3) After some thousands of years, any released radionuclides will have migrated into the host rock. Depending on the radionuclide and Boom Clay properties, weakly

retarded or non-retarded mobile species (particularly some fission products) will have migrated a few tens of meters through the host rock, whereas migration of retarded, almost immobile nuclides such as the actinides, will not be more than one meter.

4) After a few tens of thousands of years the more mobile nuclides will have reached the aquifer system. Subsequently, migration to the biosphere can be relatively fast (within a few thousands of years) as a result of advective flow processes in the aquifer system enhancing the transport rates. Due to the large delay and dilution in space and time, only a small fraction of the mobile radionuclides will reach the biosphere, potentially resulting in radiological exposures of future humans or other biota[3].

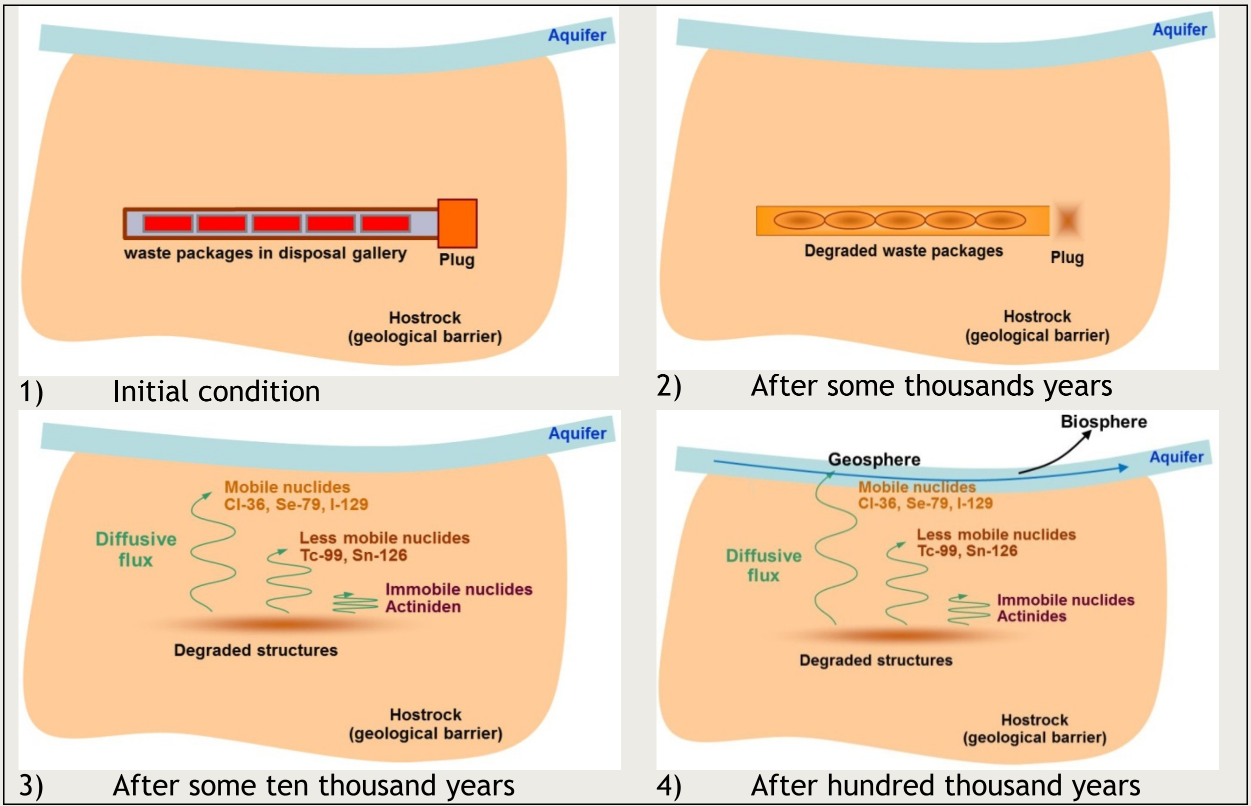

Figure 3-1 Schematic illustration of the Normal Evolution Scenario

The broad-brush sketch described above is elucidated in more detail in the following sections.

3.1.1. Normal Evolution Scenario - Near Field

The near field includes the waste packages, the backfill and sealing materials of the repository and that part of the geological host formation whose characteristics have been or could be altered by the excavation works, the presence of the repository and its contents.

The functions of the near field (normal evolution scenario) are:

[3] For a well-designed and normal functioning disposal system, previous studies suggest that the exposure is much less than the exposure to the natural background radiation.

1. to serve as a hydraulic barrier to avoid advective flow around the waste, through the underground structures, and, on the longer term, its remainders.
2. to provide (geo-)mechanical stability
3. to serve as a thermal buffer to avoid overheating of the Boom clay near the heat generating high active waste
4. to serve as a buffer to store gas (mainly generated by anaerobic corrosion of metals, or biological activity in the LLW and ILW) and to allow dispersion of gas into the clay by preferably diffusion only. A separate 'assessment case' will be defined to determine whether gas generation can have significant impacts.
5. to provide a chemical environment that mitigates leaching of the waste and radionuclide migration.
6. to confine the LLW/ILW for 100 years (Verhoef, 2011a; Figure 3) and the HLW for 1,000 years (Verhoef, 2011a; Figure 2) in the waste container.

Initially, the lining and the plugs are intact, and therefore the inside of the disposal gallery is dry. The lining and the plugs are made of porous materials like concrete or bentonite. These low-porosity materials show high capillary suction. Because the hydrostatic pressure at 500 m depths is about 500 m pressure head, and the pressure head in the engineered barriers is in the range of -100 to -1000 m pressure head (depending on the water retention curve and initial saturation degree of the porous materials), there is a steep pressure gradient in the early stage along the engineered barriers and the adjacent Boom Clay saturated with pore water. As a result, the gallery internals will become saturated with pore water from the Boom Clay relatively fast (presumably some decades).

In the present OPERA disposal concept no additional engineered containment of the ILW and LLW containers is foreseen. As a consequence, the ILW/LLW waste may start to leach (slowly) relatively soon after closure. For the HLW, the watertight canister and overpack are designed to initially prevent contact with the pore water. However, also these engineered barriers will ultimately fail after some thousands of years, and soluble species will start to leach from the vitrified HLW. Eventually, all sections of the disposal facility including the waste packages will be saturated with pore water from the clay.

In the Normal Evolution Scenario diffusion is the dominant process of radionuclide transport in the near field. It must therefore be shown that there is a very low probability of advective flow processes or other processes that might enhance the transport of radionuclides.

3.1.2. Normal Evolution Scenario - Far Field - host rock

The far field includes the geological formations outside the near field, i.e. the undisturbed Boom Clay and the overburden. The ambient characteristics and properties of the far field may be affected by chemical and mechanical effects induced by the disposed waste or repository materials and to a lesser extent by thermal effects as a result of heat generated by the waste. It is presupposed that these changes are relatively mild adjacent to the repository’s near field, and become negligible further away from the facility.

Boom Clay

The safety functions of the Boom Clay host rock are to delay and attenuate releases of radionuclides from the disposed waste, and to isolate the waste from man and the environment (cf. Figure 2-1).

For most radionuclides the undisturbed clay layer is the main barrier in the disposal system (see e.g. ONDRAF/NIRAS, 2001; Section 11.5.2.2.1, p.13). The radionuclides that are released from the waste packages and dissolved in the near field pore water migrate through the clay layer primarily by molecular diffusion and to a very limited extent by advection; as a result of physical and/or electro-chemical interactions many radionuclides are sorbed on the clay minerals or on organic matter present in the clay layer.

The radionuclide migration through the Boom Clay layer may be influenced by the chemical complexation by mobile organic matter present in the Boom Clay and by the formation of colloids. Some radionuclide species could migrate more rapidly through the Boom Clay as a result of complexation with mobile (non-retarded) organic molecules. In addition, radionuclides can also be exchanged between mobile and immobile organic matter, thereby enhancing or decreasing their diffusion rates through the far field.

The hydraulic conductivity of Boom Clay depends on the vertical depth and is of the order of $3 \cdot 10^{-12}$ m/s (e.g. ONDRAF/NIRAS, 2001; Section 3.3.3.3.6; Vis, 2014, 2014, Fig. 3-18a, p. 50), which corresponds to an intrinsic permeability in the order of $3 \cdot 10^{-19}$ m^2. Taking into account the maximum feasible pressure gradients caused by the overlying and underlying aquifers (several hundred Pa/m in the OPERA-hydraulic model (Valstar, 2016), and using Darcy's law for estimating the advective flow rate of pore water in Boom clay, the maximum water velocity would be in the order of $2 \cdot 10^{-6}$ m/a. Compared to the rate of diffusion of dissolved materials the advective flow rate is completely negligible in the Normal Evolution Scenario. As a consequence, events that may lead to increased advective flow are assumed not to be part of the Normal Evolution Scenario and will be treated in altered evolution scenarios.

The Boom Clay in the far field may to a limited extent be affected by the waste disposed of in the repository, e.g. by the heat output and chemical and mechanical effects.

Like most other geological media, Boom Clay shows a natural spatial variability (heterogeneity) of its lithology and related THMC properties (e.g. ONDRAF/NIRAS, 2001; Section 11.2.7.1, Table 13-3), which needs to be accounted for in the performance assessment.

3.1.3. Normal Evolution Scenario - Far Field - aquifer

Interface between host rock and the aquifer system

Radionuclides dispersed through the clay into an aquifer migrate relatively fast through the aquifers compared to the migration rate in the clay. The radionuclide concentrations at the interface between host rock and clay are therefore lower than the concentrations in the clay itself. Since diffusion driven transport follows the concentration gradient, the aquifer "attracts" the radionuclides reaching the interface area. Except for this influx of radionuclides, the groundwater flow in the aquifers is not affected by phenomena in the host rock (see also discussion of compaction in Section 4.9).

Transport through the aquifer system

After having reached the aquifer system the radionuclides will be transported mainly by advection and dispersion in flowing groundwater. It should be noted that other clay layers may be present between the host formation (Boom Clay) and the aquifer.

In aquifers, molecular diffusion is usually negligible compared to kinematic dispersion and advective transport. In the aquifers, as in the clay, some of the radionuclides can be sorbed on the minerals that are present in the aquifer system, e.g. glauconite (ONDRAF/NIRAS, 2001; Section 11.5.2.2.1, p.13).

In accordance with the assumptions proposed in SAFIR 2 the radionuclides can reach the biosphere along a number of different paths through the Neogene Aquifer above the Boom Clay:

- Discharge of groundwater to rivers and possibly ponds or lakes;
- Seepage of soils by contaminated groundwater;
- Extraction of groundwater from a well.

If the host rock is located below the salt water table, radionuclides have to cross the salt water/fresh water interface before they can reach the biosphere.

Climate evolution

Based on the orbital theory of Milankovitch, a future moderate cooling and more severe cooling may occur after about 24 000 years and about 56 000 years, respectively. There is a probability that the cooling periods result in glacial conditions at the location of the site. Glacial conditions will bring about significant changes to the uppermost part of the geosphere and relevantly alter the movement of water in the aquifers as a result. It is unlikely that the detailed groundwater models developed for today's geographical and climatological conditions will still be representative for periods beyond 10,000 years. As a consequence, some rigorous assumptions are postulated to account for the potential effects of future climate evolutions.

In SAFIR 2 two complementary approaches are proposed for analysis of climate evolution (ONDRAF/NIRAS, 2001; Section 11.5.2.2.1):

- The first approach assumes that the present hydrogeological system is a reference condition that can be used for the whole of the period considered;
- The second approach attempts to assess the impact of the expected glacial periods on the hydrogeological system and to use the results of these assessments when calculating the effects of the scenario.

In relation to the second approach, the Normal Evolution Scenario assumes a glacial period accompanied by changes in precipitation and lowering of the temperature, the formation of permafrost, the expansion of an ice sheet from Scandinavia to more southern latitudes, and sub-glacial erosion. Sea level will fall as a consequence of ice sheet formation. In addition, melt water, produced at the basis of the ice sheet, may be charged to the subsurface groundwater system. It is crucial to include information on the time dependency of these processes in the safety assessment.

The reference scenario for Gorleben in Germany includes the occurrence of glacial-interglacial cycles within the next one million years, some of which will lead to glaciation and subglacial erosion to 300 m in unconsolidated sediments (Beuth, 2012; p.142).

In the OPERA safety assessment, the expected climate evolution is part of the Normal Evolution. Within the next 100 to 1,000 ka climatic deterioration is to be expected, leading to global cooling, lowering of the sea level and the formation of permafrost, which will be included in the Normal Evolution Scenario. Unlikely extremes in the evolution, such as intensified glaciation with the presence of a massive ice sheet and deep subglacial erosion is not part of the Normal Evolution Scenario; instead it will be assessed in a dedicated Altered Evolution Scenario (see Section 4.7).

For the Normal Evolution Scenario it is assumed that mid-latitude ice sheets are formed which might cover the repository area.

Other natural processes

On very long time scales (hundreds of thousands/millions of years) tectonic movement of the earth's surface can become apparent. The larger part of the Netherlands is subsiding, which in itself will not lead to significant erosion. In contrast, on the long term the risk of flooding due to see level rise might increase (see also Altered Evolution Scenario with the greenhouse effect, Section 4.5), and marine transgression cannot be excluded.

The mineral composition of the Boom Clay may change as a result of diagenetic processes, in particular when the current composition is not in equilibrium with the ambient temperature, pressure and fluid composition.

Deep Well Events

It is probable that at one or more points in time, drinking water will be pumped from a large depth (e.g. 100 - 200 m). These practices (events) are included in the Normal Evolution Scenario (NES, Case N5) and will short-cut a part of the travel path for the radionuclides through the aquifer system. In accordance with the assumptions of the SAFIR-2 study, a very unfavourable location is assumed for the well, i.e. deep in the aquifer and just downstream from the periphery of the disposal system (ONDRAF/NIRAS, 2001; Section 11.5.2.2.1, p13). An input variable potentially affecting the safety assessment simulations is the pumping rate at this well.

3.1.4. Normal Evolution Scenario - Far Field - biosphere

Interface between the aquifer system and the biosphere

The biosphere receptors which can receive the radionuclides after their migration through the aquifer are according to SAFIR 2 (ONDRAF/NIRAS, 2001; Section 11.3.10.2, p3/31):

- A well;
- Surface water (a river or pond);
- Soil, where the aquifer extends into root zone.

The groundwater flow rates in the shallow aquifers and the surface water bodies (e.g. rivers) are much higher than in the deep aquifer system (that connects to the host rock).

Radionuclides will enter the shallow aquifers and surface water bodies with the groundwater from the deep aquifer system that feed into the shallow aquifers and surface water bodies. Except for this influx of radionuclides, it can be assumed in good approximation that the water flow in the shallow and surface water bodies is not affected by phenomena in the deep aquifer system.

In order to obtain an effective model for the interface between the aquifer system and the biosphere, the shallow aquifers and surface water bodies are regarded as part of the biosphere.

Dispersion *in* the biosphere

From the shallow aquifers and surface water bodies, the radionuclides will be dispersed into the biosphere by a number of natural processes and by human actions, and accumulate in certain media including air, water, soil, and food. Eventually, humans will be exposed by the presence or through the use of the contaminated media. This can happen via the exposure pathways:

- Ingestion of contaminated food or water;

- Inhalation of contaminated air;
- Direct radiation from contaminated soil, water or sediment.

In SAFIR 2, one distinguishes between two types of biospheres for the Normal Evolution Scenario (ONDRAF/NIRAS, 2001; Section 11.3.10):

- Present day conditions - these may be representative for thousands of years (see also 'climate evolution'.
- Changing conditions - these are highly likely on the long term (ten thousands to hundred thousands of years) and must be accounted for in the Normal Evolution.

Present day conditions

According to SAFIR 2, the receptors in the present biosphere through which radionuclides can reach the biosphere are (ONDRAF/NIRAS, 2001; Section 11.3.10.3):

- A well sunk into the radionuclide bearing aquifer on the edge of the repository (in the direction of the groundwater current). A limited flow rate is attributed to this well so that the dilution with uncontaminated groundwater is minimized;
- Small water courses, brooks, etc., which the radionuclides can reach through transport by the groundwater
- Larger water courses, rivers which the radionuclides can reach through transport by the groundwater and/or via smaller water courses
- Fish ponds fed by contaminated groundwater downstream of the repository.
- The soil (root zone)

These assumptions are also considered in the OPERA safety assessment.

Changing conditions

The time scale for the PA is one million years. The exposure of individuals in the future and far future will depend on their behavior and their biological characteristics. An aspect of the present policy for the protection of the public from ionizing radiation is to distinguish '*reference groups*' (or critical groups), who, in comparison with the rest of the population, are at a greater risk from a given source of ionizing radiation. Such groups should be protected with special care for that particular source. In analyzing any radiological consequences of the source, the reference group is assumed to possess a common set of characteristics which may have an influence on the level of risk which individuals in the group incur. These characteristics can be either biological (such as age or sex) or cultural (such as consumption pattern).

A common approach is to assume that, for the next million years, the reference group consists of a relative small community living in a closed agricultural society near the discharge points of the aquifer, which could be a natural discharge point or a human built well. The exit point of the aquifer delivers water from the deep aquifer receiving radionuclides from the underlying clay host rock surrounding the disposal facility. Under these conditions, the transfer of nuclides through the biosphere to individuals is at its maximum.

It can be expected that the reference group will aim at increasing the agricultural production, in particular by implementing some type of water control to compensate for too wet or too arid climate conditions. Examples of such measures are digging wells, building irrigation and/or drainage systems, and utilizing greenhouses. The consequences of these actions on the nuclide migration must be treated consistently in the aquifer and biosphere modelling.

Extreme changes, or temporary changes, like flooding of the site, penetration by drilling or mining, or extremely deep wells are treated in alternative scenarios.

Climate changes

In SAFIR 2, several alternative biosphere conditions were identified depending on the timescales considered (ONDRAF/NIRAS, 2001; Section 11.3.10.4, p.26). These conditions relate to the assumed prevailing climate types including the present-day climate, a warm climate ('Mediterranean' type), a cold climate ('boreal' type) and a very cold climate ('periglacial' type).

One very important factor here is the groundwater balance which is highly sensitive to changes of climate. These changes will have a significant effect on precipitation, evapo-transpiration and irrigation which, in turn, determine the rate of infiltration.

Flow rates and patterns in the deep aquifer system depend on the climate, in particular on the amounts and locations of rainfall. Also the biosphere type (arid, wet) depends on the amount of rainfall. This coupling is part of the Normal Evolution Scenario.

In the OPERA safety assessment, the expected climate evolution is part of the Normal Evolution. Unlikely extremes in the evolution, such as intensified glaciation with the presence of a massive ice sheet and subglacial erosion is not part of the Normal Evolution Scenario; instead it will be assessed in a dedicated Altered Evolution Scenario (see Section 4.7).

3.2. Altered Evolution Scenarios

In general, scenarios represent structured combinations of features, events and processes (FEPs, see also Section 2) relevant to the performance of the disposal system. Besides a "Normal Evolution Scenario", representing the most probable sequence of events, usually in a safety assessment other, less probable types of scenario are considered as well. These 'Altered Evolution Scenarios' include disturbing processes and events (IAEA, 2012; p. 53). The various Altered Evolution Scenarios considered in a safety assessment will have most features, events and processes in common with the Normal Evolution Scenario. However, some particular features, events and processes will differ between the scenarios, which characterize each particular scenario. An assessment of the FEPs that play a role in a particular Altered Evolution Scenario is provided in Sections 4.3 to 4.9 of the present report.

The altered evolution scenarios considered in the OPERA safety assessment are partly based on the scenarios analyzed in the SAFIR-2 study (ONDRAF/NIRAS, 2001; Section 11.5.2.2.2), and partly on scenarios considered in the CORA program (Grupa, 2000; Section 1.3). The following altered evolution scenarios are described in the following:

- Abandonment Scenario
- Poor Sealing Scenario
- Anthropogenic greenhouse scenario
- Fault Scenario
- Intensified glaciation scenario
- Human Intrusion and Human Action Scenarios

3.2.1. Abandonment Scenario

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 that may lead to abandonment of the facility are:

- Economic distortion
- War, national disaster
- Mining disaster

In the worst case these events could lead to abandonment of the repository without proper closure. This event was considered in a few desk studies (e.g. Grupa, 2000; Grupa, 2009) where it has been assumed that abandonment would lead to the following chain of events:

1) Flooding of unsealed galleries
2) Dissolution of soluble parts of the waste in the water, much earlier compared to the Normal Evolution Scenario
3) Advective flow and diffusion through the remains of the underground infrastructure (galleries, shafts)
4) Transport of early-released radioactive material into the aquifer and biosphere
5) Exposure of humans to radioactive material

In defining the abandonment scenario in (Grupa, 2000; Section S.4.2) it was assumed that:

- waste canisters will be emplaced in the horizontal disposal boreholes;
- the horizontal disposal boreholes have been sealed with a plug;
- the shafts and access galleries have not yet been backfilled and sealed;
- the access galleries are filled with water as a result of flooding;
- the main shaft that is connected to shallow groundwater layers is also filled with water.

In a subsequent study, performed as part of the EU FP6 project PAMINA, it was additionally assumed that the high level waste will be contained by 70 cm of cement and that the disposal cell will be sealed with a (clay) plug of 3 m (Schröder, 2009; p.43).

An Abandonment Scenario was also considered in ANDRA's Dossier 2005 Argile (ANDRA, 2005a) as a special case in the "Seal Failure" scenario, i.e. Calculation Case 4: "Abandonment of repository without shaft seals" (ANDRA, 2005a; p.476). An important difference with the presently adopted Abandonment scenario is that ANDRA assumed that only the shafts would not be sealed, whereas all other engineered structures (main and secondary connecting drifts, cell access drifts) would be backfilled and efficiently sealed.

Section 4.3 evaluates the FEPs that potentially could affect the repository's safety functions taking into account the Abandonment scenario (AA1).

3.2.2. Poor Sealing Scenario

The Poor Sealing Scenario (ONDRAF/NIRAS, 2001; Section 11.5.4.5: *Poor sealing of the repository*) is based on the assumption that the shafts, access galleries and disposal galleries are poorly sealed, e.g. due to construction errors, poor construction materials or errors in the design and testing of the facility and/or the seals. In contrast to the Abandonment scenario, the sealing is assumed to be present. Poor sealing of the shafts may result in the formation of a hydrological connection between an aquifer overlying the host rock and the (remains of the) access and disposal galleries. Depending on the hydraulic situation, the pore water pressure in the Boom Clay can be higher than the water pressure in the (remains of the) galleries. In that case, pore water can be squeezed into the (remains of the) galleries, inducing a water flow through the (remains of the) galleries and shaft(s) to the overlying aquifer.

ANDRA's Dossier 2005 Argile (ANDRA, 2005a; Section 7.2) assumed a "Seal Failure" scenario, intended to consider a failure of all or part of the seals so as to assess the robustness of the repository system with respect to various combinations of such defects in repository components (shafts, drifts, module separation) or cell plugs. The Seal Failure scenario also included any failure associated with the development of a damaged zone around the engineered structures (EDZ), more significant than that considered in the Normal Evolution Scenario. This could potentially constitute a radionuclide transfer pathway and influence the long-term evolution of the repository.

For the OPERA safety assessment it is assumed that, compared to the Normal Evolution Scenario, an advective water flow, resulting from the difference in pore water pressure in the Boom Clay and the water pressure in the (remains of the) galleries, bypasses the Boom Clay host rock and may bypass the deep aquifers, potentially resulting in a faster and less diluting nuclide migration process to the biosphere. The flow pathway could be an inflow through one shaft and an outflow through another shaft. More likely is an inflow through the poorly sealed shafts and an outflow through the Boom Clay - or the reverse flow. For the latter pathway, the water flow rate and the migration rate are limited by the limited amount of water that can flow through the Boom Clay layer taking into account the low permeability of the Boom Clay layer.

Section 4.4 evaluates the FEPs that potentially could affect the repository's safety functions taking into account the Poor Sealing scenario (AS1).

3.2.3. Anthropogenic greenhouse scenario

This scenario considers the changes in the overlying aquifers due to global warming of the atmosphere and analyses the resulting radiological impact. The greenhouse effect may cause the present moderate climate to evolve into a warmer, more Mediterranean climate over the coming centuries. This climate type is not anticipated on the basis of the orbital theory which predicts that future climates will be colder than today's.

In the SAFIR-2 safety assessment, the "greenhouse effect" scenario has been considered too, viz. the AES2 scenario (ONDRAF/NIRAS, 2001; Section 11.5.4.1). In SAFIR 2 the 'greenhouse effect' scenario was assessed to have only a very limited impact on the disposal system, affecting mainly the biosphere and to a lesser extent the hydrogeological environment. The scenario seemed to have no direct impact on the Boom Clay or the near field, and no radionuclides were released into the aquifer during the first 5000 years. Therefore, that scenario was excluded from further study in SAFIR 2.

The Anthropogenic Greenhouse Scenario which will be analyzed in the OPERA safety assessment (modified after AES2 scenario in SAFIR 2; ONDRAF/NIRAS, 2001; Section 11.5.2, p18) assumes that the atmospheric conditions will have changed, implying an increased risk of flooding of the repository as a consequence of the rising sea-level. As a result, brackish water may infiltrate in the shallow subsurface or in the repository in case it has not yet been closed.

An important feature in this scenario, and a difference with the Abandonment scenario, is the timing of radionuclide release to the geosphere and the biosphere and the prevailing biosphere conditions at the time of release; this may happen well after the greenhouse effect has come to an end.

The calculation methodology of the anthropogenic greenhouse scenario is, in principle, equivalent to that of the Normal Evolution Scenario. In addition, the anthropogenic greenhouse scenario assumes the following additional features and processes:

- An enhanced transport through the aquifer system compared to the Normal Evolution Scenario.
- Changing chemical conditions, especially in the aquifer system.

Section 4.5 evaluates the FEPs that potentially could affect the repository’s safety functions taking into account the Anthropogenic Greenhouse scenario (AGr1).

3.2.4. Fault Scenario

Site characterization must carefully screen for the presence of faults transecting the repository or the surrounding host rock. However, the existence or formation of faults in the subsurface cannot be excluded beforehand.

The Fault Scenario considers the consequences of a tectonic fault through the host rock and the repository, which has the potential to form a preferential flow path for nuclide migration. Such a fault may be formed by the reactivation of an already existing fault following increased tectonic activity in the surrounding area. On the other hand, also an non-detected fault may exist that transects the repository and reaches into the shallow subsurface.

If the clay is highly plastic, a sharply defined fault plane will likely not be formed. Instead, the clay will be deformed plastically over a broader zone, resulting in a change of the hydraulic and mechanical properties of the clay within the fault zone compared to those of the undisturbed clay.

In the SAFIR-2 study, ONDRAF/NIRAS evaluated the Fault activation (“AES4”) scenario, for which it was assumed that an active fault line is formed through the repository as a result of tectonic activity, compromising the containment and isolation capacity of the geological barrier (ONDRAF/NIRAS, 2001; Section 11.5.2.2.2).

The calculation methodology of the Fault Scenario is, in principle, equivalent to that of the Normal Evolution Scenario. In addition, the Fault Scenario assumes the following additional topics:

- The modeling of a fault in the Boom Clay of dimensions to be determined in the next iteration of the safety assessment;
- The modeling of alternate properties in the fault, potentially enhancing the transport of radionuclides, i.e. enhanced hydraulic conductivity and diffusion coefficient, and declined retardation properties[4].

[4] In the SAFIR-2 study the migration of radionuclides along the fault plane was calculated assuming that the hydraulic conductivity increases by a factor of 20, the diffusion coefficient by a factor of 2 and that the retardation factor decreases by a factor of 5 (ONDRAF/NIRAS, 2001; Section 11.5.4.3.2).

Potential features and processes that may be of concern for this scenario include:

- Mechanical processes concerning the waste packages;
- Formation of transport pathways through and near the repository;
- Enhanced water-mediated transport processes (advection) through the repository, the Boom Clay, and the geosphere.

Section 4.6 evaluates the FEPs that potentially could affect the repository's safety functions taking into account the Fault scenario (FS1).

3.2.5. Intensified glaciation scenario

Over the past 1.3 million years permafrost developed and degraded intermittently in large parts of northern Europe where periglacial conditions prevailed (Figure 3-2; Wildenborg, 2013; pp. 5,6) and where permafrost is estimated to have reached depths ranging from a few tens of meters in the case of the Mol site in Belgium (Marivoet, 2000) to 100-300 m in the Netherlands, Germany and northern England (Shaw, 2012, Grassmann, 2009).

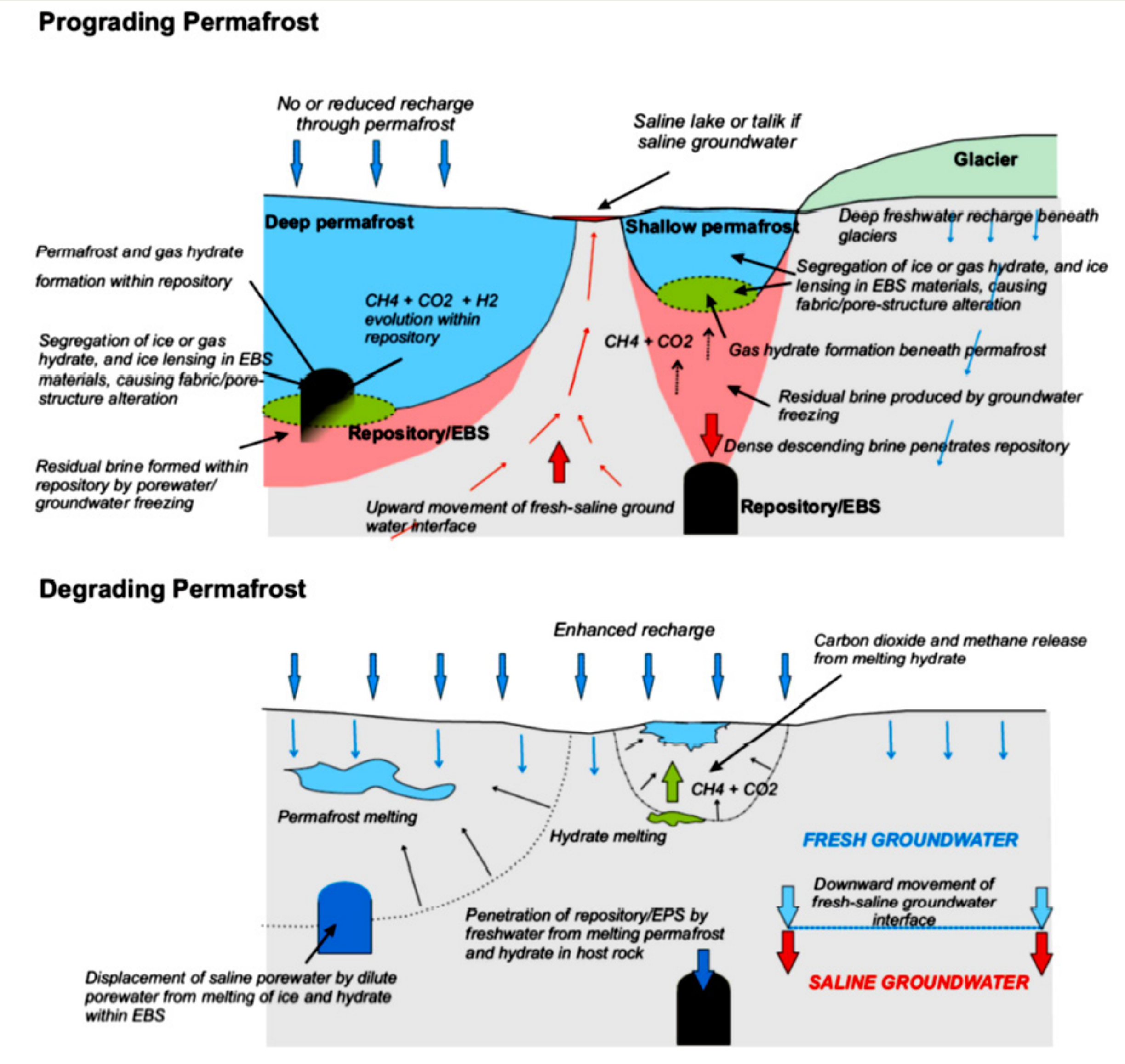

Figure 3-2 Potential permafrost impact on the disposal system

Future permafrost development may influence a considerable number of potential European disposal locations in the northern and central parts of Europe. Direct impacts at repository depth, including possible damage to the EBS, may occur at several locations when deep (> 200 m) permafrost develops. However, even if repository depth is deeper than the zone likely to be directly affected by permafrost development, impacts on the host rock and indirect effects such as brine formation and migration, intrusion of freshwater from melting permafrost or gas hydrate (formed beneath the permafrost layer (Rochelle and Long, 2009), and cryogenic pore pressure changes associated with volume change during the water-ice phase transition may affect the integrity of the geological barrier. These processes may have impact on the transport processes of any released nuclides through the Boom Clay and the geosphere, and the subsequent uptake into the biosphere.

It cannot be excluded that a future glaciation might have a larger extent than was experienced during the last 1 million years and subsequently leads to a more intense subglacial melt water production and erosion than is known from the past. For example, in VSG: AP8 “Szenarienentwicklung” (Beuth, 2012; p.117) it is assumed that subglacial erosion in the next 500,000 years could lead to an erosion depth of 300 meters.

An intensified glacial period has also been evaluated in Belgium, viz. the AES5 scenario (ONDRAF/NIRAS, 2001; Section 11.5.2.2.2), for which a more severe glacial period than the last glacial periods of the Quaternary has been assumed, with the possible formation of glaciers in the Mol-Dessel region and subglacial erosion compromising the geological and engineered barriers.

The methodology used for the consequence analysis of the intensified glaciation scenario is, in principle, equivalent to the calculation methodology of the Normal Evolution Scenario, in which the occurrence of glacial periods will also be taken into account. However, in the intensified glaciation scenario analysed as part of the OPERA safety assessment the following assumptions apply:

- Presence of a massive ice sheet producing meltwater;
- Deep subglacial erosion;
- Thick permafrost in front of the ice sheet.

Section 4.7 evaluates the FEPs that potentially could affect the repository’s safety functions taking into account the Intensified Glaciation scenario (FS1).

3.2.6. Human Intrusion Scenarios

Future human actions may disrupt a disposal facility for radioactive waste. Human actions affecting the integrity of a disposal facility and potentially giving rise to radiological consequences are known as human intrusion (IAEA, 2013; p.79). In a closed deep geological repository the scenario of human intrusion is one in which all barriers – both engineered and natural – are short-circuited. Human intrusion may lead to increased release of radioactive material and increased long term exposure of individuals or groups around the disposal facility.

IAEA SSG-23 states that, in a safety assessment for a waste disposal facility, inadvertent (unintentional) human intrusion should be considered, assuming that it will occur at some point in time following the loss of knowledge about the site and its hazardous contents (IAEA, 2012; p.80). In carrying out human intrusion scenarios no distinction should be made between the intruder and the residents (IAEA, 2012; p.81).

SSG-23 recognizes that the relevance of human intrusion scenarios for geological disposal facilities is limited, as the depth and location of such facilities make human intrusion unlikely. In addition, the time frames of concern are judged too large to enable meaningful estimates of possible impacts from intrusion events. SSG-23 nevertheless recommends to assess the consequences of human intrusion to demonstrate the robustness of the disposal system.

The most likely activity of human intrusion in a closed geological repository is by deep drilling. The presently assumed human intrusion scenarios involve the following events:

- perforation of the remains of the facility as a result of exploration and production drillings for oil and gas, geothermal energy, energy storage etc.;
- exploration of deep wells, i.e. over several hundred meters, for water extraction.

Mining of the host rock material itself is highly unlikely, since the clays of the same or better quality are easily accessible and locally available from surface mining.

Compared to the Normal Evolution Scenario, the Human Intrusion Scenario assumes the following features:

- Post-closure human activities, also referred to as future human actions, viz. drilling;
- Locally degraded properties of the engineered barriers and (some) waste packages;
- The formation of a preferential flow path, i.e. the drilling hole(s), for nuclide transport;
- The (very local) bypassing of the isolating properties of the engineered barriers, the Boom Clay, and the geosphere;
- Alternative exposure modes (biosphere).

Section 4.8 evaluates the FEPs that potentially could affect the repository's safety functions taking into account the Human Intrusion scenario (AH).

3.3.Evaluation

The Normal Evolution Scenario and the Altered Evolution Scenarios described in the previous sections are based on assumptions about the sequence of events and features, events, and processes that are considered to be relevant for each scenario. In order to check for completeness a FEP screening process has been undertaken in order to identify potential alternative scenarios which are additional to the above-mentioned ones. This 'top-down' method for developing scenarios is based on analyses of how the safety functions of the disposal system may be affected by possible events and processes.

That FEP screening process is also used to identify FEPs that potentially may lead to assessment cases for each of the scenarios.

The following chapter describes the results of the FEP screening and identifies the impact of the FEPs on the repository's safety functions.

4. Results of the FEP screening

4.1. Overview of the screening process

Following the procedure illustrated in Section 2.5, the safety assessment experts have evaluated all 366 FEPs in the OPERA FEP catalogue (Schelland, 2014) and identified FEPs that can have an effect on one or more of the safety functions. In addition a large number of FEPs were identified to be relevant for completing the system description of radionuclide migration from the waste to receptors in the biosphere, the larger part of which ended up in the Normal Evolution Scenario (Schelland, 2014). For each of the FEPs which can affect one or more safety functions, it has been decided how the FEP must be treated:

- FEPs as part of the central assessment case of the NES described in Section 3.1;
- FEPs leading to new assessment cases as part of the NES;
- FEPs which are covered by the present set of altered evolution scenarios described in Section 3.2;
- FEPs leading to additional What-If cases;
- FEPs potentially leading to alternative transport modes or an impact on the transport in the aquifers and/or biosphere. These cases are also treated as What-If cases, but are judged not to have a significant impact on the safety functions of the disposal system.

Considerations of the experts are not detailed in the present report but they have been recorded in the above-mentioned OPERA FEP catalogue.

The following sections evaluate each of the scenarios in terms of FEPs that have been allocated to them by the safety assessment experts. The additionally identified What-If cases are addressed in Section 4.9.

4.2. Normal Evolution Scenario

On the basis of the FEP screening of the NES, FEPs were identified that will be treated in assessment cases of the Normal Evolution Scenarios. These assessment cases are expected to cause moderate deviations from the Central Assessment case (N1), but highlight specific aspects of the normal evolution.

Table 4-1 lists the FEPs that potentially may affect and weaken the safety functions, and are sufficiently probable to be included in the Normal Evolution Scenario (NES). Being attributed to the NES, it is assumed that the indicated FEPs do not severely degrade the respective safety functions. However, they do need special attention when represented in the integrated safety assessment model.

Normal evolution assessment cases

N1 Central assessment case: all safety functions are assumed to be operating as intended, see also Section 3.1.

N2 Radioactive gas transport case. The consideration for adopting this assessment case is that gas, generated in the repository by processes like corrosion, organic degradation, volatilisation, may potentially drive advective flow and the flow of radioactive gases which are released from the waste packages.

N3 Gas pressure build-up case (normal expected range). In case gas, formed in the repository by processes like corrosion, organic degradation, volatilisation, is not able to disperse sufficiently through the engineered barriers or the host rock, a build-up of gas pressure may be induced. Although in principle the facility must be designed to handle a moderate build-up of gas pressure, potentially this process may impact several of the safety functions, more explicitly the *Engineered containment* (C), and *Limitation of water flow through the system* (R2), cf. Table 4-1. Assuming that the gas pressure build-up is limited, this process is considered an assessment case of the Normal Evolution Scenario. Excessive gas pressure build-up is considered as a separate What-If case, EGC1, see also Section 4.9.2.

N4 Early canister failure case (normal expected range). A gradual degradation of steel and concrete in the EBS is part of the NES. However, increased corrosion rates could cause early container failures, e.g. as a result of stress-corrosion cracking. Early canister failure may potentially impact the safety functions *Engineered containment* (C) and *Limitation of containment releases from the waste forms* (R1), and to a lesser extent *Limitation of water flow through the system* (R2). Excessive early canister failure is addressed as a What-If case, EEC1, see Section 4.9.1.

N5 Deep well assessment case. The central assessment case assumes the extraction of groundwater from a moderately deep well (see Section 3.1.3). There is a probability that at one or more points in time, drinking water will be pumped from larger depths (e.g. 100 - 300 m). Such activities would short cut a part of the travel path of the radionuclides through the aquifer system, mainly affecting the safety functions *Retardation and spreading in time of contaminant migration* (R3), and *Reduction of the likelihood of inadvertent human intrusion and of its possible consequences* (I1). An extreme case of the Deep well scenario is treated as a Human Intrusion assessment case, *Deep well scenario – extreme case* AH2, see Section 4.8.

Table 4-1 Identified FEPs for *Normal Evolution Scenario* assessment cases (N)

No	FEP Name	Affected safety function					
		Engineered containment (C)	Delay and attenuation of releases (R)			Isolation (I)	
		Preventing as long as required the release of contaminants from the waste container	Limitation of containment releases from the waste forms (R1)	Limitation of water flow through the system (R2)	Retardation and spreading in time of contaminant migration (R3)	Reduction of the likelihood of inadvertent human intrusion and of its possible consequences (I1)	Ensuring stable conditions for the disposed waste and the system components (I2)
N1 Central assessment case							
N2 Radioactive gas transport case							
3.2.07.08	Impact of gas generation on other processes (repository)		•				
N3 Gas pressure build-up case (normal range)							
2.3.02.03	Gas effects (waste package)	•		•			
2.3.05.03	Impact of biological processes on other processes (waste package)	•					
2.3.07.01	Metal corrosion (waste package)	•		•			
2.3.07.02	Organic degradation (waste package)	•	•	•			
3.2.02.01	Resaturation/desaturation (repository)			•	•		
3.2.07.08	Impact of gas generation on other	•		•			

No	FEP Name	Affected safety function					
		Engineered containment (C)	Delay and attenuation of releases (R)			Isolation (I)	
		Preventing as long as required the release of contaminants from the waste container	Limitation of containment releases from the waste forms (R1)	Limitation water flow through the system (R2)	Retardation and spreading in time of contaminant migration (R3)	Reduction of the likelihood of inadvertent human intrusion and of its possible consequences (I1)	Ensuring stable conditions for the disposed waste and the system components (I2)
	processes (repository)						
3.3.03	Gas-mediated transport (repository)	•		•	•		
EBS-C 6	Corrosion - gases	•		•			
EBS-C 13	Microbial / biological / biochemical activity	•					
EBS-C 14	Gas generation	•		•			
EBS-H 11	Gas flow and transport	•		•			
EBS-H 12	Gas-induced flow and transport	•		•			
N4 Early canister failure case (normal range)							
2.3.02.03	Gas effects (waste package)	•		•			
2.3.03.04	Stress-corrosion cracking	•	•				
2.3.04.04	Corrosion (waste package)	•					
3.2.04.04	Corrosion (repository)	•		•			•
EBS-D 2	Overpack - dimensions and properties	•					
EBS-D 4	Envelope - dimensions and properties	•					
EBS-C 3	Corrosion - causes / processes	•					
EBS-C 6	Corrosion - gases	•		•			
EBS-P/M 1	Cracking	•	•				
EBS-P/M 3	Corrosion - stress cracking	•	•				
N5 Deep well assessment case							
3.3.05	Human-action-mediated transport (repository)				•	•	
4.1.04	Geological resources				•	•	
4.3.05	Human-action-mediated transport (geosphere)				•	•	

4.3. Abandonment Scenario

Accidents and unplanned events could lead to a loss of control of the facility and consequently only partial closure of the repository, because either attempts to regain control fail or such attempts are not even made. The long term consequences of this are reflected in the Abandonment Scenario, where it is assumed that the construction of the EBS, including the plugs and seals, will not be completed, and the safety function of the EBS is partly lost.

Potential features and processes that may be relevant in this scenario are listed in Table 4-2 and include:

- An early release of contaminants from the waste containers due to the presence of water;
- Enhanced water-mediated transport in the shafts and galleries;
- Enhanced water-mediated transport in the aquifer system;
- Hydraulic processes in the geosphere.

Table 4-2 Identified FEPs for *Abandonment* Scenario (AA1)

No	FEP Name	Affected safety function					
		Engineered containment (C)	Delay and attenuation of releases (R)			Isolation (I)	
		Preventing as long as required the release of contaminants from the waste container	Limitation of containment releases from the waste forms (R1)	Limitation of water flow through the system (R2)	Retardation and spreading in time of contaminant migration (R3)	Reduction of the likelihood of inadvertent human intrusion and of its possible consequences (I1)	Ensuring stable conditions for the disposed waste and the system components (I2)
AA1 Abandonment							
1.1.08	Accidents and unplanned events	X	X	X	X		
1.2.12.01	Flooding			X	X		X
1.3.01	Global climate change			X	X		X
1.3.03	Sea level change						X
1.4.01	Human influences on climate			X	X		X
3.2.03.03	Collapse of openings			X			X
EBS-D 8	Seals / tunnels - dimensions and properties			X			

The Abandonment scenario affects the following safety functions (cf. Table 4-2):

- Engineered containment (C). Obviously, assuming an absent sealing of the various open volumes in the repository, the engineered containment will be affected as water may reach the waste containers very early and much more abundantly.
- Delay and attenuation of the releases (R1, R2, R3). As all seals are assumed to be affected in this scenario, all three safety (sub)functions are degraded. For example, as likely the water circulation through the engineered structures is intensified, the performance characteristics of the safety function R2 (Limitation of water flow through the disposal system) related to the water circulation are degraded compared to the Normal Evolution Scenario.
- Isolation (I2). Stable conditions for the disposed waste will not be guaranteed in the long term assuming degraded seal properties, or even the absence of seals.

Assessment case

AA1 Abandonment

4.4. Poor Sealing Scenario

The FEPs that are related to a possible Poor Sealing Scenario are either of geological or technical origin. The more obvious FEPs, related to construction and design features, are included in the FEP-list. Since at present there is no detailed repository construction plan, only the generic FEP design and construction are specified.

Table 4-3 Identified FEP for *Poor Sealing* Scenario (AS1)

No	FEP Name	Affected safety function					
		Engineered containment (C)	Delay and attenuation of releases (R)			Isolation (I)	
		Preventing as long as required the release of contaminants from the waste container	Limitation of containment releases from the waste forms (R1)	Limitation of water flow through the system (R2)	Retardation and spreading in time of contaminant migration (R3)	Reduction of the likelihood of inadvertent human intrusion and of its possible consequences (I1)	Ensuring stable conditions for the disposed waste and the system components (I2)
AS1 Poor sealing							
1.1.05	Construction			X			
1.1.07	Closure			X	X		
3.1.06	Excavation damaged and disturbed zones			X			X
3.2.02.02	Piping/hydraulic erosion	X		X	X		X
3.2.03.01	Material volume changes (repository)			X			X
3.2.03.03	Collapse of openings			X			X
3.2.04.04	Corrosion (repository)	X		X			X
3.3.01	Transport pathways (repository)			X			
EBS-D 1	Repository geometry			X			
EBS-D 6	Backfill / supports - dimensions and properties			X			
EBS-D 7	Tunnel lining - dimensions and properties			X			
EBS-D 8	Seals / tunnels - dimensions and properties			X			
EBS-D 9	Host-rock EDZ - thickness and properties			X			X
EBS-H 1	Hydraulic properties			X			
EBS-P/M 6	Stress changes			X			X
EBS-P/M 7	Mechanical effects			X			X

Potential features and processes that may be relevant in this scenario include:

- An early release of contaminants from the waste containers due to the enhanced presence of water;
- Enhanced water-mediated transport in the shafts and galleries
- Enhanced water-mediated transport in the aquifer system
- Hydraulic processes in the geosphere

The Poor Sealing scenario affects the following safety functions:

- Engineered containment (C). Obviously, assuming a poor sealing of the various open volumes in the repository, the engineered containment is affected.
- Delay and attenuation of the releases (R2, R3). As all seals are assumed to be affected in this scenario, all three safety (sub)functions are degraded compared to the Normal Evolution Scenario.
- Isolation (I2). Stable conditions for the disposed waste will not be guaranteed in the long term assuming degraded seal properties.

Assessment case

AS1 Poor sealing

4.5. Anthropogenic Greenhouse Scenario

Global warming caused by anthropogenic emission of greenhouse gases to the atmosphere, could lead to melting of part of the Antarctic or Greenland ice sheets which would result in sea-level rise. Consequently, the risk of flooding would increase, in particular in lowland areas like the Netherlands (see also discussion of FEP 4.2.02.02 Hydraulic effects of climate change in Section 4.9.6).

Flooding of the repository could potentially short-circuit the host rock with the biosphere and create direct contact between fluids and the waste containers. This scenario is only relevant in the pre-closure phase of the repository.

Potential features and processes that may influence this scenario include:

- Enhanced water-mediated transport, especially in the aquifer system;
- Chemical conditions, especially in the aquifer system.

Table 4-4 Identified FEPs for *Anthropogenic Greenhouse* Scenario (AGr1)

No	FEP Name	Affected safety function					
		Engineered containment (C)	Delay and attenuation of releases (R)			Isolation (I)	
		Preventing as long as required the release of contaminants from the waste container	Limitation of containment releases from the waste forms (R1)	Limitation of water flow through the system (R2)	Retardation and spreading in time of contaminant migration (R3)	Reduction of the likelihood of inadvertent human intrusion and of its possible consequences (I1)	Ensuring stable conditions for the disposed waste and the system components (I2)
AGr1 Flooding of the site							
1.1.08	Accidents and unplanned events			X	X		
1.2.12.01	Flooding			X	X		X
1.3.01	Global climate change			X	X		X
1.3.03	Sea level change						X
1.4.01	Human influences on climate			X	X		X

The Anthropogenic Greenhouse Scenario affects the following safety functions:

- Limitation of water flow through the system (R2). In the case of an early flooding of the repository this safety function may be by-passed.
- Retardation of contaminant migration (R3). Due to the potentially enhanced transport of water the migration of contaminants may also be enhanced, especially in the aquifer system.
- Isolation (I2). As a result of the short-circuit of the host rock with the biosphere and the potentially resulting direct contact between fluids and the waste containers the this safety function may be affected.

Assessment case

AGr1 Anthropogenic greenhouse

4.6. Fault Scenario

Faults or fractures in the Boom Clay may not be detected because of limitations in the resolution of site-characterisation techniques or inherently limited quality assurance (see Table 4-5). Hydraulic properties of faults may also adversely be altered as a consequence of unforeseen geologic events such as movement along the fault plane and the formation or increase of a fault gauge. Fault movement may influence the integrity of the EBS as well.

The existence or formation of faults mostly affects the following safety functions:

- Limitation of water flow through the disposal system (R2). In the case of faults with enhanced hydraulic conductivity the transport of water to and from the repository may be enhanced, potentially resulting in increased transport of radionuclides.
- Retardation of contaminant migration (R3). Due to the potentially enhanced transport of water the migration of contaminants may also be enhanced.
- Ensuring stable conditions for the disposed waste and the system components (I2). The mechanical disturbances that may accompany the formation of faults may influence the stable conditions normally present in the Boom Clay host rock.
- An undetected fault may lead to a hydraulic coupling between the repository and a more widespread rock zone. Human actions in this wider rock zone may disturb the repository. This increases the likelihood of human intrusion[5] (I1).

Table 4-5 Identified FEPs for *Undetected fault* Scenario (FS1)

No	FEP Name	Affected safety function					
		Engineered containment (C)	Delay and attenuation of releases (R)			Isolation (I)	
		Preventing as long as required the release of contaminants from the waste container	Limitation of containment releases from the waste forms (R1)	Limitation of water flow through the system (R2)	Retardation and spreading in time of contaminant migration (R3)	Reduction of the likelihood of inadvertent human intrusion and of its possible consequences (I1)	Ensuring stable conditions for the disposed waste and the system components (I2)
FS1 Undetected fault scenario							
1.1.02	Site investigations			X			
1.2.01.03	Movement along faults		X	X	X		
1.2.01.04	Glaciotectonic movement			X	X		
1.2.03.01	Deformation by intraplate fault movement		X	X	X		
1.2.04.01	Intraplate seismic movement			X			
1.2.04.02	Glaciotectonic seismicity			X			
3.2.02.02	Piping/hydraulic erosion	X		X	X		X
4.1.05	Undetected features			X	X		
4.3.01	Transport pathways (geosphere)			X	X	X	X
EBS-P/M 4	Seismic activity / earthquakes			X			X
EBS-P/M 5	Faulting / fracturing		X	X	X		X

[5] Intrusion (human): The term human intrusion is used for human activities that could affect the integrity of a disposal facility and which could potentially give rise to radiological consequences. Only those human activities (such as construction work, mining or drilling) that could result in direct disturbance of the disposal facility (i.e. disturbance of the waste itself, of the contaminated near field or of materials of the engineered barrier) are included. (from: IAEA Safety Glossary, 2016 Revision, June 2016.)

Large scale discontinuities, heterogeneity and undetected features (undetected faults), in which there is the potential of a water flow through the host rock, may lead to increased advective transport through the host rock. From Table 4-5 it appears that potentially the Undetected Fault scenario may affect all safety functions of the repository system.

Assessment case

FS1 Undetected fault scenario

4.7. Intensified glaciation scenario

Within the next 100 to 1,000 ka climatic deterioration is to be expected, leading to global cooling, lowering of the sea-level and the formation of permafrost, which will be included in the Normal Evolution Scenario. For the Normal Evolution Scenario it is assumed that mid-latitude ice sheets are formed which might cover the repository area.

In the proposed Intensified glaciation scenario it is assumed that global cooling is accompanied by the formation of a massive ice sheet which does cover a larger part of the Netherlands. As a consequence, mechanical and hydraulic effects caused by the presence of the ice sheet may influence the disposal system. In addition, cooling and the influx of significant amounts of melt-water into the sub-surface may change the stability of dissolved and precipitated minerals. Moreover, deep subglacial valleys can be formed due to subglacial erosion.

Table 4-6 Identified FEPs for *Intensified Glaciation* Scenarios (AGl1, AGl2, AGl3)

No	FEP Name	Affected safety function					
		Engineered containment (C)	Delay and attenuation of releases (R)			Isolation (I)	
		Preventing as long as required the release of contaminants from the waste container	Limitation of containment releases from the waste forms (R1)	Limitation of water flow through the system (R2)	Retardation and spreading in time of contaminant migration (R3)	Reduction of the likelihood of inadvertent human intrusion and of its possible consequences (I1)	Ensuring stable conditions for the disposed waste and the system components (I2)
AGl1 Deep permafrost case							
1.3.04	Periglacial effects				X		
AGl2 Deep subglacial erosion case							
1.3.05	Local glacial and ice-sheet effects			X	X		X
AGl3 Glacial loading case							
1.2.03.02	Deformation by glacial loading			X	X		
1.3.05	Local glacial and ice-sheet effects			X	X		X
4.2.03.02	Mechanical effects of climate change (geosphere)			X	X		

The intensified glaciation affects the following safety functions:

- The Limitation of water flow (R2), as a result of permanently frozen ground with discontinuities thereby changing groundwater flow patterns;
- The Retardation function (R3), due to indirect effects of changing temperature and changing groundwater salinity, thereby affecting the stability of clay minerals;
- The Isolation function (I2), induced by a significant reduction of the subsurface geologic consistency.

Assessment cases

AGl1 Deep permafrost case. An important characteristic of periglacial environments is the seasonal change from winter freezing to summer thaw with large water movements and potential for erosion. The frozen subsoils are referred to as permafrost. Meltwater of the seasonal thaw is unable to percolate downwards due to permafrost and saturates the surface materials, this can result in a mass movement called solifluction (literally soil-flow). Permafrost layers may isolate the deep hydrological regime from surface hydrology, or flow may be focused at “taliks” (localised unfrozen zones, e.g. under lakes, large rivers or at regions of groundwater discharge).

AGl2 Deep subglacial erosion case. Erosional processes associated with glacial action, especially advancing glaciers and ice sheets, and with glacial meltwaters beneath the ice mass and at the margins, can lead to the formation of e.g. U-shaped valleys, hanging valleys, fjords and drumlins. Deposits associated with glaciers and ice sheets include accumulated earth, sediments, and stones. The pressure of the ice mass on the landscape may result in significant hydrogeological effects and even depression of the regional crustal plate.

AGl3 Glacial loading case. Glacial cycles have a significant impact on sea level as a result of ice formation, and local and regional glacial loading and unloading effects. Glacial loading and unloading may lead to deformation of the repository’s components and to mechanical effects on the engineered barriers.

4.8. Human Intrusion Scenarios

Human Intrusion Scenarios can have an impact on all safety functions. Loss of administrative control makes the facility vulnerable to future mining activities. Table 4-7 lists the FEPs that are assumed to affect the repository’s safety functions for the two considered human intrusion scenarios.

Table 4-7 Identified FEPs for *Human Intrusion* and *Human Action* Scenarios (AH1, AH2)

No	FEP Name	Affected safety function					
		Engineered containment (C)	Delay and attenuation of releases (R)			Isolation (I)	
		Preventing as long as required the release of contaminants from the waste container	Limitation of containment releases from the waste forms (R1)	Limitation of water flow through the system (R2)	Retardation and spreading in time of contaminant migration (R3)	Reduction of the likelihood of inadvertent human intrusion and of its possible consequences (I1)	Ensuring stable conditions for the disposed waste and the system components (I2)
AH1 Penetration by drilling or mining							
1.1.09	Repository administrative control					X	
1.4.02	Social and institutional developments					X	
1.4.04	Knowledge and motivational issues (repository)					X	
1.4.05	Drilling activities		X	X	X	X	X
1.4.06	Mining and other underground activities		X	X	X	X	X
1.4.12	Deliberate human intrusion	X	X	X	X	X	X
2.4.04	Human-action-mediated release	X	X	X	X	X	X
2.5.01	Transport pathways (waste package)	X	X	X	X	X	X
3.3.05	Human-action-mediated transport	X	X	X	X		X

No	FEP Name	Affected safety function					
		Engineered containment (C)	Delay and attenuation of releases (R)			Isolation (I)	
		Preventing as long as required the release of contaminants from the waste container	Limitation of containment releases from the waste forms (R1)	Limitation of water flow through the system (R2)	Retardation and spreading in time of contaminant migration (R3)	Reduction of the likelihood of inadvertent human intrusion and of its possible consequences (I1)	Ensuring stable conditions for the disposed waste and the system components (I2)
	(repository)						
4.1.04	Geological resources			X	X	X	
4.2.03.03	Other processes affecting future stress conditions in geosphere			X	X		
4.2.07.01	Gas sources (geosphere)					X	
EBS-H 14	Preferential pathways	X	X	X	X	X	X
EBS-P/M 9	Post-closure activities - effects	X	X	X	X		X
AH2 Deep well scenario – extreme case							
1.1.09	Repository administrative control					X	
1.4.02	Social and institutional developments					X	
1.4.04	Knowledge and motivational issues (repository)					X	
1.4.06	Mining and other underground activities		X	X	X	X	X
1.4.08	Surface environment						X
2.4.04	Human-action-mediated release			X	X	X	X
2.5.01	Transport pathways (waste package)			X	X	X	X
3.3.05	Human-action-mediated transport (repository)			X	X		X
4.1.04	Geological resources			X	X	X	
4.2.03.03	Other processes affecting future stress conditions in geosphere			X	X		
4.2.07.01	Gas sources (geosphere)					X	

Assessment cases that have been considered are:

AH1 - penetration of the facility as a result of a drilling for exploration, oil and gas or geothermal energy exploitation, thermal storage, gas storage or other purposes, may lead to:

- direct transport of radioactive material to the surface;
- a preferential advective transport pathway through the clay;
- unfavorable changes of the chemical environment of the waste.

AH2 - exploration of deep wells, i.e. over several hundred meters, for water extraction, potentially leading to unfavorable changes in surrounding geological formations and in the aquifer (and biosphere) characteristics.

These human intrusion scenarios affect the following safety functions:

- Engineered containment (C). Drilling activities would lead to a (local) degradation of this safety function.

- Delay and attenuation of the releases (R1, R2, R3). A result of drilling activities these safety function can be bypassed, although this is judged to be a very local effect due to the small volumes involved.
- Isolation (I2). Also this safety function may locally be bypassed as a result of drilling and exploration activities.

Assessment cases

AH1 Penetration by drilling or mining

AH2 Deep well scenario - extreme case

4.9. What-If cases

In the process of FEP screening a number of FEPs have been identified which, taking into account extreme or excessive conditions, potentially might affect the repository's safety functions. Some of these FEPs relate to (1) the waste, (2) temperature effects of the waste and (3) gas related phenomena which were not assigned to a specific scenario and need further evaluation:

- EEC1 Excessive Early Container Failure
- EGC1 Excessive Gas assessment case
- EFD1 Fast and radical dissolution of the waste
- ECC1 Criticality event
- EHP1 Excessive heat production

As will be elucidated in the following sections these FEPs may mainly affect the repository's safety functions *Engineered containment* (C) and *Delay and attenuation of releases* (R).

In addition FEPs have been identified that may lead to alternative transport modes in the aquifers or that have a strong impact on the transport in the aquifers and/or biosphere, thereby also challenging the safety function *Isolation* (I), including the sub-functions *Reduction of the likelihood of inadvertent human intrusion* (I1) and *Ensuring stable conditions for the disposed waste and the system components* (I2):

- SGH1, SGC1 Geological phenomena
- SHE1 Human-induced phenomena
- SBM1 Biological phenomena
- SAT1 Transport phenomena

The following sections describe the identified What-If cases in more detail.

4.9.1. Excessive early containment/canister failure

The Normal Evolution Scenario assessment case N4 (Early canister failure case – normal range) assumes a gradual failure of the engineered containment, earlier than the several thousand years as assumed for the Central assessment case N1.

In case of an *excessive* early containment/canister failure scenario it is assumed that a very early loss of the functionalities of the engineered containment will occur on a series of containers and for the entire inventory. This extreme «What-If» case is in line with the assumptions made by ANDRA about their "Package Failure" scenarios (ANDRA, 2005b; p.513), and covers all forms of uncertainty concerning the corrosion conditions for the waste packages and engineered barriers.

In this What-If case, it is assumed that all of the waste containers' overpacks fail early and allow pore water coming into contact with the waste form relatively early after their emplacement. Although unlikely, this situation might be the result of, for example, a poor assessment of container lifetime for the whole repository. Early canister failure can lead to enhanced corrosion rates and gas generation rates, potentially resulting in increased stresses in the surrounding host rock. As a result, water transport through the host rock might also increase.

The identified FEPs and their potential impact on the safety functions are shown in Table 4-8.

Table 4-8 Identified FEPs for What-If case *Excessive early containment failure* (EEC1)

No	FEP Name	Affected safety function					
		Engineered containment (C)	Delay and attenuation of releases (R)			Isolation (I)	
		Preventing as long as required the release of contaminants from the waste container	Limitation of containment releases from the waste forms (R1)	Limitation of water flow through the system (R2)	Retardation and spreading in time of contaminant migration (R3)	Reduction of the likelihood of inadvertent human intrusion and of its possible consequences (I1)	Ensuring stable conditions for the disposed waste and the system components (I2)
EEC1 Excessive early containment failure							
1.1.06	Operation	X	X				
2.3.03.04	Stress-corrosion cracking	X	X				
2.3.04.04	Corrosion (waste package)	X					
3.2.04.04	Corrosion (repository)	X		X			X
EBS-D 2	Overpack - dimensions and properties	X					
EBS-D 4	Envelope - dimensions and properties	X					
EBS-C 3	Corrosion - causes / processes	X					
EBS-P/M 1	Cracking	X	X				
EBS-P/M 3	Corrosion - stress cracking	X	X				

The premature failure of the containers affects the following safety functions:

- Engineered containment. The period of engineered containment is assumed to be shortened substantially. Except for an early release of radionuclides, this may also affect corrosion rates of the engineered barriers, inducing an enhanced gas formation rate.
- Limitation of contaminant releases from the waste forms. Water reaching the waste during the transient may jeopardize release kinetics. The effects of temperature are judged as limited since the temperature increase of the engineered barriers and the surrounding host rock are relatively mild due to the extended surface storage period.
- Limitation of the water flow through the disposal system. Early failure of engineered barriers (including the waste packages) results in an enhanced water transport (desaturation/resaturation) in the disposal system, although this effect is judged of relatively less importance due to the low hydraulic conductivity of the Boom Clay.

As the Boom Clay remains unaffected the safety function "Retardation and spreading in time of contaminant migration (R3)" is judged to remain intact.

What-if case

EEC1 Excessive Early Container Failure

4.9.2. Excessive gas generation

The normal and expected gas generation in the facility is part of the normal evolution and has to be dealt with in the normal evolution scenario. Some additional and potentially adverse effects of gas generation will be treated in Normal Evolution Scenario N3, the *Gas pressure build-up case (normal range)*.

During the FEP screening questions arose what consequences would follow from an *excessive* gas generation and the resulting effects. Excessive gas generation could potentially result from an early and relatively large ingress of (pore) water, or unforeseen chemical and/or biological interactions between disposed waste compounds and/or between these compounds and the ambient materials (Boom Clay, pore water). The potentially affected safety functions are indicated in Table 4-9.

At present, it is unclear whether these excessive effects could significantly disturb the normal evolution of the repository, since the Boom Clay seems capable of assimilating the gas without losing its safety functions. Therefore it has been proposed to study the effects of excessive gas generation in a What-If case.

Table 4-9 Identified FEPs for What-If case *Excessive gas generation* (EGC1)

No	FEP Name	Affected safety function					
		Engineered containment (C)	Delay and attenuation of releases (R)			Isolation (I)	
		Preventing as long as required the release of contaminants from the waste container	Limitation of containment releases from the waste forms (R1)	Limitation of water flow through the system (R2)	Retardation and spreading in time of contaminant migration (R3)	Reduction of the likelihood of inadvertent human intrusion and of its possible consequences (I1)	Ensuring stable conditions for the disposed waste and the system components (I2)
EGC1 Excessive gas assessment case							
2.3.02.03	Gas effects (waste package)	X		X			
2.3.05.03	Impact of biological processes on other processes (waste package)	X					
2.3.07.01	Metal corrosion (waste package)	X		X			
2.3.07.02	Organic degradation (waste package)	X	X	X			
2.3.07.07	Gas-induced failure	X		X			
2.3.07.08	Impact of gas generation on other processes (waste package)	X		X			
3.2.07.08	Gas-induced dilation (repository)	X		X			
3.3.03	Gas-mediated transport (repository)	X		X	X		
4.2.07.04	Gas dissolution (geosphere)				X		
4.3.03	Gas-mediated transport (geosphere)				X		
EBS-C 6	Corrosion – gases	X		X			
EBS-C 13	Microbial / biological / biochemical activity	X					
EBS-C 14	Gas generation	X		X			
EBS-H 11	Gas flow and transport	X		X			
EBS-H 12	Gas-induced flow and transport	X		X			

The excessive gas generation may affect the following safety functions:

- Engineered containment (C). The period of engineered containment is assumed to be shortened substantially in case excessive gas generation results from excessive corrosion of the waste packages and/or engineered barriers.
- Limitation of contaminant releases from the waste forms (R1). Water reaching the waste during the transient may jeopardize release kinetics. The effects of temperature are judged as limited since the temperature increase of the engineered barriers and the surrounding host rock are relatively mild due to the extended surface storage period.
- Limitation of the water flow through the disposal system (R2). Early failure of engineered barriers (including the waste packages) results in an enhanced water transport (desaturation/resaturation) in the disposal system, although this effect is judged of relatively less importance due to the low hydraulic conductivity of the Boom Clay.
- Retardation of contaminant migration (R3). It is still an open question whether the migration of any released (volatile) radionuclides will be enhanced by an excessive gas generation.

What-if case

EGC1 Excessive Gas assessment case

4.9.3. Fast and radical dissolution of the waste

Dissolution of the waste form is in the Normal Evolution Scenario limited by the design and properties of the waste matrix, engineered barriers, and the geochemical environment. In addition, a significant amount of the involved waste compounds, including the radionuclides, does not or hardly dissolve in pore water and will therefore not migrate through the Boom Clay.

However, it cannot be ruled out beforehand that co-disposal of a variety of chemical compounds and potentially reactive wastes would result in a relatively fast degradation of the waste matrix.

The FEP screening led to several dissolution/precipitation related FEPs, that potentially could affect some of the repository's safety functions in case these FEPs would contribute excessively to the evolution of the disposal system (see also Table 4-10).

The What-If case *Fast and radical dissolution of the waste* (EFD1) concerns an unexpectedly fast and complete dissolution of the full waste inventory.

Table 4-10 Identified FEPs for What-If case *Fast and radical dissolution of the waste* (EFD1)

No	FEP Name	Affected safety function					
		Engineered containment (C)	Delay and attenuation of releases (R)			Isolation (I)	
		Preventing as long as required the release of contaminants from the waste container	Limitation of containment releases from the waste forms (R1)	Limitation of water flow through the system (R2)	Retardation and spreading in time of contaminant migration (R3)	Reduction of the likelihood of inadvertent human intrusion and of its possible consequences (I1)	Ensuring stable conditions for the disposed waste and the system components (I2)
EFD1 Fast and radical dissolution of the waste							
2.3.04.06	Dissolution (waste package)	X	X				
2.4.01.02	Dissolution (waste form)	X	X				

No	FEP Name	Affected safety function					
		Engineered containment (C)	Delay and attenuation of releases (R)			Isolation (I)	
		Preventing as long as required the release of contaminants from the waste container	Limitation of containment releases from the waste forms (R1)	Limitation of water flow through the system (R2)	Retardation and spreading in time of contaminant migration (R3)	Reduction of the likelihood of inadvertent human intrusion and of its possible consequences (I1)	Ensuring stable conditions for the disposed waste and the system components (I2)
EBS-C 1	Solubility / solubility limits	X	X				
EBS-C 2	Precipitation / crystallization / dissolution	X	X				
EBS-C 7	Mineralogical changes	X	X				

The fast and radical dissolution of the waste affects the following safety functions:

- Engineered containment (C). The period of engineered containment is assumed to be shortened substantially in case the waste matrix will be dissolved much faster than expected.
- Limitation of contaminant releases from the waste forms (R1). Early dissolution of the waste forms will likely lead to earlier releases of radionuclides. In addition, water reaching the waste during the transient may jeopardize chemical reaction kinetics. The effects of temperature are judged as limited since the temperature increase of the engineered barriers and the surrounding host rock are relatively mild due to the extended surface storage period.

What-if case

EFD1 Fast and radical dissolution of the waste

4.9.4. Criticality

Nuclear criticality may occur if a sufficient amount of fissile material is concentrated to a level where spontaneous fission may be induced. The presence of any water may increase the potential for nuclear criticality as it can act as a moderator. In general, criticality of fissile material will lead to a very large and sudden heat production and pressure waves.

A criticality *accident* in a deep geological repository leading to a nuclear explosion is principally impossible since that would require maintained critical conditions which can only be achieved in a special designed device. In addition, design measures and waste acceptance criteria apply that prevent or at least significantly minimize the improbable spontaneous concentration of disposed fissile materials.

Criticality *incidents* are best described by one or a sequence of intermittent, limited uncontrolled chain reactions, also called "localized criticality." Localized criticality results in a series of bursts of heat and radiation.

In conditioned LLW, ILW any present fissile materials are dispersed over a large volume, and nuclear criticality is impossible. Vitrified high level wastes may contain only minute amounts of fissile materials since the majority of these compounds have been recycled and separated from the fission products that are contained in the HLW.

In spent fuel, in particular in highly enriched uranium (HEU), localized criticality has to be avoided by design (Dodd, 2000; p. 84).

In this What-If case the consequences of localized criticality will be assessed. The related FEPs and their potential impact on the safety functions are indicated in Table 4-11.

Table 4-11 Identified FEPs for assessment case *Criticality event* (ECC1)

No	FEP Name	Affected safety function					
		Engineered containment (C)	Delay and attenuation of releases (R)			Isolation (I)	
		Preventing as long as required the release of contaminants from the waste container	Limitation of containment releases from the waste forms (R1)	Limitation of water flow through the system (R2)	Retardation and spreading in time of contaminant migration (R3)	Reduction of the likelihood of inadvertent human intrusion and of its possible consequences (I1)	Ensuring stable conditions for the disposed waste and the system components (I2)
ECC1 Criticality event							
2.3.01.01	Radiogenic heat production and transfer	X	X	X			
3.2.06.05	Criticality	X	X	X			
EBS-R 5	Criticality	X	X	X			
EBS-T 2	Thermal effects - physical/mechanical	X	X	X			

A localized criticality event could potentially affect the following safety functions:

- Engineered containment (C). The engineered containment might fail in case of a localized criticality event as a result of e.g. excessive heat production and sudden related thermo-mechanical effects.
- Limitation of contaminant releases from the waste forms (R1). Early rupture of waste packages and engineered barriers may result from the abovementioned sudden thermo-mechanical effects.
- Limitation of water flow through the system (R2). A disruption of the integrity of the waste packages, engineered barriers and perhaps also the near field affects this safety function.

What-if case

ECC1 Criticality event

4.9.5. Excessive heat production

High temperatures and temperature gradients can lead to enhanced thermal stresses and chemical alteration of materials. Although part of the waste is heat generating waste, undue high temperatures are avoided by design. In addition, the long-term surface storage of the waste and the resulting decrease of the decay heat reduces the potential of high temperatures in the repository. Excessive heat production may be generated in the case of e.g. a criticality event.

In this What-If case the consequences of undue high temperatures will be explored.

Table 4-12 Identified FEPs for assessment case *Excessive heat production* (EHP1)

No	FEP Name	Affected safety function					
		Engineered containment (C)	Delay and attenuation of releases (R)			Isolation (I)	
		Preventing as long as required the release of contaminants from the waste container	Limitation of containment releases from the waste forms (R1)	Limitation of water flow through the system (R2)	Retardation and spreading in time of contaminant migration (R3)	Reduction of the likelihood of inadvertent human intrusion and of its possible consequences (I1)	Ensuring stable conditions for the disposed waste and the system components (I2)
EHP1 Excessive heat production							
2.3.01.01	Radiogenic heat production and transfer	X	X	X			
EBS-T 2	Thermal effects - physical / mechanical	X	X	X			

An excessive heat production could potentially affect the following safety functions:

- Engineered containment (C). The engineered containment might be affected in case of excessive heat production as a result of e.g. thermo-mechanical effects.
- Limitation of contaminant releases from the waste forms (R1). Early rupture of waste packages and engineered barriers may result from the abovementioned thermo-mechanical effects.
- Limitation of water flow through the system (R2). A disruption of the integrity of the waste packages, engineered barriers and perhaps also the near field due to thermo-mechanical effects may affect this safety function.

What-if case

EHP1 Excessive heat production

4.9.6. Geological phenomena induced by climate change

Climate is a dynamic process which has shown dramatic changes in the past. Presently, human activities are suspected to interfere with climate, e.g. through the vastly increased emission of greenhouse gases. Potential consequences of these human activities are warming of the global climate, changes in precipitation patterns, increase of the frequencies of severe storms and sea-level rise. The research question in the context of geological disposal is whether these changes will have a noticeable influence on the safety functions of the host rock or even the EBS in the deep subsurface.

Taking into account these considerations the following two What-if cases have been defined:

- **SGH1**, Study of hydraulic effects of climate change. The related FEP is 4.2.02.02, *Hydraulic effects of climate change (geosphere)*. The hydrogeological regime is the characterisation of the composition and movement of water through the relevant geological formations in the repository region and the factors that control this. This requires knowledge of the recharge and discharge zones, the groundwater flow systems, saturation, and other factors that may drive the hydrogeology, such as density effects due to salinity gradients or temperature gradients. Changes of the hydrogeological regime due to e.g. the influx of glacial meltwater as a result of global warming, may affect the safety function “R2”.
- **SGC1**, Study of compaction of the Boom Clay and resulting flow, e.g. by glacial loading. Compaction of semi-consolidated clays will result in deformation of the clay matrix and expulsion of formation water. The related FEP is 1.2.03.04, *Deformation by compaction*. The Study/Assessment case will assess whether the Boom Clay pore will become over-pressured, i.e. not in equilibrium with the hydrostatic pore pressure, resulting in an increased water flow through the disposal system, thereby challenging safety functions “R2” and “I2”.

Table 4-13 Identified FEPs for What-if cases *Geological phenomena induced by climate change* (SGH1, SGC1)

No	FEP Name	Affected safety function					
		Engineered containment (C)	Delay and attenuation of releases (R)			Isolation (I)	
		Preventing as long as required the release of contaminants from the waste container	Limitation of containment releases from the waste forms (R1)	Limitation of water flow through the system (R2)	Retardation and spreading in time of contaminant migration (R3)	Reduction of the likelihood of inadvertent human intrusion and of its possible consequences (I1)	Ensuring stable conditions for the disposed waste and the system components (I2)
SGH1 Hydraulic effects of climate change (geosphere)							
4.2.02.02	Hydraulic effects of climate change (geosphere)			X			
SGC1 Compaction of Boom Clay							
1.2.03.04	Deformation by compaction			X			X

What-if case

SGH1 Hydraulic effects of climate change

SGC1 Compaction of Boom Clay

4.9.7. Human phenomena

Many human activities are ongoing at the earth's surface and in the subsurface, which are acknowledged under FEP 1.4 *Future Human Actions*. Social and institutional developments (FEP 1.4.02) do not constitute on their own intrusion into the facility but they may potentially lead to an increased possibility of Human Intrusion. In particular the situation with complete loss of institutional control could increase the likelihood of human interference with the host rock and geosphere overlying the repository.

For the production of geo-materials and fossil fuels like brown coal, quarries and open pits may be created to depths of up to a few hundreds of metres which may drastically change the hydraulic regime in the geosphere, potentially affecting the safety function "I2". The research question is whether this type of excavations can have an influence on the safety functions of the host rock in the deep subsurface.

Table 4-14 Identified FEPs for What-if Case *Human phenomena* (SHE1)

No	FEP Name	Affected safety function					
		Engineered containment (C)	Delay and attenuation of releases (R)			Isolation (I)	
		Preventing as long as required the release of contaminants from the waste container	Limitation of containment releases from the waste forms (R1)	Limitation of water flow through the system (R2)	Retardation and spreading in time of contaminant migration (R3)	Reduction of the likelihood of inadvertent human intrusion and of its possible consequences (I1)	Ensuring stable conditions for the disposed waste and the system components (I2)
SHE1 Deep excavation and groundwater flow							
1.4.02	Social and institutional developments						X

What-if case

SHE1 Study of deep excavation and groundwater flow

4.9.8. Biological phenomena

The presence of microbial life in the subsurface, in particular in the host-rock environment, is supposed to potentially affect the ambient conditions, see e.g. the SAFIR-2 study (ONDRAF/NIRAS, 2001; Section 11.3.6.5.2.4). The IGD TP Exchange Forum meeting in 2013 directed a specific session to microbiological effects on the safety of RN waste disposal (IGD-TP, 2013). The research question in OPERA is whether microbial life can influence the safety functions of the EBS and the host rock. The related FEP is 4.1.10 *Current biological state*. Table 4-15 provides a preliminary qualitative judgement of the safety functions affected by this particular FEP.

Relevant processes mentioned in the SAFIR-2 study for this FEP are:

- Decomposition of organic matter
- Conversion of hydrogen by methane forming bacteria

Table 4-15 Identified FEPs for What-if case *Biological phenomena* (SBM1)

No	FEP Name	Affected safety function					
		Engineered containment (C)	Delay and attenuation of releases (R)			Isolation (I)	
		Preventing as long as required the release of contaminants from the waste container	**Limitation of containment releases from the waste forms (R1)**	**Limitation of water flow through the system (R2)**	**Retardation and spreading in time of contaminant migration (R3)**	**Reduction of the likelihood of inadvertent human intrusion and of its possible consequences (I1)**	**Ensuring stable conditions for the disposed waste and the system components (I2)**
SBM1 Microbiological effects on EBS and host rock							
4.1.10	Current biological state	X	X		X		X

What-if case

SBM1 Study of microbiological effects on the EBS and host rock

4.9.9. Transport phenomena

During the FEP screening process the following FEPs were judged to have an impact on the transport modes in the Normal Evolution Scenario:

3.3.02.01 Advection (repository)
3.3.02.02 Dispersion (repository)
3.3.02.03 Molecular diffusion (repository)
3.3.02.04 Dissolution, precipitation and mineralisation (repository)
3.3.02.05 Speciation and solubility (repository)
3.3.02.06 Sorption and desorption (repository)
3.3.02.07 Complexation (repository)
3.3.02.08 Colloid transport (repository)

These FEPs are presently not attributed to a specific (set of) stand-alone scenario(s) since they constitute processes which all play a role to some extent in the NES and AES's. Including or excluding these transport FEPs may be done by parameter variations less than defining separate scenarios.

The potential impact of these transport FEPs on the OPERA safety functions is summarized in Table 4-16).

Table 4-16 Identification of safety functions potentially affected by transport FEPs

No	FEP Name	Affected safety function					
		Engineered containment (C)	Delay and attenuation of releases (R)			Isolation (I)	
		Preventing as long as required the release of contaminants from the waste container	Limitation of containment releases from the waste forms (R1)	Limitation of water flow through the system (R2)	Retardation and spreading in time of contaminant migration (R3)	Reduction of the likelihood of inadvertent human intrusion and of its possible consequences (I1)	Ensuring stable conditions for the disposed waste and the system components (I2)
SAT1 Transport modes							
3.3.02.01	Advection (repository)			X			
3.3.02.02	Dispersion (repository)			X			
3.3.02.03	Molecular diffusion (repository)			X			
3.3.02.04	Dissolution, precipitation and mineralisation (repository)		X		X		
3.3.02.05	Speciation and solubility (repository)		X		X		
3.3.02.06	Sorption and desorption (repository)		X		X		
3.3.02.07	Complexation (repository)		X		X		
3.3.02.08	Colloid transport (repository)		X		X		

What-if case

SAT1 Study of additional transport modes

4.10. Discussion

In this section the FEP screening and the resulting assessment cases are viewed against the results presented in SAFIR 2 (ONDRAF/NIRAS, 2001) and PROSA (Prij, 1993). Table 4-17 shows all SAFIR-2 altered evolution scenarios and the equivalent OPERA assessment cases.

Table 4-17 SAFIR-2 scenarios and OPERA assessment cases

SAFIR-2 scenarios		**OPERA assessment case**	
AES1	Exploitation drilling	AH2	Deep well scenario - extreme case
AES2	The greenhouse effect	AGr1	Flooding of the site
AES3	Poor sealing of the repository	AS1	Poor sealing
AES4	Fault activation	FS1	Undetected fault scenario
AES5	A severe glacial period	AGl1 AGl2 AGl3	Deep permafrost case Deep subglacial erosion case Glacial loading case
AES6	Failure of the engineered barriers	N4 EEC1 EFD1	Early canister failure case (normal range) Excessive Early Container Failure Fast and radical dissolution of the waste
AES7	Gas-driven transport	N3 EGC1	Gas pressure build-up case (normal range) Excessive Gas generation
AES8	Exploratory drilling	AH1	Penetration by drilling or mining

Overall there is agreement between the SAFIR-2 scenarios and the OPERA scenarios, which should be expected because

- both are based on the same disposal concept and host rock, and
- the approaches to scenario identification are related (see below).

Differences are a result of:

- differing inventory (SAFIR 2 describes a disposal concept for HLW only, while the OPERA concept also contains ILW and LLW);
- other terminology (SAFIR 2 uses "scenario", OPERA distinguishes between "scenario", "assessment case" and "what if case").

Both in SAFIR 2 and in the PROSA study, the safety of the disposal system was thought to depend on a sequence of subsequent barriers (Prij, 1993; Section 2.3):

i) The engineered barriers: waste form, waste container, borehole backfill, borehole plugs and seals, backfilled gallery, dams, and backfilled shafts.

ii) The isolation shield between the repository and the boundary of the salt formation (host rock).

iii) The overburden between the salt formation and the biosphere. This barrier includes the groundwater system with the aquifers and aquitards (geosphere).

The subsequent barriers together form a multi-barrier system: multiple, redundant, and independent layers of safety systems. The aim of a multi-barrier system is to reduce the risk that a single failure of a critical system could cause a failure of the whole system.

In PROSA and SAFIR 2, the FEP screening has been used to identify the states of each of the three above-mentioned barriers. It was assumed that there are in principle two possible states of each of the barriers:

i) the barrier is present

ii) the barrier is not present (bypassed).

The combination of three barriers with each having two states leads to a total of eight possible “damage states” of the repository’s multi-barrier system (Prij, 1993; Table 2.4), as elucidated in the following figure.

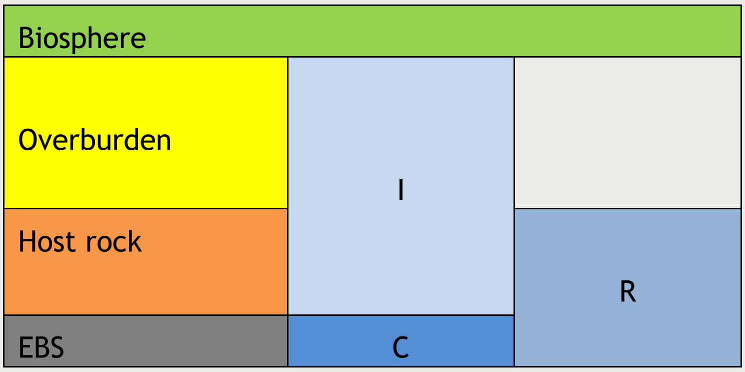

Figure 4-1 Scheme representing the relation between the principal safety functions and the various barriers and subsurface compartments

The present analysis and the FEP screening methodology resemble largely those utilized in the PROSA project. However, instead of allocating a damage state to individual physical barriers, we have attempted to define damage states for each of the *safety functions*, as illustrated in Table 4-18. The reason to consider safety functions instead of the individual barriers is that the safety function concept is more flexible: the safety functions, unlike the individual physical barriers, comprise a range of physical and chemical phenomena and processes characterizing specific functions of the barrier system.

As indicated in Table 4-18 the consequence of a failure of a safety function is indicated as a “Damage State”, whereas the “Damage State Qualifiers” denote the severity of the safety function failure.

Table 4-18 Safety Functions and Damage States

Safety function	Damage State	Damage State Qualifiers		
		Limited Damage	Slight Damage	Significant Damage
Engineered containment (C)	Failure timing	Late	Modest	Early
Limitation release (R1)	RN mobilisation	Slow	Modest	Fast
Limitation water flow (R2)	Water flow	Slow	Modest	Fast
Retardation (R3)	Mobility	Small	Modest	Large
Isolation (I)	Vulnerability	Small	Modest	Large

Based on these "Damage States" an overview has been compiled of all system states for the set of scenarios and What-If cases in Table 4-19. This table shows that the scenarios mainly affect the safety function R2, R3 and I, while the What-If cases mainly affect the safety functions C and R1. The table also shows that for this set of assessment cases all safety functions are more or less challenged.

Table 4-19 Safety functions and defense-in-depth

	Safety Functions				
	Containment (C)	**Delay and attenuation of the releases (R)**			**Isolation (I)**
		Limitation release (R1)	Limitation flow (R2)	Retardation (R3)	
Damage State	Failure timing	RN Mobilisation	Water flow	Mobility	Vulnerability
Scenarios					
Normal Evolution Scenario	late	slow	slow	small	small
Abandonment	late	slow	fast	modest	modest
Poor Sealing	late	slow	modest	modest	small
Anthropogenic Greenhouse	late	slow	slow	small	small
Fault	late	slow	fast	modest/large	small
Intensified Glaciation	late	slow	modest	small	modest
Human Intrusion	early	fast	fast	large	large
What-If Cases					
Excessive Early Containment Failure	early	slow	slow	small	small
Excessive Gas Generation	unknown	unknown	slow	small	small
Fast and Radical Waste Dissolution	early	fast	slow	large	small
Criticality Event	early	fast	modest	small	modest
Excessive Heat Production	unknown	unknown	slow	small	small

5. Conclusions

The FEP screening process has confirmed that the originally proposed set of scenarios, based on the scenarios analysed within the SAFIR-2 study, is adequate for the present, generic stage of the OPERA safety assessment. Nevertheless, a detailed screening of the OPERA FEP catalogue has resulted in the addition of “What-If” assessment cases for further analysis.

The screening of the FEP catalogue was done by examining which FEPs could have an adverse effect on one or more of the safety functions of the OPERA disposal system. For each of the FEPs it has been decided how the FEP should be treated:

- FEPs as part of the central assessment case of the Normal Evolution Scenario (NES);
- FEPs leading to new assessment cases as part of the NES;
- FEPs which are covered by the present set of Altered Evolution Scenarios (AES);
- FEPs leading to additional What-If cases;
- FEPs potentially leading to alternative transport modes or a strong impact on the transport in the aquifers and/or biosphere. These cases may be analyzed further to reduce uncertainties.

The following list gives an overview of the 24 assessment cases identified during the FEP screening.

Normal Evolution Scenario	
N1	Central assessment case
N2	Radioactive gas transport case
N3	Gas pressure build-up case (normal range)
N4	Early canister failure case (normal range)
N5	Deep well assessment case
Abandonment Scenario	
AA1	Abandonment
Poor sealing scenario	
AS1	Poor sealing
Anthropogenic Greenhouse Scenario	
AGr1	Flooding of the site
Fault scenario	
FS1	Undetected fault scenario
Intensified glaciation scenario	
AGl1	Deep permafrost case
AGl2	Deep subglacial erosion case
AGl3	Glacial loading case

Human Intrusion Scenarios	
AH1	Penetration by drilling or mining
AH2	Deep well scenario - extreme case
What-If cases	
EEC1	Excessive Early Container Failure
EGC1	Excessive Gas generation
EFD1	Fast and radical dissolution of the waste
ECC1	Criticality event
EHP1	Excessive heat production
SGH1	Study of hydraulic effects of climate change
SGC1	Study of compaction of the Boom Clay and resulting flow
SHE1	Study of deep excavation and groundwater flow
SBM1	Study of microbiological effects on the EBS and host rock
SAT1	Study of additional transport modes

For each of the scenarios, assessment cases, and What-If cases, the potential impacts of the FEPs on the safety functions have been indicated.

The screening of FEPs to identify scenarios, assessment cases and What-If cases to be implemented in the OPERA safety assessment depends to a large extent on expert judgement. As a result there is a risk that FEPs are incorrectly classified, and ultimately that important alternative scenarios or assessment cases have been missed.

The procedure can be improved if the screening is done by a larger number of experts, and by recording extensively the motivations of the experts for making their judgements. However, such an extensive study was beyond the scope of the present project's budget and timeline.

The identification of FEPs and description of scenarios is an iterative revision process using results from detailed process studies, characterisation and performance assessment during the successive research phases in the preparation, site selection and implementation of a repository.

Nevertheless, identification of additional alternative scenarios for a generic site is deemed unlikely because scenario identification has been an ongoing effort performed in several safety assessment studies in various countries during the last 25 years.

For the identified set of assessment cases all safety functions attributed to the OPERA disposal concept in Boom Clay are to greater or lesser extent challenged.

References

(ANDRA, 2005a) ANDRA, Dossier 2005 Argile, Architecture and management of a geological repository, December 2005.

(ANDRA, 2005b) ANDRA Dossier 2005 Argile, Safety evaluation of a geological repository, December 2005.

(Beuth, 2012) Beuth T, et al.: Szenarienentwicklung: Methodik und Anwendung, Bericht zum Arbeitspaket 8, Vorläufige Sicherheitanalyse für den Standort Gorleben, GRS-284, Köln, August 2012.

(CORA, 2001) Commissie Opberging Radioactief Afval, Terugneembare berging, een begaanbaar pad? Onderzoek naar de mogelijkheden van ”terugneembare berging van radioactief afval in Nederland”, Ministry of Economic Affairs, The Hague, February 2001.

(Dodd, 2000) Dodd DH, Grupa JB, Houkema M, de Haas JBH, Van der Kaa Th, Veltkamp AC, Direct Disposal of Spent Fuel from Test and Research Reactors in the Netherlands - A Preliminary Investigation, NRG 21406/00.30934/P, 2000.

(Grassmann, 2009) Grassmann S, et al.: pT effects of Pleistocene glacial periods on permafrost, gas hydrate stability zones and reservoir of the Mittelplate oil field, northern Germany, Marine and Petroleum Geology, Elsevier, Oxford, United Kingdom, Volume 27, Issue 1, pp. 298-306, 2010.

(Grupa, 2000) Grupa JB, Houkema M, Terughaalbare opberging van radioactief afval in diepe zout en kleiformaties; Modellen voor een veiligheidsstudie, Petten, NRG 21082/00.33017/P, March 2000.

(Grupa, 2009) Grupa JB, Trial of formal Use of Expert Judgement for Scenario Conceptualisation, PAMINA RTDC 2 - M2.2.C.3, 2009.

(Grupa, 2014) Grupa JB, Report on the safety assessment methodology, OPERA-PU-NRG2121, 2 April 2014.

(IAEA, 2012) International Atomic Energy Agency, Safety Standards Series, The Safety Case and Safety Assessment for the Disposal of Radioactive Waste, Specific Safety Guide No. SSG-23, STI/PUB/1553, Vienna, September 2012.

(IGD-TP, 2013) IGD-TP, Exchange Forum n°4, Presentations and outcomes, Working Group 5 - Microbiological Studies, Prague, Czech Republic, October 29-30th, 2013.

(Marivoet, 1988) Marivoet J, Bonne A, PAGIS : Performance Assessment of Geological IsolationSystems, Clay Option, EC, Luxembourg, Report EUR 11776 EN, 1988.

(Marivoet, 2000) Marivoet J, et al., A palaeohydrogeological study of the Mol site (PHYMOL project), Final report for EC, Contract n° F14W-CT96-0026, DG EUR 19146 EN, 2000.

(NAGRA, 2002) NAGRA Project Opalinus Clay Safety Report Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis), Technical Report 02-05 , 2002.

(NEA, 2004) Nuclear Energy Agency, Post-Closure Safety Case For Geological Repositories Nature And Purpose, NEA No. 3679, OECD, 2004.

(NEA, 2012) Nuclear Energy Agency, Methods for Safety Assessment of Geological Disposal Facilities for Radioactive Waste, Outcomes of the NEA MeSA Initiative, NEA No. 6923, OECD, 2012.

(ONDRAF/NIRAS, 2001) ONDRAF/NIRAS, Safety Assessment and Feasibility Interim Report 2, NIROND 2001–06 E, December 2001.

(ONDRAF/NIRAS, 2009) ONDRAF/NIRAS, The Long-term Safety strategy for the geological disposal of radioactive waste, NIROND-TR-2009-12E, 2009.

(Prij, 1993) Prij J., PROSA, Probabilistic Safety Assessment - final report, ECN, Petten, 1993.

(Schelland, 2014) Schelland M, Hart J, Wildenborg AFB, Grupa JB, OPERA FEP-database, OPERA-PU-TNO2123A; OPERA-PU-TNO2123B (Excel file), May 2014.

(Schröder, 2009) Schröder TJ, Rosca-Bocancea E, Hart J, Costescu-Badea A, Bolado Lavin R, Techniques for Sensitivity and Uncertainty Analysis - Analysis of a repository design in argillaceous rock, PAMINA Milestone Report M2.1D.12, 2009.

(Shaw, 2012) Shaw, RP, Auton, C A, Baptie, B, Brocklehurst, S, Dutton, M, Evans, DJ, Field, LP, Gregory, SP, Henderson, E, Hughes, AJ, Milodowski, AE, Parkes, D, Rees, JG, Small, J, Smith, N, Tye, A, and West, JM, Potential Natural Changes and Implications for a UK GDF, British Geological Survey, Minerals and Waste Programme, Commissioned Report CR/12/127, 2012.

(Valstar, 2016) Valstar JR, Goorden N, Hydrological transport in the rock formations surrounding the host rock, OPERA-PU-DLT621, 2016.

(Verhoef, 2011a) Verhoef E, Schröder TJ, Research Plan, OPERA-PG-COV004, COVRA N.V., 2011.

(Verhoef, 2011b) Verhoef E, Neeft E, Grupa JB, Poley AD. Outline of a disposal concept in clay OPERA-PG-COV008, COVRA N.V., 5 July 2011.

(Vis, 2014) Vis GJ, Verweij JM, Geological and geohydrological characterization of the Boom Clay and its overburden, OPERA-PU-TNO411, March 2014, 1-91.

(Wildenborg, 2013) Wildenborg T, Shaw R, Norris S, Impact of permafrost on repository safety, IGD TP Exchange Forum, Prague, 29 October 2013.

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