Scenario model representation
Part A:
Main report

OPERA-PU-TNO7121A

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.

OPERA-PU-TNO7121A
Title: Scenario model representation – Part A: Main report
Authors: J. Grupa, J. Hart, T. Wildenborg
Date of publication: June 2017
Keywords: scenario, FEP, normal evolution, altered evolution, safety assessment

Contents

Summary

The larger part of the OPERA Research Programme is directed to the development of a generic safety case for a radioactive waste repository in the Boom Clay. The central activity of the Programme is the performance assessment of the long-term safety of the disposed waste which provides the main building block for the safety case. As part of the assessment work a series of scenarios has been developed; each scenario describes a possible future state or evolution of the repository and its surroundings.

The scenarios which have been identified and characterized in a previous step are now translated into model representations. For this purpose close to 50 FEPs have been pre-selected for discussion with process experts in several expert elicitations. The results of these discussions have been used to further define the model representation of the individual scenario Assessment Cases. Most scenario Assessment Cases can be properly represented with the OPERA Baseline Model (OBM). The OBM is a description of scenario models primarily focussing on the assessment of the Normal Evolution Scenario, but also including scenarios with glacial phenomena e.g. permafrost, ice loading or subglacial erosion, or clay compaction. The present OBM does not cover all scenarios: a few warrant the development of alternative PA models, e.g. for direct exposure, gas migration, microbial interaction or specific transport processes.

Future work should concentrate on the completion of the scenario analysis, development of dedicated PA models for gas migration and microbial interaction and should study the transient aspects of FEPs like salinity changes and their effect on radionuclide migration.

Samenvatting

Het overgrote deel van het OPERA Onderzoeksprogramma is gericht op de ontwikkeling van een generieke veiligheidscasus (“safety case”) voor een berging van radioactief afval in de Klei van Boom. De belangrijkste bouwsteen voor de safety case wordt geleverd door de evaluatie van de veiligheid (“performance assessment”) van de berging op de lange termijn. Onderdeel van de veiligheidsevaluatie is de ontwikkeling van een serie scenario’s die elk een mogelijke toekomstige toestand of evoluties van de ondergrondse berging en zijn omgeving beschrijven.

De scenario’s die zijn geïdentificeerd en gekarakteriseerd in een voorafgaande stap zijn nu vertaald in modelrepresentaties. Ter ondersteuning van dit doel zijn bijna 50 gepreselecteerde FEPs met experts besproken in meerdere expert elicitaties. De resultaten van deze discussie zijn gebruikt om de modelrepresentaties van de verschillende scenario’s en “Assessment Cases” te definiëren. De meeste Assessment Cases worden goed weergegeven door het OPERA Baseline Model (OBM). Het OBM is een beschrijving van scenariomodellen dat toepasbaar is op het Normale Evolutie Scenario, maar ook op scenario’s die glaciale verschijnselen omvatten zoals permafrost, ijsbelasting of subglaciale erosie, of kleicompactie. Het huidige OBM is niet voor alle scenario’s geschikt. Voor enkele scenario’s is het noodzakelijk om een alternatief model op te stellen, namelijk voor directe blootstelling, gasmigratie, microbiële interactie en enkele specifieke transportprocessen.

Toekomstig werk zou zich moeten richten op het afronden van de scenarioanalyse, de ontwikkeling van specifieke modellen voor gasmigratie en microbiële interactie en het onderzoeken van transiënte aspecten van FEPs zoals de verandering van het zoutgehalte en het effect daarvan op radionuclidenmigratie.

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 disposal in two host rocks present in the Netherlands, salt rock and Boom Clay[1] (Verhoef, Neeft, Grupa, & Poley, 2011, 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, Neeft, Grupa, & Poley, 2011, 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, Neeft, Grupa, & Poley, 2011, 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 J. , 2014) "*Report on the safety assessment methodology*".

The present report is the result of the research proposed for Task 7.1.2, S*cenario representation,* in the OPERA Research Plan (Verhoef & Schröder, Research Plan, 2011). 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. The development of the scenarios was part of Task 7.1.1 in the OPERA Research Plan and reported separately in OPERA-PU-NRG7111 (Grupa, Hart, & Wildenborg, Description of relevant scenarios for the OPERA disposal concept, 2017). The present report builds on the findings of OPERA-PU-NRG7111.

1.2. Objectives

The main objective of this report is to translate the scenarios identified in OPERA-PU-NRG7111 (Grupa, Hart, & Wildenborg, 2017) into physical and geochemical models. In addition, the OPERA FEP database (Schelland, Hart, Wildenborg, & Grupa, 2014) has been expanded with several attributes which are relevant for the involvement of process experts and the model representation (Wildenborg, Grupa, & Hart, 2017).

More specific, the purposes of the present work is to map how the various FEPs are represented in the PA model, to record the argumentations and decisions made in this mapping process, to prepare for more detailed expert elicitation, and to record the results of the expert elicitation in terms of scenario models.

Table 1 describes the position of the current deliverable with respect to other documents in the OPERA Research Programme. A list of relevant OPERA reports has been included in Appendix 1.

[1] "Rupel Clay" is the modern time lithostratigraphical designation of "Boom Clay". This report will use the term "Boom Clay" as is common practice in research on geological disposal of radioactive waste.

Table 1 Overview of the scenario analysis and related OPERA reports; * = Present report

Overall approach in scenario analysis	OPERA Reports
A narrative: Description of a succession of events	• Description of relevant scenarios for the OPERA disposal concept in OPERA-PU-NRG7111 (Grupa, Hart, & Wildenborg, 2017))
Identification of the processes and possible initiating events	• Translation of the processes in models, parameters and boundary conditions in OPERA-PU-TNO7121A* (Grupa, Hart, & Wildenborg, 2017) and OPERA-PU-TNO7121B (Wildenborg, Grupa, & Hart, 2017)
The properties and related parameter values (in time)	• Report on model parameterization - Normal Evolution Scenario in OPERA-PU-NRG7251-NES (Schröder, 2017) • Reference set of model parameters - NES in OPERA-PU-NRG7252-NES (Rosca-Bocancea, 2017)
Used assumptions and simplifications	• Migration of radionuclides in Boom Clay PA model 'Clay' in OPERA-PU-NRG7212 (Grupa J. , et al., 2017) • Migration in the formations surrounding the host rock PA model 'Aquifer' in OPERA-PU-GRS7222 (Grupa J. , et al., 2017) • Migration and uptake of radionuclides in the biosphere - PA-model 'Biosphere' in OPERA-PU-SCK631&NRG7232 (Grupa J. , et al., 2017)

1.3. Realization

This report presents the model representation of the identified scenarios relevant for the assessment of the long-term safety of a repository in Boom Clay. The set of scenarios and related Assessment Cases are based on OPERA-PU-NRG7111 (Grupa, Hart, & Wildenborg, 2017). Along with the current report a reference list of model parameters for all scenarios has been compiled in OPERA-PU-NRG7122 (Hart, Meeussen, & Grupa, 2015). Results of the initial FEP screening have been included in an update of the FEP database (Wildenborg, Grupa, & Hart, 2017).

The study and analysis presented in this report are performed by members of the OPAP-consortium, consisting of NRG and TNO in cooperation with experts from the OPERA Work Packages 3 to 6. For this task NRG delivered the expertise on the Engineered Barrier System and TNO on the geological features. The methodology for the FEP representation is developed in a joint effort of NRG and TNO.

After the initial characterisation of the FEPs in terms of relevance for the PA model and their preliminary model representation (Wildenborg, Grupa, & Hart, 2017), 5 expert elicitations were held during which pre-selected FEPs in the related expertise domain were discussed in terms of their possible representation in the PA model.

1.4. Explanation contents

The methodology for the model representation of the scenarios and related Assessment Cases is elucidated in Chapter 2. Chapter 3 describes the OPERA Baseline Performance Assessment Model (OBM). In the next chapter (Chapter 4) the results of the screening of the FEPs by the PA-experts and the expert elicitations with various expert groups are presented. Chapter 5 summarizes the outcome for the model representation of the various scenarios. The last two chapters conclude with a short discussion of the methodology and its limitations, conclusions and recommendations.

2. Method for scenario model representation

A scenario model is "*a word picture of sufficient detail so that it can be developed into mathematical equations and data requirements*". This is similar to the definition of 'conceptual' model developed by NIREX in 1999 (OECD-NEA, 1999), and this definition fits also well to 'scenario models' in OPERA. The scenario model should provide information concerning the scope of the model and its interaction with other parts of the system.

In OPERA-PU-NRG7111 (Grupa, Hart, & Wildenborg, 2017) a set of scenario narratives was developed, describing in broad terms the various potential future states or evolutions of a disposal system. In the present report, scenario models are added to these narratives. PA modelling in OPERA is developed along two largely parallel tracks:

1) a track involving experts from various disciplines in order to implement or use process models or phenomenological observations. In this process the OPERA FEP database is used in order to maintain a systematic approach where decisions of the experts are traceable. This expert driven model representation is the main ingredient of the present report.
2) a track using the available mathematical models developed in previous research programmes, which have been further elaborated during OPERA using the process experts input, see Appendix 1.

The resulting mathematical model, described conceptually in the OPERA Baseline Model (OBM; see Chapter 3), can be regarded as a mould into which the scenario models have to fit in order to be able to perform calculations.

It is anticipated that the OBM can serve as a tool for many scenarios, where the various scenarios are represented by different parameter values and the selection or deselection of some of the OBM modules. However, for some scenarios, the OBM may not be able to address one or more of the relevant processes and an extra module should be developed or even a completely different approach might be needed.

The work on the scenario model representation is done by PA experts and process experts:

- PA-experts are responsible for defining the scenarios and performing the safety analyses (OPERA WP7);
- Process experts develop models and provide data which are supporting specific parts or modules of the PA-model (OPERA WP3, WP4, WP5 and WP6).

In track 1, the scenario model representation is based on expert judgement. The PA-experts have set out the scenario narratives in broad lines, and have specified their needs regarding the processes involved. The process experts deliver process concepts and models, and also can specify more precisely what the impact is of the processes on the scenarios.

The identification of scenarios, and corresponding narratives and FEPs have already been described in OPERA PU-NRG7111 (Grupa, Hart, & Wildenborg, Description of relevant scenarios for the OPERA disposal concept, 2017). The method for scenario representation thus builds on the work described in the aforementioned report.

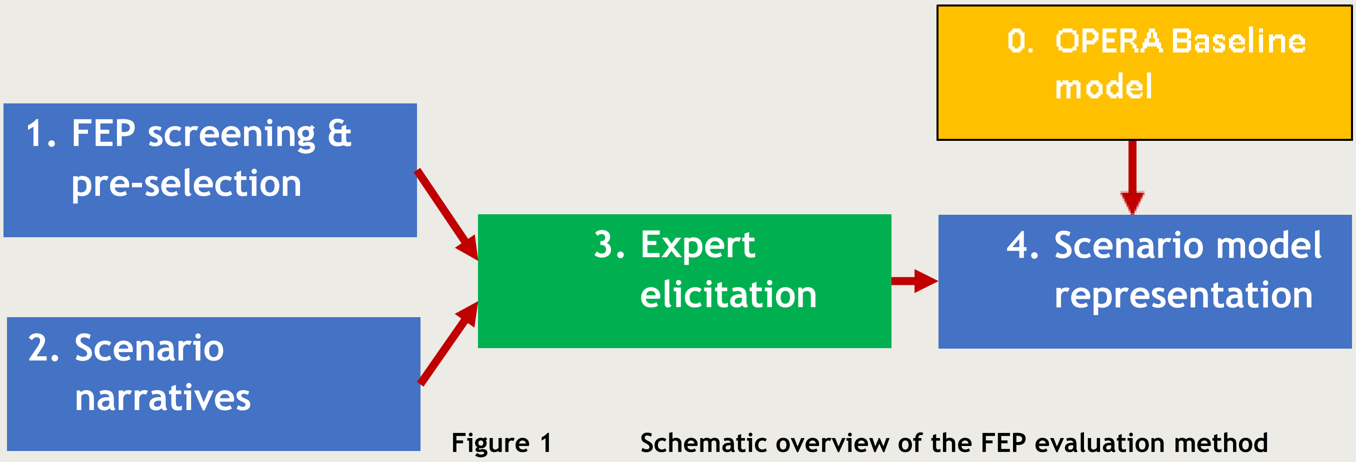


Figure 1 Schematic overview of the FEP evaluation method

The process for the model representation of the scenarios consists of 4 (+1) steps, which is schematically presented in Figure 1.

0. In parallel to the scenario model representation the OBM has been developed, which is used as reference for the scenario model representation (step 4).
1. The PA-experts have screened the FEP list and pre-selected FEPs for which an elicitation by process-experts is needed.
2. These pre-selected FEPs are combined with the relevant scenario narratives (OPERA-PU-NRG7111) and presented to the process experts.
3. The process experts discuss the relevance and the impact of the selected FEPs.
4. The PA-experts develop scenario models based on the process-expert discussion.

2.1. FEP screening process

In previous stages of the performance assessment in OPERA, features, events and processes (FEPs) relevant for the OPERA disposal concept have been assigned to various scenarios and Assessment Cases (Grupa, Hart, & Wildenborg, Description of relevant scenarios for the OPERA disposal concept, 2017). In that process, FEPs have been assigned to the central Assessment Case of the Normal Evolution Scenario (N1), to the other Assessment Cases of the Normal Evolution Scenario and to the Altered Evolution Scenarios (AES). These FEPs have again been assessed here, in particular in the way they are or can be represented in the PA model.

To that end, the OPERA FEP database (Schelland, Hart, Wildenborg, & Grupa, 2014) has been extended with four further columns (Table 2):

1. The FEP aspects that are relevant to the PA modelling
2. An assessment of the current representation of the FEP in the OBM
3. Connection of the FEP with the relevant OPERA expert(s) and tasks in the OPERA Programme
4. Optional questions for the expert(s).

This expanded FEP database represents the starting point of the FEP evaluation depicted in Figure 2).

Note, that during this screening process, the experts were not always able to judge the extent of the impact of a FEP. For many of these FEPs the experts could provide two parallel judgements: 1) it is considered likely that the FEP occurs and has a mild impact on the system development. In that case the FEP is to be considered in one of the NES Assessment Cases. 2) It is considered unlikely that the FEP has a strong impact and affects one or more of the safety functions. This is to be considered in an Assessment Case of one of the AES's. As an example, FEP 3.3.03 *gas mediated transport* is treated in NES case N3 *Gas pressure build-up* (normal range), as well as in AES case EGC1 *Excessive Gas generation*. For these FEPs, the FEP database contains two statements about the FEP representation in the OBM: one statement about the representation of the FEP in the NES, and another statement about the representation of the FEP in an AES.

Table 2 Additional attributes in the FEP database accounting for the representation of the FEPs in the OBM

FEP Description	FEP aspects relevant to PA modelling	How is this FEP represented in the OBM?	Relevant OPERA expert(s)	Specific questions for the OPERA expert(s)
(already exists in the OPERA FEP database)	Short description of the possible impact of the FEP on the evolution of the system in the given scenario	The impact of the FEP has the following possible representations: 1. is included in a mathematical model 2. is represented by a (range of) parameter value(s) 3. is a condition of applicability of the OBM 4. is too minor to be addressed in the OBM 5. is addressed in a special Assessment Case 6. is out of the scope of the OBM.	specified by the task number in the OPERA Research Plan	Optional

Examples of the various categories of model representation of FEPs are given here:

1- Included in the mathematical model
The FEP is explicitly included in the mathematical PA-model.

Example:

FEP 3.2.06.01	Radioactive decay and ingrowth (repository)
Type of FEP	System description
Relevant to	All scenarios
FEP aspects relevant to PA modelling	Simulations of the migration of actinides must take account of the decay chains. The most relevant 4 decay chains are: 4N: (^{248}Cm etc.), 4N + 1 (^{245}Cm etc.) 4N+ 2 (^{242}Pu etc.) and 4N + 3 (^{247}Cm etc.) These decay chains gives rise to a secondary dose peak after 1e6 years, see the example graph taken from SAFIR.
PA model representation	1 - Mathematical decay-ingrowth model is included in PA model
Questions to process experts	No

2 - Represented by a parameter value in the mathematical model
The FEP can be represented in a value for a parameter in the mathematical PA-model.

Example:

FEP 4.3.02.07	Water-mediated transport (geosphere) (3.2.07) Sorption and desorption (geosphere) (3.2.03)
Type of FEP	System description
Relevant to	All scenarios
FEP aspects relevant to PA modelling	thermodynamic properties of the various geochemical elements will enable evolutionary computations. Reaction rates seem to be not well-known in relevant cases.
PA model representation	2 – radionuclides reflected in a linear absorption factor 3 - other processes, such as alkaline plume, do not affect the provision of the safety functions
Questions to process experts	No

3 - A condition to the applicability of the PA- model
These FEPs typically describe features of the disposal system that lead to the conclusion that the PA-model is applicable, or alternatively could be regarded as requirements to the design and the selected site in order to ensure that the results of the performance assessment are applicable.

Example:

FEP 3.1.03	Room/tunnel seals (2.1.05)
Type of FEP	System description
Relevant to	All scenarios
FEP aspects relevant to PA modelling	The hydraulic barrier performance of the seals must be sufficient to suppress advective transport.
PA model representation	3 - The PA model for the NES assumes that no advective transport occurs in the EBS or the host rock.
Questions to process experts	Task 7.2: Description of the conceptual model of the OPERA design? Task 3.1.1: Do you support the conceptual model representation? Task 3.1.1: Are the EB-properties well established?

4 - Included in the uncertainty range of the PA - model (the impact is smaller than the overall uncertainty)
The FEPs of category 1 (included in PA model) and 2 (parameter value in the mathematical model) determine the mathematical PA model and the bandwidth of the input parameter values. The majority of the FEPs, however, is expected to have a relative small impact on the calculations result, and if the impact of a FEP is smaller than the uncertainty bandwidth, the FEP can be placed in category 4 and ignored in the PA.

Example:

FEP 3.2.06.04	Radiation damage (repository)
Type of FEP	System description
Relevant to	All scenarios
FEP aspects relevant to PA modelling	radiation levels too low for significant damage to EBS. It contributes to the slow degradation of waste packages and container integrity (included in normal evolution)
PA model representation	4 - no impact
Questions to process experts	No

5 -Not included in the PA-model. It will be addressed in a special assessment or study case

Some FEPs are not included in the PA-model, and the extent of the impact of the FEP on the performance is not clear to the experts who have been screening the FEP list. It is highly relevant that the potential impact of these FEPs will be investigated in special study cases.

Example:

FEP H11	Gas flow and transport The flow and transport of non-radioactive gases and radioactive gases, and the entrainment of gaseous or volatile radionuclides in gas flow.
Type of FEP	System description
Relevant to	All scenarios
FEP aspects relevant to PA modelling	Anaerobic metal corrosion causes gas (H_2) production. Anaerobic organism can produce gases (CO_2, CH_4) from various organics. These gases can drive transport indirectly by pore water displacements or directly by transporting radioactive gases (^{14}C)
PA model representation	3 - in the NES gas production will not cause significant radionuclide transport 5 - assessed in a study case
Questions to process experts	Tasks 5.1.5+6.1.6: Are these processes (in the waste packages) sufficiently well understood and modelled in the Integrated Model? See also questions for "Related FEPs"

6 -Not included in the PA-model. The FEP must be listed for treatment after OPERA.

Some FEPs are not included in the PA model, the impact is unknown but expected to be relevant, but there is no task in the Research Plan addressing the FEP. Therefore, such FEPs must be listed for treatment after OPERA.

Example:

FEP 5.4.06.02	Radiological toxicity/effects for biota other than humans
Type of FEP	System description
Relevant to	All scenarios
FEP aspects relevant to PA modelling	Not evaluated. Only effects on humans due to consumption of other biota are evaluated.
PA model representation	6 - relatively new ICRP guides give methods for calculating doses for other biota.
Questions to process experts	No

All FEPs assigned to the various Assessment Cases of the Normal Evolution Scenario and the Altered Evolution Scenarios have been assessed. The relevant FEPs with the added attributes are represented in OPERA-PU-TNO7121B (Wildenborg, Grupa, & Hart, Scenario model representation Part B: FEP Decomposition, 2017).

2.2. Structured expert elicitation

To integrate the results of other OPERA work packages in the performance assessment of WP7, the expert elicitation process described below was executed. This process is aimed at collecting feedback from OPERA experts with respect to the model representation of the most relevant FEPs.

The request for feedback from the experts centres around the PA model representation of the pre-selected FEPs. The OPERA FEP database is used as a key tool here. At this stage, the experts are not explicitly asked for comments on the FEP identification itself presented in (Grupa, Hart, & Wildenborg, Description of relevant scenarios for the OPERA disposal concept, 2017); for merely practical reasons their input is restricted to the representation of the identified FEPs in the PA model. The FEP identification can be reviewed at a later (post-OPERA) stage.

The following steps in the expert elicitation were anticipated:

1. The PA team makes a textual description of the Central Assessment Case and the other cases in the Normal Evolution Scenario and the Altered Evolution Scenarios.
2. For each expert or group of experts, connected to a specific task or work package, the PA team lists the FEPs that those experts are competent to judge.
3. The PA team pre-selects 25 FEPs per expert (group) at a maximum which are to be sent to the expert(s). The maximum of 25 FEPs was chosen because more will not be manageable in the expert elicitations.
4. The PA team asks the experts to select the five most important FEPs of the list and invites them to attend an expert elicitation to discuss the FEP model representation. The experts are also free to add missing FEPs that they consider important for the PA model representation. The following information is provided to the experts:
   - 4.1. a short description of the PA context (PA modelling with ORCHESTRA including its purpose, approach and restrictions, FEPs as a tool to structure, trace and aim for completeness, expert feedback needed);
   - 4.2. the descriptions of the Central Assessment Case and other cases in the Normal and Altered Evolution Scenarios;
   - 4.3. the pre-selected FEPs (max 25) to be evaluated
5. The experts choose the five most important FEPs from the list and respond to the PA team.
6. The PA team may add 3 to 5 FEPs that they consider important.
7. The PA team checks if extra experts need to be invited to cover the new selection of FEPs.

8. The PA modellers and experts meet in a maximum three-hour expert elicitation, centred around the selected 8 to 10 FEPs. The expert elicitation contains the following elements:
   8.1. Short presentation by the PA team about the objectives of the expert elicitation, the context of PA modelling, FEP analysis, model representation of various scenarios and Assessment Cases and the OBM.
   8.2. Quick check – why have these FEPs been chosen?
   8.3. Structured discussion about the model representation of the selected FEPs. The experts should provide information on specified features, phenomena and/or processes relevant to the disposal system (detailed data, models, uncertainty estimates). The information should be in line with the information needed for OPERA Performance Assessment, i.e. the long-term performance assessment, and should take into account any restrictions and boundary conditions specified.
   8.4. In case of dispute between experts more than one interpretation might emerge and if necessary recommendations for solving the disagreement will be defined.
   8.5. Inventory: what data is needed to finish the model representation, who will provide that?
9. The PA team summarizes the expert elicitation output including recommendations for the new model representation and asks the experts for agreement.

After this interactive process, the PA team will adjust the model representation of the NES Central Assessment Case and the other identified cases to the agreed recommendations.

3. OPERA Baseline Model (OBM)

The OBM is the modelling approach, which was initially developed in the CORA Programme (CORA, 2001) and is similar to the PA-model described in e.g. SAFIR-2 (ONDRAF/NIRAS, 2001). It has been further refined in the OPERA Programme (Verhoef & Schröder, Research Plan, 2011) and combined with the outline of the OPERA repository system (Verhoef, Neeft, Grupa, & Poley, 2011). In OPERA, many tentative assumptions and model steps used in the CORA Programme have been replaced by data and models specifically developed for potential sites in The Netherlands (see the overview of the process studies in Appendix 1).

This chapter provides a qualitative description of the OBM, since the mathematical description is given in the reports:

- OPERA-PU-NRG7212: PA model 'Clay' (Grupa J. , et al., Migration of radionuclides in Boom Clay, PA model 'Clay' , 2017),
- OPERA-PU-GRS7222: PA model 'Aquifer' (Grupa J. , et al., Migration in the formations surrounding the host rock - PA model 'Aquifer' , 2017), and
- OPERA-PU-SCK631-NRG7232: PA model 'Biosphere' (Grupa J. , et al., 2017).

3.1.Qualitative description of the OBM

This chapter very concisely describes the baseline model, i.e. the model knowledge available to the PA-experts and the information about the OBM that was presented to the process experts.

The PA model actually is a chain of models – representing four spatial compartments – the mobilisation and migration of radionuclides in the repository, host rock and aquifer and the exposure to radionuclides in the biosphere.

Repository (Waste, EBS) compartment

Each disposal tunnel is closed and sealed after the waste containers have been emplaced in the disposal tunnel. Porewater from the clay will intrude into the disposal tunnel and in a period of ten to twenty years all pore volume of the disposal tunnel becomes water saturated. Note that already during operation pore water is intruding, but generally it evaporates and is carried away by the underground air ventilation system.

Once the disposal tunnel is saturated, the pressure of the pore water increases to the hydrostatic pressure at 500 m depth, i.e. about 5 MPa. Only the Supercontainer and the DepU container can resist this pressure for more than 100 years, all other containers will probably fail shortly after saturation of the disposal tunnel. Once a container has failed, water intrudes and is in direct contact with the waste. When the water is in direct contact with the waste, nuclides can dissolve in the water and can start migrating.

PA-model: Mixing tank model
After saturation of the disposal tunnel, all natural processes are very slow. Given this slow evolution, it is conservative to assume that all nuclides that leach from the waste are practically immediately homogeneously dispersed over all water in the disposal tunnel, i.e. nuclides reach the EBS-clay interface instantaneously, instead of by diffusion through the EBS. The PA model treats the water in the disposal tunnel as a mixing tank, in which all constituents are mixed homogeneously. Moreover, it is assumed that all containers fail directly and all nuclides dissolve instantaneously into the disposal tunnel 'mixing tank', unless process studies show a long container lifetime, a low leaching rate, and/or a

solubility limitation. Starting from this mixing tank, the nuclides can migrate further into the clay, which is the next compartment in the PA-model. It is expected that these assumptions are only slightly conservative in comparison with homogeneous diffusive transport in the EBS.
In case of preferential transport pathways in the EBS, local concentrations may be higher than in the mixing tank. However, because the diffusive transport in the host rock is very slow compared to both the mixing time and the release time, the initial local concentration variations will vanish.

Features, events and processes
In order to perform calculations on the nuclide migration, features (data) of the facility need to be known: the radionuclide inventory, the dimensions of each disposal tunnel and the amount of water after saturation. Events and processes such as failure of the container and leaching rates have to be determined in process studies that are underlying to the safety assessment.

Host Rock (Clay) compartment

The host rock compartment is modelled as a homogeneous porous saturated medium positioned between the 'mixing tanks' representing the repository, and the aquifers that underlie and overlie the host rock.

The water in the clay layer surrounding the repository is in direct contact with the water in the repository. Because of the short distance between the outer water layer in the repository and the clay layer directly surrounding the repository, diffusion ensures equal concentrations in the first centimetres of the enclosing clay layer and the concentration in the repository (which is modelled as a mixing tank).

PA-model: Diffusion-advection model
Migration of nuclides is modelled by a diffusion-advection equation including adsorption by the clay, radioactive decay and ingrowth and a solubility limit, as described e.g. in (ONDRAF/NIRAS, 2001, p. 11.2.6.3).

In the Normal Evolution there is no water flow pathway that accommodates advective transport through the clay rock, there is only diffusive transport. Some Altered Evolution Scenarios, such as the Poor Sealing Scenario, contain an event that induces such a new pathway. Once the pathway is described, a process study is needed to determine the amount of water flowing through the new pathway. Once the water flow is determined, it serves as input to the diffusion-advection equation.

Features, events and processes
The properties of the clay are such that diffusive transport is the dominant transport mode over the about 50 m clay between the repository and the aquifer. Also, adsorption processes in the clay strongly delay the migration (by diffusion as well as by advection) of the nuclides that are adsorbed by the clay. Some events may reduce the adsorption capacity (heat) or increase the advective transport (fault, poor seal, future drilling). The impact of these events can be analysed with the diffusion-advection model, but since these events are considered unlikely, these are treated as Altered Evolution Scenarios.

The response to gas pressure and the weight of an ice layer (glacial) may be included in the model by using an adequate set of parameter values, but these need to be determined in process studies.

Aquifer (overburden) compartment

Once nuclides have crossed the clay layer, they reach the aquifer overlying or underlying the clay formation. The flow of water in the aquifer removes the nuclides from the interface between the clay and the aquifer.

The water cycle drives all water flows, including the ground water flows. Water from the ocean evaporates and can precipitate on land, charging the water volumes on land. Some water infiltrates deep into the ground and replenishes aquifers, where water can reside for long periods of time. Over time, the water returns to the ocean, to continue the water cycle.

The flow patterns start in infiltration areas such as the Veluwe and North-Brabant and flow over a large distance towards seepage areas, such as the polders in the western part of the country, the Wieringermeerpolder in the north-west and to the valleys of the IJssel and Rhine rivers in Gelderland. In the Northern part of the country flow distances are relatively short and the pathlines end up in polder areas close to their starting locations.

The shape of the nuclide transport pathway is determined by the cross width size of the repository or a section of the repository, the length of the transport path in the aquifer system and the amount of transverse dispersion (= perpendicular to the flow). Typical dimensions of the nuclide bearing part of the aquifer system are: path length of 20 to 50 km, cross width of 2 to 3 km, and transverse extension of 10 to 100 m (caused by diffusive and dispersive mass transfer). Because of the relatively small transverse extension, the transport pattern has the form of a "sheet".

PA-model: Residence time model
The transport is characterised by the time it takes nuclides that enter the aquifer near the repository to reach the surface and near surface waters. This time is often referred to as the residence time. The residence times are obtained by process models that contain the groundwater flow model for a sufficiently large region. If adsorption properties of the aquifer are known, these can be reflected in a retardation factor that can be applied to the residence time. A mathematically identical expression of the residence time model can be achieved by using the diffusion-advection equation, and choosing a water flow speed and transport path length such that the transport time is equal to the residence time.

Features, events and processes
The flow pathways through the underground depend on the permeability of each of the (remaining) geological layers that were deposited during (at least) the last 50 million years. An important parameter is the ratio of clay and sand in each layer, increasing amounts of clay generally decrease the permeability. Vertical connections between the more permeable layers can occur at faults or at the location where the clay layer that separates two sandy layers is absent. The permeability pattern is fairly constant over time, but may change e.g. near faults, or due to glacial erosion and human activities (drillings, deep wells).

The water flow velocity depends on the amount of precipitation (climate) and the ways water flow at the surface. These factors are variable over time, so predictions of the residence time are presented as a broad bandwidth.

The residence times are determined in process studies using the data about the geological layers, climate (precipitation), charge and discharge locations, and surface water locations.

The impact of events like deep wells and glacial erosion on residence times have to be considered in the process study.

Biosphere compartment

The future individuals and communities that have to be protected against the radioactive components of the waste live in a biosphere. Radionuclides in the groundwater that is taken up into this biosphere, where they spread out over the water, food products and materials and everyday articles. Radionuclides in food and water will lead to an ingestion dose, while radionuclides in materials and articles cause a radiation dose to all individuals in the vicinity (e.g. radionuclides in sediments on river banks).

For a given biosphere (covering a few squared kilometres) there is a certain intake of radionuclides, but also an outflow of radionuclides in the water that leaves the biosphere. These radionuclides eventually accumulate in the oceans. Considering an individual's lifetime (of e.g. a hundred years) the radionuclide concentrations in the various components of a biosphere are quasi-stationary: the inflow of nuclides equals the outflow on average.

In biosphere process modelling, a biosphere is divided into several components such as waters (from various sources), soils (e.g. for growing crops), various plants, in particular those that are used as food by animals and humans, various animal products (milk, meet, eggs) and humans. Between each two components, nuclide specific transfer coefficients are determined (mainly based on measurements for chemical species). Once the model and all data are available, a direct relation can be determined between the concentration of a nuclide in water that the biosphere 'feeds', and the dose rate by that nuclide in an individual.

PA biosphere model
The PA biosphere model consists of two parts. First, the radionuclide fluxes into the biosphere water, that result from the residence time model, have to be converted to concentration in the biosphere waters. To that end the water flow rate through the biosphere water components of the biosphere model are used.

Then the concentration of the radionuclides in biosphere water is multiplied by a (dose) conversion coefficient to determine the annual dose to individuals in that biosphere.

Features, events and processes
Features of the biosphere are taken from present day biospheres in moderate, Mediterranean, and boreal climates. The largest exposures are found in biospheres representing small, self-supporting agricultural communities. Processes to be accounted for are climate change, changes in use of the surface, changes of the surface itself, changes of habits and diets.

Although the uncertainties are large for predictions into the future of 10^3-10^6 years, it seems that for the 'agricultural community biosphere', the dose coefficients do not depend strongly on habits and diets, because a large part of the dose is caused by direct use of biosphere water for drinking water. The amounts of drinking water (and food) a person needs are determined by evolution. Evolutionary development of the gastro-intestinal system of humans is slow: the water usage and diet of modern man is in many ways comparable with that of Homo erectus of 1 million years ago and even comparable with that of Homo habilis of 5 million years ago.

On the other hand, the doses from radionuclides (escaping from a repository) to an individual in a modern society would be orders of magnitudes smaller than the dose to an individual in a small, self-supporting agricultural community. The actual exposure depends strongly on the human habits and social and technical arrangements in the society, and is therefore difficult to predict.

3.2.Initial model understanding of the experts

The initial model understanding available at the start of the OPERA Programme is based on the work performed in the CORA Research Programme and EU research projects. Of particular relevance is:

CORA-04	Terughaalbare opberging van radioactief afval - modellen voor een veiligheidsstudie (METRO) (Grupa & Houkema, Terughaalbare opberging van radioactief afval in diepe zout- en kleiformaties. Modellen voor een veiligheidsstudie, 2000)

This report contains a scenario study and a performance assessment.

Several other CORA deliverables provide more detail on the characterisation of the subsurface and the migration processes:

CORA-15	Kartering slecht-doorlatende laagpakketten Tertiaire formaties (Bremmer, 1996)
CORA-16	Inventarisatie eigenschappen van Tertiaire kleipakketten (Rijkers, 1998)
CORA-19	Transport of radionuclides disposed of in clay (TRACTOR) (Wildenborg, Orlic, & a.o., Transport of radionuclides disposed of in clay (TRACTOR), 2000)

The work in CORA was sufficient to perform a preliminary safety study for disposal in clay.

3.3.Exchange of information about the OBM

The description of the OBM provided to the experts was qualitative and contained little scientific information. The emphasis in the information provided to the process experts was on the relation between the processes and the safety functions, scenarios and underlying FEPs. *Vice versa*, the process-experts developed the model approaches and parameter values for specific processes that will be used to inform the PA-experts in developing specific compartments or modules in the safety assessment.

The presented principle of the geological repository system is straightforward: multiple man-made and geological barriers will isolate the radioactive waste from our environment until the radioactive waste has decayed. A promising host rock for a repository is clay rock, as it is expected that a site can be found with the following qualities:

- The clay deposit is sufficiently stable.
- The clay deposit is available in large areas in The Netherlands and Belgium as thick, almost homogeneous layers at a suitable depth.
- The clay deposits may show plastic deformation behaviour, and is therefore self-healing against cracks. This is an advantage for the long term safety when building and operating an underground repository in clay.
- The clay deposits have a low permeability, as an intrinsic property of the clay particles that form the clay. As a result, the ground water in the clay is practically stagnant, and all transport of pollutants and radionuclides is limited to a slow diffusion process.
- The clay deposit adsorbs most of the pollutants and radionuclides. This causes further delay of the radionuclide migration and spread in time, and limits the far future exposure of men to the radionuclide to negligible levels.

The process experts have been asked to confirm these statements or to challenge them, following the procedure using the safety concept (safety functions), scenarios and related FEPs. The safety concept as presented to the experts is summarised in Figure 2.

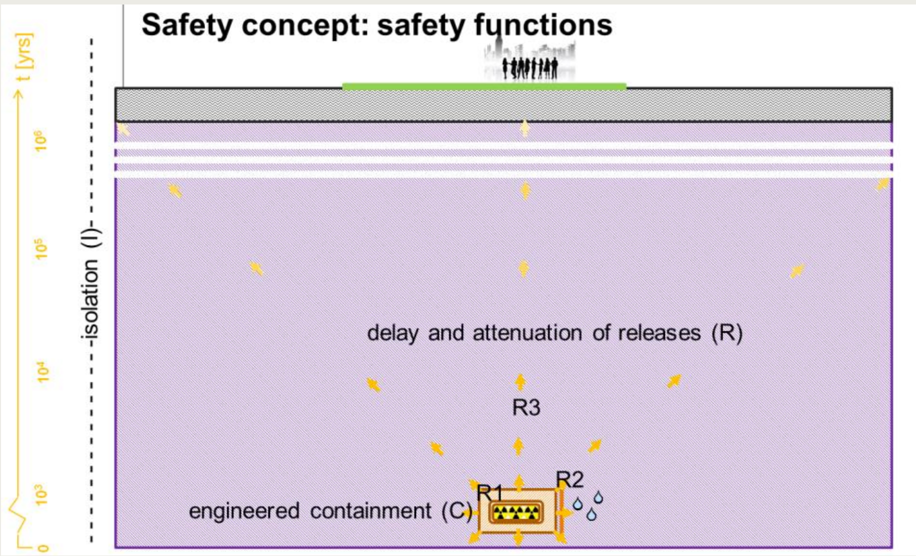


Figure 2 Summary of the safety concept

More details on the OPERA PA model, its compartment modules including the mathematical equations can be found in the reports OPERA-PU-NRG7212 with the PA model 'Clay' (Grupa, et al., 2017), OPERA-PU-GRS7222 with the PA model 'Aquifer' (Grupa, et al., 2017) and OPERA-PU-SCK631-NRG7232 with the PA model 'Biosphere' (Grupa J. , et al., 2017).

4. Evaluation of the OBM

The key objective of the expert elicitations was to arrive at a common understanding of the representation of selected FEPs related to specific categories of process-expertise underlying the PA models, in order to gain an understanding of the relevance of the selected FEPs and to arrive at a practical representation of the FEPs in the PA modelling. The process-categories are:

- Behaviour of waste and container;
- Geomechanics;
- Geochemistry;
- Gas migration;
- Geology and hydrogeology.

These categories have been chosen on several practical grounds:

- They reflect major expertise areas which facilitates the organisation of the expert elicitations.
- They coincide with the major geoscientific and engineering research areas of the OPERA Programme.

Five expert elicitations have been held:

- On 11 March 2016 Guido Deissmann, André Filby (Brenk) and Bruno Kursten (SCK.CEN) were interviewed on FEPs related to waste and container behaviour in the OPERA disposal concept. The report of this expert elicitation is included in Appendix 3, p. 76 ff.
- On 5 Nov 2015 Phil Vardon, Michael Hicks (TU Delft) and Rob Wiegers (IBR Consult) were interviewed on FEPs related to (geo-)mechanics. The report of the expert elicitation is included in Appendix 3, p. 81 ff.
- On 20 Oct 2015 Hans Meeussen (NRG), Jasper Griffioen (TNO) and Thilo Behrends (UU) were interviewed on FEPs related to (geo-)chemistry. The report of the expert elicitation is included in Appendix 3, p. 94 ff.
- On 22 July 2015 Richard Shaw and Jon Harrington (BGS) were interviewed on aspects of gas generation and migration. The report of this expert elicitation is included in Appendix 3, p.98 ff.
- On 18 Nov 2014 FEPs related to Geohydrology with Johan ten Veen (TNO, WP4) were discussed. This expert elicitation treated FEPs which relate in particular to the FEP Groups 'External factors' and 'Geosphere'. The report of this expert elicitation is included in Appendix 3, p. 106 ff.

4.1. FEP decomposition and selection

As explained in Section 2.1, all FEPs assigned to the various Assessment Cases of the Normal Evolution Scenario and the Altered Evolutions Scenarios have been preliminary assessed by the PA-experts in order to evaluate their role in the PA-model. The screening results are recorded in OPERA-PU-TNO7121B. A few examples of this screening are listed in Table 3.

Table 3 Some examples of the preliminary screening by the PA experts

FEP Number level 4/ No	FEP Title (original NEA IFEP no) level 4/ Supercontainer EBS FEP Name	Part of scenario - assessment case	FEP aspects relevant to PA modelling	How is this FEP represented in the PA model?	Relevant OPERA expert(s)	Specific questions for the OPERA expert(s)
3.2.07.08	Impact of gas generation on other processes (repository)	N2 Radioactive gas transport case	Additional transport way	Specific analyses are needed	Task 6.1.6	Task 6.1.6: What are the possible impacts of gas generation on HMC processes? (expert interview)
2.3.02.03	Gas effects (waste package)	N3 Gas pressure buildup case (normal range)	(Qualitative) Analyses are needed to determine the 'normal' gas effects	Can be simulated by appropriate input	Task 3.1.1 Task 5.1.3 Task 5.1.5	Task 3.1: What is the rate of gas production (waste package)? Task 5.1.3/5: What is the rate of gas production (waste package)?
2.3.05.03	Impact of biological processes on other processes (waste package)	N3 Gas pressure buildup case (normal range)	(Qualitative) Analyses are needed to determine the 'normal' gas effects	Can be simulated by appropriate input	Task 3.1.1 Task 5.1.3 Task 5.1.5	Task 5.1.5: How do microbes in the waste package affect the RN mobilization? (Topic discussed during OPERA Expert Meeting, 27 Nov 2014 at TNO)
2.3.07.01	Metal corrosion (waste package)	N3 Gas pressure buildup case (normal range)	(Qualitative) Analyses are needed to determine the 'normal' gas effects	Can be simulated by appropriate input	Task 3.1.1 Task 5.1.3 Task 5.1.5	Tasks 5.1.3/5: Appropriate model for metal corrosion? What is the uncertainty range?
2.3.07.02	Organic degradation (waste package)	N3 Gas pressure buildup case (normal range)	(Qualitative) Analyses are needed to determine the 'normal' gas effects	Can be simulated by appropriate input	Task 1.1.1 (Inventory) Task 3.1.1 Task 5.1.3 Task 5.1.5	Tasks 5.1.3/5: Appropriate model(s) for organic degradation? What is the uncertainty range?
3.2.02.01	Resaturation/desaturation (repository)	N3 Gas pressure buildup case (normal range)	(Qualitative) Analyses are needed to determine the 'normal' gas effects	Can be simulated by appropriate input	Task 3.1.1 Task 5.1.3 Task 5.1.5	Task 3.1.1: in case of gas-pressure buildup: What is the degree of saturation; how much does it extend into the Boom Clay; how long does it take before the desaturation zone has resaturated?
3.2.07.08	Impact of gas generation on other processes (repository)	N3 Gas pressure buildup case (normal range)	Gas pressure may cause relative early containment failure and additional fluid displacements. Also poor heat conductor an dincrease of temperatures around HLW	Specific analyses are needed	Task 6.1.6	Task 6.1.6: What are the possible impacts of gas generation on HMC processes? (expert interview)

The PA-experts and the process experts have jointly selected FEPs for further discussion following the procedure described in Section 2.2. The next sections summarize the main results of the expert elicitations.

4.2. Process category "Behaviour of waste and container"

The FEPs which were discussed in the process category "Behaviour of waste and container" with the "waste and container" experts and the PA experts, are listed in Table 4. A summary of the expert elicitation has been included in Appendix 3, p. 76 ff.

Table 4 Overview of discussed FEPs discussed with waste package/EBS experts; EBS = Engineered Barrier System; SF = Spent Fuel; FEP Id codes fit with FEP records in the database (Schelland, Hart, Wildenborg, & Grupa, 2014)

FEP Id	FEP name	Scenario/AC	Relevant compartment model	PA treatment
2.2.01	Containers	all	EBS -containment	containment lifetime
2.2.02	Overpack	all	EBS -containment	containment lifetime
2.3.03	Mechanical processes	all	EBS -containment	containment lifetime
3.2.04	Chemical processes	all	EBS -waste stability + containment	containment lifetime waste leach rate
C3	corrosion – causes / processes	all	EBS -containment	containment lifetime
M1	Cracking	all	EBS -containment	containment lifetime
2.3.04.06	Dissolution	all	EBS - waste stability	waste leach rate
2.3.01.01	Radiogenic heat production and transfer (temperature in the SF section)	all	EBS / clay	containment lifetime waste leach rate degradation of the clay barrier near the EBS
R1	Inventory/source term (amount of fissile material in research reactor fuels)	all	EBS - waste stability	waste leach rate
R5	Criticality (In-container criticality SF)	What-If Case	EBS/clay	containment lifetime waste leach rate degradation of the clay barrier near the EBS additional fluid displacement
2.3.4.05	Polymer degradation	all	EBS waste stability	gas production

The discussion was structured along two themes, Container Lifetime and Waste Matrix durability. A summary is presented in the following two sections.

4.2.1. Container Lifetime

In this section, first the selected FEPS are described, in particular their relevance to Container Lifetime, and then a summary of the discussion is given, which was split in two parts: discussion about the LILW containers and lifetime and discussion about the OPERA Supercontainers for HILW and HLW.

OPERA FEP 2.2.01 Containers
Containers are a feature of the facility, specifications are provided in the OPERA disposal facility outline report. For the discussions between the experts, the design of the containers was used as given input. The design itself was not reviewed during the discussions.

OPERA FEP 2.2.02 Overpack
Overpacks are a feature of the facility, specific for the HLW and HILW category of the waste. Specifications of the overpack (super-container) are provided in the OPERA disposal facility outline report. For the discussions between the experts, the design of the overpacks was used as given input. The design itself was not reviewed during the discussions.

OPERA FEP 2.3.03 Mechanical processes/
OPERA FEP M1 Cracking
Mechanical stresses are expected after re-saturation of the facility, where the pressure of the intruding water will increase to about 5 MPa. After collapse of the tunnel linings, the pressure increases to the lithostatic pressure of about 10 MPa. Gas production could produce stresses up to 10 MPa before failure of the tunnel linings. These stresses lead to mechanical deformations and failures of parts of the EBS, gas pressures may extend into the clay.

These processes were discussed in order to get the conceptual model for container lifetime and some quantitative predictions.

OPERA FEP 3.2.04 Chemical processes/
OPERA FEP C3 Corrosion
Chemical processes cause corrosion of metals and degradation of cementitious materials. Corrosion and degradation lead to failure of parts of the EBS. These processes were discussed in order to get the conceptual model for container lifetime and some quantitative predictions.

Discussion about the LILW containers and lifetime

Figure 3 Disposal of the LILW containers in the LILW disposal gallery

Assuming uniform corrosion and oxic conditions, the corrosion rate of steel could be as high as 0.1 µm/year to 1 µm/year. As discussed on pages 98-99 of OPERA-PU-IBR512 (Filby, Deissmann, & R., 2016) and according to the findings of Kursten 2015, the re-saturation should take place in one to five years. After this time, anoxic conditions can be expected. Corrosion rates in anoxic conditions are much lower.

Most LILW drums have a wall thickness of 1 mm: the container then would not fail due to corrosion within 100 years, but will certainly fail within 1000 years. The Konrad II type drums have a wall thickness of 3 mm, and will not fail within 1370 years (oxic conditions) to 15 000 years (anoxic) due to corrosion, see OPERA-PU-IBR512 (Filby, Deissmann, & R., 2016, p. 99).

During the oxic conditions, pitting corrosion may occur due to the high chloride content of the pore water in the OPERA disposal concept. A container could fail within months if pitting corrosion occurs.

Mechanical integrity of the LILW containers under underground conditions has not been considered in OPERA. After closure, the pressure can increase to about 10 MPa (lithostatic pressure at 500 m depth), which will probably lead to mechanical failure of the LILW-canisters.

Discussion about the OPERA Supercontainer
The lifetime of the OPERA HLW containers plus overpack plus concrete shield plus steel envelope was discussed between the process experts and the PA-experts.

All HLW and the high active fraction of the LILW will be disposed of in OPERA Supercontainers, which are similar to the NIRAS/ONDRAF Supercontainers.

Figure 4 Design of the OPERA Supercontainer

The OPERA outline report gives the following provisional properties for the OPERA Supercontainer: The HLW canister is placed in an 3 cm carbon steel overpack, which is surrounded by 50 to 60 cm concrete, which is surrounded by a 4 mm stainless steel envelope. (N.B. In the Belgium Supercontainer concept, the concrete is saturated with water to 80% to ensure sufficient heat conduction.)

The concrete passivates the carbon steel, which virtually does not corrode under these circumstances, leading to a container lifetime of at least 80 000 years.
Failure of the Supercontainer occurs in five stages:

1. Steel envelope is intact, the carbon steel is passivated by the concrete, i.e. a thin corrosion layer develops on the steel, which is chemically stable in contact with concrete and inhibits further corrosion of the steel.
2. Steel envelope has failed. Pore water with 'aggressive' species intrudes into the concrete. The concrete buffers the 'aggressive' species. The carbon steel remains passivated by the concrete, virtually no corrosion.
3. Concrete buffer becomes exhausted, aggressive species reach the carbon steel. the corrosion rate of the carbon steel increases to a value in the range of 0.1 μm/year to 1 μm/year. The overpack will not fail as long as the steel thickness is more than 14 mm - at 200 m depth. (See the discussion on mechanical integrity below.) This phase will last between 16 000 and 160 000 years.
4. The overpack fails and the HLW container will start to corrode. The waste is still confined by the HLW container.
5. The HLW container has failed, radionuclide bearing species will leach from the waste and start migrating.

It is expected that the Supercontainer condition will gradually flow from one stage to the next, rather than as a sudden change in the system.

It is relevant that in the OPERA concept the clay pore water contains much more 'aggressive' species than in the Belgium reference concept, in particular much more chlorides.

If the chloride reaches the steel overpack during the oxic stage, pitting corrosion may occur and the overpack may fail within months. This could occur as a result of leakage of the steel envelope, intrusion of chloride containing pore water from the clay, chloride is not buffered by the concrete Supercontainer, there is a sufficient amount of oxygen available for pitting corrosion of the overpack.

Mechanical structural integrity of the Supercontainer has not been treated in OPERA. For the Belgium concept, mechanical analyses show that the container can endure the underground pressure. In the OPERA design, the containers are disposed of at much larger depth and therefore the pressure is much larger.

Mechanical integrity of the Supercontainer system at 500 m depth has still to be shown. However, in CORA 18, Appendix B, it is estimated that a steel lining of 25.4 mm can endure the lithostatic pressure at 500 m depth of about 10 MPa with a safety factor of 1.7. Since engineering practise requires a minimum safety factor of 1.5, the minimum thickness of the steel lining at 500 m depth is 22.5 mm. At an initial thickness of 30 mm, and a maximum corrosion rate of 0.1 to 1 μm/year, the duration of stage 3 of the OPERA Supercontainer evolution is at least 7500 to 75 000 years.

4.2.2. Waste Matrix durability

In this section, first the selected FEPS are described, in particular their relevance to Waste Matrix Durability, and then a summary of the discussion is given, which was split in two parts: discussion about LILW waste form stability and discussion about HLW waste form stability.

<u>OPERA FEP 2.3.04.06 Dissolution (waste package)</u>
At some point in time the containment provided by the EBS will fail, and the waste will be in direct contact with water from the host rock. Depending on the waste form (varying from glass and metals to contaminations on the outside of materials (cloths), the radionuclides in the waste can dissolve in the water and start migrating through the EBS

and clay host rock. The waste form is a feature described in the inventory reports prepared in OPERA: OPERA-PU-NRG1112A (Hart, 2015), OPERA-PU-NRG1112B (Meeussen & Rosca-Bocancea, 2014) and OPERA-PG-COV023 (Verhoef E. , et al., 2016).
The experts discussed the conceptual model for the waste dissolution for different waste types and quantitative predictions for the dissolution rates.

OPERA FEP 2.3.01.01 Radiogenic heat production and transfer (temperature in the SF section)
The HLW generates heat for several decades to centuries, which will lead to an increase in temperature in the repository. In OPERA-PU-TUD311 (Arnold, Vardon, Hicks, Fokkens, & Fokker, 2015), it is shown that the maximum temperature at the Boom Clay-tunnel lining interface is likely to be between 328 K and 345 K (between 55 ºC and 72ºC).
The increased temperature may increase chemical reaction rates and also cause thermal stresses. The temperature is considered given input to the discussion.

OPERA FEP R1 Inventory/source term (amount of fissile material in research reactor fuels)
The inventory is a feature of the facility, and described in OPERA-PU-NRG1112A (Hart, 2015), OPERA-PU-NRG1112B (Meeussen & Rosca-Bocancea, 2014) and OPERA-PG-COV023 (Verhoef E. , et al., 2016). The inventory is considered given input to the discussion.

OPERA FEP R5 Criticality (In-container criticality SF)
A part of the HLW is Spent Fuel from the research reactors. The amount of fissile materials in the Spent Fuel is sufficient to potentially cause criticality incidents. For OPERA it can be assumed that containers are designed such that criticality cannot occur during storage, handling and disposal. Although this was shown in the CORA studies for the predecessor of the OPERA design (the "TRUCK-design"), there are no studies in the OPERA Programme to support this for the present design.

OPERA FEP 2.3.4.05 Polymer degradation (2.3.4.05)
Polymers can degrade as a result of radiolysis, microbial activity, but also spontaneously. This can lead to gas production (e.g. CH_4, CO_2) and reactive degradation products dissolved in the water. Spent fuel and vitrified waste do not contain polymers, but ILW-H, ILW-L and LLW may. The experts discussed the conceptual model for the waste dissolution for different waste types and quantitative predictions for the dissolution rates.

FEP C3 Corrosion causes/processes
Any process by which a solid, especially a metal, is degraded and changed by a chemical reaction. See OPERA FEP 2.3.04.06 above.

Discussion about LILW waste form stability

Because of the wide variety of waste forms, where many show large leaching rates on repository time scales (i.e. > 100 years), no credit is to be given to (partial) immobilisation of radionuclides because of the waste and cement matrix. It is however important to determine the chemical form in which the radionuclides are released from the waste, since the absorption by the clay and solubility in the clay pore water depends on the species that carry the radionuclide.

Degradation products of the cement, and organic material from the cement and the clay, will form chemical complexes with some of the radionuclide bearing species. In many cases these complexes are equally or less mobile than the original species. In some case the complex can be more mobile than the original species.

Cement and cement degradation products may adsorb anionic species better than the clay. Some of the degradation products are 'aggressive' to other parts of the EBS.
Organic material and metals in the LILW will be a source of gas.

Discussion about HLW waste form stability

Spent fuel of research reactors: There is not much known about the durability of Al-based spent fuel plates in cementitious and underground clay conditions. Generally, aluminium metal will corrode quickly under cementitious conditions under oxic and anoxic conditions. Under anoxic conditions H_2 gas is generated.

For the fission products in the fuel plates, an almost instantaneous release can be assumed. For Al-U alloys (HEU), it is expected that the U will precipitate as amorphous U-oxide. If there is a specific area in the disposal cell where precipitation preferentially occurs accumulation of U is possible, and criticality should be addressed.

Other HLW: This waste is not addressed in OPERA WP5. Instantaneous release can be assumed. There is interest in:
1) the chemical form of the U in the U filters
2) C-14 from the caps and claddings (CAST)
where future research may provide a less conservative estimate of the release rates.

Vitrified waste
It is acceptable to assume congruent dissolution of the waste and glass. Glass dissolution rate depends on the glass surface evolution and pH. At extremely high pH (pH > 13) the glass dissolution rate may increase by a factor 10 to 1000. Species containing Ca and K may alter the dissolution rate. Data will be published in OPERA-PU-IBR511A (vitrified waste) and OPERA-PU-IBR511B (spent fuel).

4.2.3. Summary "Behaviour of waste and container"

Table 5 Summary "Behaviour of waste and container"; for an explanation of the abbreviations see Table 4

Process expert finding	Implementation in PA-model EBS
N1 Mechanical integrity of the LILW containers: after closure, the pressure will increase to about 5 to 10 MPa, which will probably lead to mechanical failure of the LILW-canisters.	**N1** All LILW containers fail immediately after closure of the facility.
N1 LILW waste forms: No credit is to be given to (partial) immobilisation of radionuclides because of the waste and cement matrix.	**N1** All radionuclides from LILW dissolve in the water immediately after container failure.
NES Depleted Uranium (DU) waste: The Konrad type drums have a wall thickness of 3 mm, and would fail in 1370 to 15000 years.	**NES** DU waste: The Konrad type drums can fail when hydrostatic and/or lithostatic pressure is larger than 3 MPa, i.e. within 100 years.
NES DU waste form: No credit is to be given to (partial) immobilisation of radionuclides because of the waste and cement matrix.	**NES** All radionuclides from DU waste dissolve in the water immediately after container failure.
N1 stage 3 of the OPERA Supercontainer-evolution is at least 7500 to 75 000 years	**N1** The Supercontainer lifetime is 7500 to 75 000 years. **N4** A small number of Supercontainers may fail earlier, e.g. due to production failures.
N1 It is acceptable to assume congruent dissolution of the waste and glass. Glass dissolution rate will be published in OPERA-PU-IBR511A	**N1** Congruent dissolution rates taken from OPERA-PU-IBR511A
N1 Metallic Spent Fuel and HILW may dissolve fast in a cementitious environment	**N1** All radionuclides from SF and HILW dissolve in the water immediately after container failure, in contrast with vitrified waste (glass).

4.3. Process category "Geomechanics"

The FEPs which were discussed in the process category "Geomechanics" with the geomechanics experts and the PA experts, are listed in Table 6. A summary of the expert elicitation has been included in Appendix 3, p. 81 ff.

Table 6 Overview of discussed FEPs discussed with geomechanical experts; NES = Normal Evolution Scenario; AC = Assessment Case; NES = Normal Evolution Scenario; EBS= Engineered Barrier System; abbreviations of specific Assessment Cases are explained in Table 14

FEP Id	FEP name	Scenario/AC	Relevant compartment model	PA treatment
T1	Thermal evolution	NES/EHP1	EBS, Clay	No effect in NES, potential containment lifetime reduction and potential clay damage zone in EHP1

FEP Id	FEP name	Scenario/AC	Relevant compartment model	PA treatment
T2	Thermal effects – physical / mechanical	NES/EHP1	EBS, Clay	No effect in PA treatment of NES, potential containment lifetime reduction and potential clay damage zone in EHP1
2.3.01	Thermal processes (waste package)	NES/EHP1	EBS, Clay	No effect in NES, potential containment lifetime reduction and potential clay damage zone in EHP1
3.2.06	Radiological processes (repository)	NES/ECC1	EBS, Clay	No effect in NES, potential containment lifetime reduction and potential clay damage zone in ECC1
C14	Gas generation	N3/EGC1	EBS, Clay	No effect in NES, potential containment lifetime reduction and potential clay damage zone in EGC1
H12	Gas transport	N3/EGC1	EBS, Clay	No effect in N1, no effect to be shown in N3, potential containment lifetime reduction and potential clay damage zone in EGC1
M7	Mechanical disturbance of components of the EBS/Gas impact on stability	N3/N4/EEC1	EBS, Clay	No effect in NES, no effect to be shown in N3, potential containment lifetime reduction and potential clay damage zone in EEC1
H1	Hydraulic properties	NES	EBS	input parameters
D6	Backfill / supports - dimensions and properties	NES	EBS	input parameters
D9	Host-rock EDZ – thickness and properties	NES	EBS	input parameters
M2	Creep	NES	EBS	No effect in NES,

The discussion between the experts was structured by four themes: thermal effects, gas effects, hydraulic effects and mechanical effects, which are described in the following four sections.

4.3.1. Elevated temperature effects

In this section, first the selected FEPs are described, in particular their relevance to Temperature Effects, and then a summary of the discussion is given, which was split in two parts: Impact of elevated temperature on the Clay, and Impact of elevated temperatures on the Concrete in the EBS.

T1 – Thermal evolution
TUD has calculated the temperature increase resulting from the heat output from the heat-generating waste containers. The increase is thought to be modest, max. 60 to 70 ºC.

T2 – Thermal effects – physical/mechanical
A temperature increase and subsequent decrease may lead to thermal expansion and later shrinkage of the EBS materials, clay rock and pore water. This expansion will be counteracted by a mechanical response of the surrounding rocks, the thermal expansion of the pore water may lead to pore water displacements and a potential of damage to the rock material.

Discussion about impact of elevated temperature on the Clay

TUD has calculated a temperature increase to about 60 to 70 ºC resulting from the heat-generating waste containers. This results in a significant increase of the pore pressure in the Boom Clay (Arnold, Vardon, Hicks, Fokkens, & Fokker, 2015). The process experts suggest that the increased pore pressure lowers the effective stress and may cause mechanical damage, more specifically shear failure, in the Boom Clay at a large scale: tens of metres from the heat producing waste. This observation imposes a potential concern for the long-term safety, and should be investigated further.

The expansion of Boom Clay pore water may extend the EDZ and potentially cause preferential pathways to occur. Moreover, it is possible to increase radial stresses on the lining and cause collapse.

A restriction to this observation is that for these preliminary scoping calculations TUD applied generic parameters for the Boom Clay Models which may not be the best-estimate of the actual *in-situ* conditions.

Discussion about impact of elevated temperatures on the Concrete in the EBS

Elevated temperatures (i.e. the range above 60-80 ºC) may induce problems with concrete backfill. The thermal stability of the CSH (Calcium silicate hydrate, the main product of the hydration of Portland cement) is relevant in case of elevated temperatures, since the mechanical strength of concrete and other cementitious materials depends up to a high extent to the so-called cement stone (hardened cement) and this cement stone is for a large part CSH.

Moreover, at temperatures of approx. 100-110 ºC the solubility of quartz is increasing and of $Ca(OH)_2$ is decreasing (the production of calcium silicate bricks is based on this phenomena). So, at elevated temperatures (> 100 ºC) several aspects have to be considered. One is the crystal structure of the CSH which can undergo transformation/re-crystallisation due to exposure to elevated temperatures and the re-crystalized CSH (e.g. from tobermorite to (maybe) thaumasite) has different and not necessarily better properties.

Concrete will not suffer from temperature effects below 50 °C. Additionally, cracks are practically inevitable in concrete. Due to the temperature increase after backfilling and expansion, the volume will increase during the first decade.

After some time saline fluids will intrude the repository; will this cause significant effects? Concrete hardening itself also produces some heat. It is however judged that this effect is negligible compared to the heat output from the waste containers.

4.3.2. Mechanical aspects of gas generation and transport

In this section, first the selected FEPS are described, in particular their relevance to Gas Effects, and then a summary of the discussion is given. Note that the issue of gas effects is treated also in the process category Gas migration in Section 0.

C14 – Gas generation
Gas production may occur from corrosion and degradation of waste or EBS materials (e.g. H_2 from anaerobic corrosion of metals), microbial activity (e.g. CO_2, CH_4 and H_2S from anaerobic microbial conversion of organics), and radiation effects (He from alpha decay and H_2 and O_2 from radiolysis).

H12 – Gas transport
If gases are soluble in water (e.g. CO_2) or produced at a low rate (e.g. H_2 from anaerobic corrosion of high quality steel), the produced gases dissolve in the pore water and move away from the gas source by diffusion of the dissolved gases.
Gas, if generated in sufficient quantities, will pressurize components of the repository, e.g. pore pressures, or total stresses on the lining if well sealed. This gas may generate pathways in the EBS and/or Boom Clay, potentially resulting in enhanced radionuclide transport.

M7 – Mechanical disturbance of components of the EBS
The question is whether gas pressures can equalize in the repository and what the mechanical effects would be. It is judged that due to the high air entry value, once the diffusive capacity is exceeded, pressures near the repository will increase.

Discussion about impact of gas generation on EBS and Clay

Gas production may occur from corrosion and degradation of waste or EBS materials (e.g. H_2), microbial activity (e.g. CO_2, CH_4 and H_2S), and radiation effects (He from alpha decay and H_2 and O_2 from radiolysis). Some scoping calculations would be useful to understand the importance of these processes (see also OPERA-PU-BGS615 (Wiseall, et al., 2015) and the H2020 MIND project: http://www.mind15.eu/). Gas production may change local chemical and hydraulic conditions, and the mechanisms for radionuclide transport (i.e. gas-induced and gas-mediated transport).

Diffusion, advection, microbial activities, storage availability affect whether gases are reduced, dissolved, cause clay dilation etc. Gas, if generated in sufficient quantities, will pressurize components of the repository, e.g. pore pressures, or total stresses on the lining if well sealed. Pressured gases may potentially generate pathways in the EBS and/or Boom Clay, potentially resulting in enhanced radionuclide transport.

Hydrogen, generated as a result of metal corrosion, may, when released in pore water, result in acidification of the pore water. On the other hand, concrete which is present as buffer and lining has a quite large buffering capacity, both chemically (e.g. pH buffering), and physically (gas buffering) due to its high porosity (approx. 40%).

The system (EBS and host rock) must be able to absorb gas that is generated in the waste. In the normal evolution, parts of the EBS will be filled with gas, meaning that the water from pores and voids in the concrete will be pushed into the clay. The gas cannot enter the clay because of the high gas entry pressure of the clay, but the gases will gradually dissolve at the gas/clay-water interface.

The question is whether gas pressures can equalize in the repository and what the mechanical effects would be. It is judged that due to the high air entry value, once the diffusive capacity is exceeded, pressures near the repository will increase. In SAFIR-2 gas generated by corrosion is transported by diffusion. In SAFIR-2 (ONDRAF/NIRAS, 2001) only HLW is considered, while in OPERA the repository also contains LILW.

Concerning the rates and amounts of gas generation, it is judged that gas generation from vitrified HLW containers will occur at a constant and slow rate as a result of corrosion induced by pore water. It this case H_2 is the main gas species.
For LILW the uncertainties related to gas are larger: more and earlier gas production may occur, and additional gas species may be formed (H_2, CO_2, CH_4) compared to vitrified HLW. On the other hand the amount of volatile radionuclides present in LILW is less than in HLW.

In the normal evolution, parts of the EBS will be filled with gas, meaning that the water from pores and voids in the concrete will be pushed into the clay. In the vicinity of plugs and seals gas may bypass the plugs through any formed EDZ preferential pathway, e.g. around the outside of the (bentonite) barriers.

It is mentioned that the chemical buffering capacity of concrete is important in assessing the contribution of gas to the overall repository safety.

In conclusion, it can be stated that gas may have a relatively small impact on the safety functions of the repository system – both chemically and physically, it may enhance the transport of volatile radionuclides, but its contribution to the overall transport of radionuclides is judged relatively small. An uncertainty in this respect is the gas generation rate, especially from LILW. Probably it is not an issue for HLW.

4.3.3. Reduction of water flow

In this section, first the selected FEPS are described, in particular their relevance to hydraulic effects, and then a summary of the discussion is given.

<u>H1 – Hydraulic properties</u>
Relevant hydraulic properties of the EBS and the EDZ are the hydraulic gradient, conductivity, porosity, permeability, and fracture properties.
The hydraulic properties will control groundwater flow. However, groundwater flow will not be present/be very limited in a Boom Clay hosted repository due to the absence of driving forces. The travel time to the top of the host rock is estimated much larger than 10 ka (e.g. for Iodine).

<u>D6 – Backfill/supports – dimensions and properties</u>
Backfill properties affect the time for host rock pore water to arrive at the surface of the emplaced containers and the relevance of this pathway. After closure the repository will be re-saturated in say half a century. As a consequence of the influx of fluids the

bentonite will swell resulting in a permeability which is lower than of the host rock. Influx might be reversed through gas pressurisation.

D9 – Host-rock EDZ – thickness and properties
The extent of the EDZ along tunnels and shafts will depend on the host rock and construction methods used. EDZ properties affect the rate of repository re-saturation and radionuclide transport from the EBS to the host rock.

Discussion about potential of (advective) water flow

One of the main safety functions of the EBS is to suppress water transport through the EBS, the EDZ and the host rock (i.e. the "near field"). The hydraulic properties of the EBS are therefore important aspects. They can be influenced by design; the overcut of the tunnel sections must be limited to the very minimum. It would be easier to build the repository by having 'straight through' tunnelling. This would however require more plugs.

Limited water flow may occur, with larger flows (albeit still limited) in the EDZ and in the backfilled repository galleries. Plugs and seals can be designed in such a way to limit any flow in the repository.

Concerning the question discussion how large water flows would be "acceptable" inside a repository, it is judged that advective water flow rates should be smaller than diffusive flow rates. The question is whether advective flow will be possible at all, taking into account the lack of a hydraulic gradient. In principle, a (very small) hydraulic gradient may occur resulting from dynamic effects during glaciation periods. In the OPAP performance assessment glaciation is one of the scenarios under consideration.

In conclusion, it can be stated that (advective) water flow will be of negligible importance in the EBS and the Boom Clay. Design measures like the placement of plugs and seals may even further reduce any suspected water flow. Only in case of dynamic forces on the repository system, e.g. resulting from glaciation, water flow might have a contribution to the overall transport rate, although it is judged small. No overall endangerment of the geological safety from the repository itself except maybe for the gas related FEPs.

4.3.4. Stress changes

In this section, first the selected FEPS are described, in particular their relevance to Mechanical Effects, and then a summary of the discussion is given.

D9 – Host-rock EDZ – thickness and properties
The extent of the EDZ along tunnels and shafts will depend on the host rock properties and construction methods used. EDZ properties affect the rate of repository re-saturation and radionuclide transport from the EBS to the host rock. Creep will cause sealing of the EDZ.

M2 – Creep
Slow plastic deformation of solids in response to deviatoric stress may be relevant. For example, creep may occur in metals used in the Supercontainer overpack or envelope, or in the EDZ as a result of stress relief in the host rock arising from tunnel excavation. The question however is whether this effect would compromise the long-term safety. Creep will cause sealing of the EDZ, but at the same time restores the full lithostatic stress on the tunnel lining. Creep can also impact the permeability further away from the local failure, following local tunnel collapses.

M7 – Mechanical disturbance of components of the EBS.
The EBS could be mechanically disturbed by physico-chemical degradation of the concrete buffer, external forces (e.g. tunnel roof or lining collapse, rock creep or faulting in near-field rock), volume increase of corrosion products, and/or the build-up of internal gas pressure. These disturbances could cause processes such as cracking, and movement of the overpack through the buffer.

Discussion about stress changes on the long term safety

Stress evolution in the near and far field will cause properties to change. It is judged that short-term effects of stress changes are quite well understood. However the long-term effects of altering stresses are less well understood.

Creep may occur in metals used in the Supercontainer overpack or envelope. The question however is whether this effect would compromise the long-term safety.

Concerning the concrete parts of the EBS, it is apparent that cracks will always occur after some decades (30-50 years). The question is whether such cracks in the EBS would impact the long-term safety.

In conclusion, it can be stated that stress changes will occur in the repository system following the excavations. It is judged that stress changes apply for the most part in the short term (several decades), and that the process understanding is quite well understood. Long-term stress changes (centuries, millennia) are less well understood, but the consequences on the long-term safety would be judged as relatively small since the dynamic processes following the excavations will have become extinct.

4.3.5. Summary "Geomechanics"

Table 7 Summary "Geomechanics"; for an explanation of the abbreviations see Table 6

Process expert finding	**Implementation in PA-model EBS**
N1 It can be stated that (advective) water flow will be of negligible importance in the EBS and the Boom Clay.	**N1** The EBS is modelled as a closed volume with no water-through flow. Conservatively, it is assumed that all nuclides released from the waste are mixed homogeneously in the EBS water volume. **AS1** in case of poor sealing or partial sealing, there is a potential for advective and diffusive transport through the shafts (or remains of the shafts) causing a partial short cut of the clay layer.

Process expert finding	Implementation in PA-model EBS
N1 TUD has calculated a significant increase of the pore pressure in the Boom Clay following the temperature increase resulting from the heat output from the heat-generating waste containers but temperature increase is thought to be modest, max 60 to 70 ºC.	**N1** The Supercontainers are designed not to fail during the thermal phase. On much longer time scales the overpack may weaken because of corrosion, but this is beyond the thermal phase. **N3** A small number of Supercontainers may fail during the thermal phase, e.g. due to production failures in combination with the increased pore pressure.
N1 Pore pressure changes, in particular due to heating, lowers the effective stress and may cause mechanical damage, more specifically shear failure, in the Boom Clay at a large scale 10s of metres from the heat producing waste.	**N1** In the project TIMODAZ the impact of shear failure mechanical damage on permeability has been studied, and there were no signs of permeability increases or other degenerations of the clay barrier function. The plasticity of the clay allows the deformations in the EDZ without loss of the low permeability. **EHP1** Assume the present ideas about healing of the EDZ are incorrect, so a hypothetical zone of high permeability is created in the EDZ, which can be treated as a fault scenario or poor sealing.
N3 It is judged that due to the high air entry value, once the diffusive capacity is exceeded, pressures near the repository will increase. More recent studies indicate that more gas is being produced than can be transported by diffusion. In the vicinity of plugs and seals gas may bypass the plugs through any formed EDZ preferential pathway, e.g. around the outside of the bentonite backfill.	**N3** As a result of the gas pressure micro-fractures may be formed in the Clay, though there is no evidence to suggest features coalesce into one or more 'large' fractures which then interact with the continuum stress field. Dilating processes create microscopic pathways with self-sealing properties and may occur already at pressures below the lithostatic pressure. One even observes a hardening effect as the pressure often needs to be higher with the next gas pressure pulse. In that sense it is not creating a preferential pathway for future RN groundwater transport. **EGC1** Assume the present ideas about gas are wrong, and a zone of high permeability is created in a hypothetical "gas damaged zone" which can be treated as a fault scenario or poor sealing.

4.4.Process category "Geochemistry"

The FEPs which were discussed with the geochemical experts, are listed in Table 8. A summary of the expert elicitation with the experts has been included in Appendix 3, p. 94 ff.

Table 8 Overview of discussed FEPs discussed with geochemical experts; NES = Normal Evolution Scenario; AES = Altered Evolution Scenario; BIO = biosphere; AQ = aquifer (overburden); HR = host rock, EBS = Engineered Barrier System

FEP Id	FEP name	Scenario /AC	Relevant compartment model	PA treatment
2.3.07.02	Organic degradation	NES AES	EBS EBS, HR	No effect in PA treatment of NES since for all non-vitrified wastes, except DepU, immediate and complete dissolution of the waste is assumed. Organic degradation has no impact on the dissolution of vitrified wastes and DepU. The EBS is expected to be able to cope with gas generation and chemical evolution, to be confirmed in process studies. Unexpected large gas generation is treated in N3 or EGC1.
2.3.07.06	Gas dissolution	NES	EBS	In the PA, gas dissolution is considered a safe mechanism to remove gases from the EBS. The EBS is expected to be able to cope with gas generation and chemical evolution, to be confirmed in process studies.
3.2.04.02	Redox conditions	NES	EBS	The Redox conditions of the system are input to the process studies that determine dissolution rates, adsorption and degeneration rate of the EBS

FEP Id	FEP name	Scenario /AC	Relevant compartment model	PA treatment
3.3.02.05	Speciation and solubility	NES What-if scenario	EBS	Speciation and solubility limits in the EBS and near field host rock are determined in process studies and used in the PA (as for depleted U). The impact of solubility limits can be studied in EFD1.
4.3.02.06	Speciation and solubility	NES	HR, AQ	For HR (host rock), see FEP 3.3.02.05. The calculated concentrations in AQ (aquifer) are generally much lower than the solubility limits.
3.3.02.06	Sorption and desorption	NES What-if scenario	EBS	The PA can ignore conservatively (de-)sorption in the EBS, because the adsorption capacity is proportional to the mass of the materials, and the mass of the EBS is negligible compared to the mass of the host rock.
4.3.02.07	Sorption and desorption	NES	HR, AQ	The PA model uses adsorption coefficients for HR and (optionally) AQ that are determined in process studies.
3.3.02.08	Colloid transport	NES What-if scenario	EBS	Can be ignored conservatively in the PA, see FEP 3.3.02.06
4.3.02.09	Colloid transport	NES	HR, AQ	The PA model uses colloid adsorption coefficients for HR and AQ that are determined in process studies.

FEP Id	FEP name	Scenario /AC	Relevant compartment model	PA treatment
4.1.09	Current geochemical state	NES	EBS, HR	This is input to the process modelling. in the PA it is assumed that EBS and HR are stable during the thermal phase.
4.2.04	Geochemical processes	NES AES	AQ HR, AQ	The PA assumes for the NES that the range of the adsorption coefficients is constant over time. The process models determine these ranges including the impact of geochemical processes. Intensified glaciation may cause deep permafrost and reduction of the salinity (AGl1)
1.3.04 4.2.02 C15 H6	Salinity change & gradients		BIO, AQ, HR	Parameter ranges for the NES should be robust towards salinity change & gradients, but more studies may be needed.

4.4.1. Chemical aspects of gas generation

<u>2.3.07.02 Organic degradation</u>
Gas can be generated by the degradation of organic materials, such as paper, present in the LLW and ILW. The degradation products are often smaller organic molecules and complex organic substances which can affect the mobility of radionuclides. The types of gases which can be released are CO_2, H_2 and CH_4. Microbial activity is necessary for organic material to deteriorate.

Regarding the production of non-gaseous dissolved organic material, this may be relevant for clays which have a low natural amount of organic material unlike the Boom Clay.

In the PA model the effect of extra dissolved organic material is covered by the considered uncertainty bandwidth of the natural dissolved organic material content of the Boom Clay. Quantitative estimates of products from organic degradation with large uncertainties are available.

Increased concentration of organic products in the host rock resulting from waste degradation has been included in the Normal Evolutions Scenario. The process of gas generation has been included in two Assessment Cases in the Normal Evolution Scenario (N2 and N3). A what-if scenario treats the consequences of excessive (radioactive) gas generation.

2.3.07.06 Gas dissolution
Dissolution of gas, e.g. CO_2 or of organic acids change the pH and enhance RN mobility. This process is part of the NES and relevant for the EBS, which includes the near-field host rock.

4.4.2. Geochemical interaction and transport

3.2.04.02 Redox conditions
The intrusion depth of oxygen from the galleries into the clay will be limited because this oxygen rapidly reacts with the pyrite in the Boom clay. The presence of dilation fractures resulting from the excavation may enhance the oxidation during the operational stage. The effect of aerated pore fluids on pyrite depends also on the carbonate content of the host rock. After closure of the repository anaerobic conditions will prevail. A high pH will generally reduce anaerobic corrosion rates.

These processes are relevant for the EBS including the near-field host rock and are part of the Normal Evolution Scenario.

3.3.02.05/4.3.02.06 Speciation and solubility
The solubility of Si-oxides (glass dissolution rate) is dependent on the porewater composition, in particular on the presence of sulphides/sulphate and their effect on the pH. The Ca-content of the clays is a main determinant in buffering the pH. Cement has an immobilizing effect on Uranium.

Once radionuclides are in contact with porewater, it is assumed that they dissolve instantaneously, except for Uranium for which a dissolution limited concentration is assumed. These processes are part of the Normal Evolution Scenario and influence the EBS and the host rock. A what-if scenario has been dedicated to speciation and solubility in the repository.

3.3.02.06/4.3.02.07 Sorption and desorption
Iodine may react with calcium (lime) causing retardation and maybe even irreversible retention.

These processes are part of the Normal Evolution Scenario and influence the functioning of the EBS and the host rock. A what-if scenario has been dedicated to sorption and desorption in the repository.

3.3.02.08/4.3.02.09 Colloid transport
Most colloid particles are practically not mobile, but a small fraction of the colloid particles can be mobile and act as a carrier for strongly adsorbing radionuclides.

For advection conditions, colloids can be assumed to travel at the same rate as water and dissolved ions. For diffusion conditions, colloids diffuse much slower than free ions, mainly because the diffusion coefficient of colloids is smaller than the diffusion coefficient of free ions because of their size and to a lesser extent because the colloid accessible pore volume is smaller than the free ion accessible pore volume. The mobility of radionuclides that strongly adsorb to these colloids will not become larger than the mobility of these colloids. Colloid transport is included in the process models and the PA model.

4.4.3. Natural geochemical processes

4.1.09 Current geochemical state
The porewater in the Boom Clay at Mol is fresh, whereas in the Netherlands Boom Clay it is saline. The salinity determines the permeability of the clay (double layer). At higher salt concentrations diffuse double layers of clay become thinner and clay becomes more porous for transport. The effect on the retardation factor is about 20%.

The Boom Clay is in a reduced state and buffers against oxidising conditions. The current geochemical state is part of the Normal Evolution Scenario and influences the EBS and the host rock.

4.2.04 Geochemical processes
A salinity change may cause geochemical changes. Changes in salinity can be caused by glacial valleys and permafrost. During glaciations one may expect changes in salinity due to influx of glacial meltwater. The reaction zone in the Boom Clay, which is in contact with low saline or fresh water, will normally be limited to a few dm; deeper penetration is not likely. The rate of change for most processes is determined by diffusion of chemical substances, which is very low for the Boom Clay. Osmotic effects during a transition could increase migration. Effects might be stronger when a deep subglacial channel is in direct contact with the Boom Clay.

Attention should be directed to glaciation and the formation of glacial valleys, where the salinity of the groundwater changes, which influences the geochemical properties of the clay. A modest glaciation is part of the Normal Evolution Scenario and a massive glaciation is considered in an Altered Evolution Scenario. Changes in salinity affect the aquifer and the host rock to some extent.

One of the process experts mentions that the creation of a salinity front should be specified as a separate FEP. Now it indirectly follows from FEP 1.3.04, 4.2.02, C15, H6.

4.4.4. Summary "Geochemistry"

Table 9 Summary "Geochemistry"; for an explanation of the abbreviations see Table 8

Process expert finding	Implementation in PA-model EBS
N1 Organic degradation may be a source of dissolved organic material (DOM) which may be a carrier for otherwise immobile nuclides. In Boom clay the natural background of DOM is relatively high, so this effect of organic degradation can be ignored.	**N1** The PA model includes a special transport mode for DOM bounded nuclides. However, this model relies on data obtained through chemical modelling and experiments on DOM.
N3 The degradation products are often smaller organic molecules and complex organic substances. The types of gases	**N3** The impact of gases is discussed in Section 4.5. For the NES it is assumed that the EBS can buffer the expected volume of

Process expert finding	Implementation in PA-model EBS
which can be released are CO_2, H_2 and CH_4. Microbial activity (**SBM1**) is necessary for organic material to deteriorate.	gas without impact on the safety functions. Presently, there is no specific gas module in the PA-model. **EGC1** A specific study case is identified in order to study the impacts of large volumes of produced gas.
N3 Dissolution of gas, e.g. CO_2 or of organic acids change the pH and enhance RN mobility. This process is part of the NES and relevant for the EBS, which includes the near-field host rock.	**N3** For the PA, it is assumed that all nuclides in the ILW dissolve shortly after saturation of the disposal tunnel, see Section 4.2. Disposal tunnels where the EBS reduces RN mobility (DepU, vitrified waste, Supercontainers) contain no or small amounts of organics.
N1/SAT1 Most colloid particles are practically not mobile, but a small fraction of the colloid particles can be mobile and act as a carrier for strongly adsorbing radionuclides	**N1/SAT1** The PA model includes a special transport mode for DOM bounded nuclides
N1 The geochemical state of the clay (salinity, redox) influences the permeability and adsorption capacity of the clay.	**N1** Process studies have determined the adsorption capacity of the clay for the relevant geochemical conditions. The results are used as input to the PA model (K_d values, diffusion coefficients). Special equations have been developed for calculating porosity and permeability of fine grained sediments (see OPERA-PU-TNO411: Yang and Aplin, 2004; Aplin and Macquaker, 2011). These are used to calculate porosity and permeability of the Boom Clay. **SAT1** A What-If Case with strongly reduced adsorption has been identified.
N1 Glaciation and permafrost may reduce the salinity in the underground.	**N1** Since the location of the disposal site presently is not fixed, even in the N1 case a large range of salinity has been accounted for, see e.g. OPERA-PU-6122, table 2-1. This range covers the changes due to glaciation.
SAT1 Dynamic effects of geochemical changes and osmotic effects could increase migration	**SAT1** A What-If Case is established for considering alternative transport modes (in addition to diffusion-advection). However, the process study to quantify such alternative transport modes has not been performed in OPERA.

4.5. Process category “Gas migration”

The FEPs which were discussed with the gas migration experts, are listed in Table 10. A summary of the expert elicitation with the experts has been included in Appendix 3, p. 98 ff.

Table 10 **Overview of discussed FEPs discussed with gas migration experts; NES = Normal Evolution Scenario; AES = Altered Evolution Scenario; WP = waste package; HR = host rock, EBS = Engineered Barrier System, WP = waste package; the abbreviations of specific Assessment Cases are explained in Table 14**

<table>
<tr><th>FEP Id</th><th>FEP name</th><th>Scenario/AC</th><th>Relevant compartment model</th><th>PA treatment</th></tr>
<tr><td>2.3.07</td><td>Gas generation</td><td>NES
AES</td><td>WP (LILW)</td><td rowspan="5">In the NES it is assumed that the EBS can cope with the gas generation without creating nuclide transport mechanisms other than diffusion in pore-water.

Assessment Cases N3 and EGC1 have been identified to treat gas-mediated transport.

Process studies that determine gas generation over time have not been completed, and are expected in follow-up research programme</td></tr>
<tr><td>3.2.07</td><td>Gas generation</td><td>NES
AES</td><td>EBS</td></tr>
<tr><td>3.3.03</td><td>Gas-mediated transport</td><td>NES
AES</td><td>EBS</td></tr>
<tr><td>4.2.07.05</td><td>Gas-induced dilation</td><td>NES
AES</td><td>HR</td></tr>
<tr><td>4.3.03</td><td>Gas-mediated transport</td><td>NES
AES</td><td>HR</td></tr>
</table>

4.5.1. Gas generation

2.3.07/3.2.07 Gas generation
In analysing gas generation one should distinguish between the various waste streams. LLW and ILW hold a lot of biodegradable cellulosic material (e.g. paper, cotton, ….) which can result in significant volumes of CH_4 and CO_2 in the first millennia after disposal. Gas production because of bioprocesses result for a big part in the formation of methane. This process occurs relatively quickly, i.e. hundreds to ~1000 years after disposal, and may result in a “gas pulse”. Although the fraction of biodegradable material in LLW/ILW is high, the degradation will be determined by the availability of water in the Boom Clay which is expected to be low due to its low hydraulic conductivity.

HLW in contrast will potentially generate far less gas: anaerobic metal corrosion (and smaller contribution by radiolysis which is dissociation of molecules by ionising radiation) will be the main source of gas (H_2) after the Supercontainer has degraded in thousands to 10,000 years. Bacterial interaction may transform H_2 into CH_4. This is especially the case if a source of carbon is present, which includes calcium carbonate.

Gas production by radiolysis is significantly smaller than by metal corrosion and organic biodegradation. Considering that, radiolysis may be insignificant in OPERA due to shielding by the concrete Supercontainer, unless water reaches the surface of the SF+HLW waste containers. There is no relation between radiolysis and the release of radionuclides from waste containers.

Metal corrosion (FEP 2.3.07.01; FEP EBS 6) and associated H_2 generation are fairly well understood. One of the FORGE reports addresses these topics: FORGE 2.5-R "Synthesis of experimental processes governing gas generation" (Dobrev, Stammose, Pellegrini, & Vokla, 2013). Rates of corrosion are well established with generally high initial rates which drop off later on (see also OPERA Tasks 5.1.1 to 5.1.5). Release of C-14 comes from activated steel and is in the form of methane and CO_2. C-14 is the topic of the EC project CAST. Also in the UK there is a specific C-14 project going on. In the Dutch waste C-14 is almost solely present in SF from the research reactors, and in vitrified HLW residues (CSD-C containers).

4.5.2. Gas transport

<u>3.3.03 Gas-mediated transport (repository)/</u>
<u>EBS 11 Gas flow and transport/EBS 12 Gas-induced flow and transport</u>
The design of a repository can be made just to minimize the impact of any gas being generated in the disposal facility. Management and mitigation will dependent on the predicted impact of the gas. The UK policy is trying to manage this gas pulse by venting of LILW containers. This also implies that water ingression would be possible. Accommodating a gas pulse by any mitigating measure, such as dispersion within the repository volume, depends on several issues e.g. permeability of Boom Clay versus engineered barriers (seals, plugs). Accessible voidage within the repository into which the gas can flow and accumulate will also impact the rate of gas pressure build-up. Excessive gas generation may be mitigated to some extent by designing a "co-located" repository, where separate sections for different types of waste share e.g. the same shafts/entries, but are located several kilometres away from each other. This does not necessarily mitigate the generation of gas but can help manage its impact. Current French research work is examining the impact of gas on their repository.

Pressure-connected galleries and plugs/seals may be an effective way of dispersing generated gases and allowing this dissolution and dilution while not potentially leading to development of a free gas pathway providing a direct route to the biosphere.

After closure of repository volumes (e.g. disposal galleries) any trapped air inside will partly be consumed in the corrosion process (O_2), and partly dissolve into Boom Clay pore water (N_2).

<u>4.2.07.05 Gas-induced dilation (geosphere)</u>
Gas entry pressure for Boom Clay is roughly estimated at about 1 to 2 MPa (depending on orientation of the clay) in excess of the pore pressure at a depth of 220 m. At greater depths say 500 m, excess gas breakthrough pressures increase to around 2.5 to 3.5 MPa. Measurements by BGS indicated that peak pressure is sensitive to the state of stress.

Measurements from one test suggest peak gas pressure is 0.85 σ_{eff}. For the Dutch disposal concept in the Boom Clay at 500 m depth the pore water pressure is about 5 MPa and the confining pressure is about 10 MPa; therefore the actual gas breakthrough pressures are likely to be around 7.5 to 8.5 MPa. Latest unpublished data suggest gas entry in longer samples occurs at higher pressures close to lithostatic stress.

The “peak pressure” largely depends on the gas production rate. It would be interesting to distinguish between slow versus fast gas production rate. This has been explored in EBS tests on compact bentonite but little data exists for Boom Clay.

As a result of building up the gas pressure micro-fractures may be formed in the Clay, though there is no evidence to suggest features coalesce into one or more ‘large’ fractures which then interact with the continuum stress field. However, the complex interaction of the gas with the stress field on all scales remains unclear, as do the number, distribution and aperture functions of the resulting pathways. Additional work is required to assess the role of dilatancy in a Boom Clay hosted repository at depths considered in the Dutch disposal concept.

Dilating processes that create microscopic pathways with self-sealing properties may occur already at pressures below the lithostatic pressure. One even observes a hardening effect as the pressure often needs to be higher with the next gas pressure pulse. In that sense it is not creating a preferential pathway for future RN groundwater transport. The “dilation effect” seems significant in Boom Clay at 500 m depth. As it is coupled with the local stress field, and since it is a dynamic process, it is still complicated to understand and to model under *in-situ* conditions.

After a “gas pulse”, which has to be confirmed for the OPERA disposal concept, rock properties may have changed. However, the effects on the Boom Clay permeability would be limited as gas pockets can serve as a blockage for water flow and diffusion (in pore water).

Since the last 15 years there is now quite a body of evidence for gas migration through dilatant pathways which partially re-seal after episodic gas pulse flow. Subsequent gas flow events may develop new pathways or follow previous ones. Depending on geology, in particular on the control of groundwater availability, and gas generation rates it is possible that a gas phase may form dilatant pathways in the host rock even in the Normal Evolution Scenario (Assessment Case N3) and certainly in an Altered Evolution Scenario (What-If Case 'Excessive gas generation’), and their longevity may be locally important.

Excessive gas generation may happen under the assumptions of maximal biodegradation and metal corrosion, and sufficient water availability, and result in an early gas pulse. However, for Boom Clay the assumption of *sufficient water availability* is perhaps overly conservative, since water in Boom Clay is less-mobile. Considering the complex coupled processes in the case of excessive gas generation, this “What-If Case” may not be simulated in the present OPERA Programme. Additional testing and modelling efforts would be needed for a better understanding.

Modelling is difficult and bulk porous models for bulk flows may be adequate. Organisations modelling gas in the repository use continuum flow codes based on two-phase flow concepts, assigning parameters for each component of the repository (e.g. EDZ, seals, host rock etc.). The applicability of such approaches to dilatant flow (if present) is however questionable. At this stage it is not known if any constitutive model exists that is able to represent the time-dependent formation, propagation and distribution of dilatant pathways within clay.

Episodic gas flow and diffusion needs to be assessed in future research as these are possible sinks for the generated gas. In an analysis of corrosion and radiolysis rates a first assessment of gas volumes can be calculated and from an estimate of the percentage of gas that can be accommodated and the pressure build-up can be computed.

4.3.03 Gas-mediated transport (geosphere)
From (only a few) experiments (performed by SCK on iodine), it appears that RN-migration by gas transport is probably limited compared to diffusive transport in pore water due to the fact that gas flow is strongly localized. However, the localisation of flow may result in greater transport distances of a small amount of RNs as flux may be concentrated through a small number of pathways. Modelling is required to confirm or reject this hypothesis (see also 4.2.07.05 Gas-induced dilation (geosphere)).

4.5.3. Summary "Gas migration"

Table 11 Summary "Gas migration"; for an explanation of the abbreviations see Table 10

Process expert finding	Implementation in PA-model EBS
N2 & N3 The design of a repository can be made just to minimize the impact of any gas being generated in the disposal facility.	**N2 & N3** This supports the assumption in the NES that gas will not affect the safety functions. A special case N3 has been defined to look into this in more detail, e.g. including the pore water flows (and subsequent RN migration) associated with a cyclic gas volume change in the EBS. Process studies on gas have progressed insufficiently in order to implement a PA-model for N3. N2 is intended to consider migration of radioactive gases.
EGC1 Excessive gas generation may happen under the assumptions of maximal biodegradation and metal corrosion, and sufficient water availability, and result in an early gas pulse.	**EGC1** A What-If Case was identified to treat excessive gas generation. From the PA-perspective, present thinking is that repetitive gas flow through the clay may cause a local increase of permeability of the host rock, and therefore may result in an increased advective flow.
N3 Localisation of flow may result in greater transport distances of a small amount of RNs.	**N3** This seems a very limited effect which can be included in N3 once quantitative data are available from a process study.

4.6. Process category “Geology and hydrogeology”

The FEPs which were discussed with the geology and hydrogeology expert, are listed in

Table 12. A summary of the expert elicitation has been included in Appendix 3, p. 106 ff.

Table 12 **Overview of discussed FEPs discussed with the geology and hydrogeology expert; NES = Normal Evolution Scenario; AES = Altered Evolution Scenario; BIO = biosphere; AQ = aquifer (overburden); HR = host rock**

FEP Id	FEP name	Scenario /AC	Relevant compartment model	PA treatment
1.2.01.01	Regional uplift	Irrelevant		
1.2.01.02	Regional subsidence	AES	BIO shortcut with repository	NES: A closed facility is not affected by flooding regional subsidence. Regional subsidence can lead to flooding, see FEP 1.2.12.01.
1.2.01.03	Movement along faults	FS	HR	NES: the repository is sited in a location where no movements along faults are expected. Moreover, such movements are not expected to induce advective transport pathways along the fault. AES **FS1** is defined to treat unexpected advective transport along such faults. The PA model includes advective transport using , parameter values derived in process studies.
1.2.12.01	Flooding	NES AES	BIO BIO, AQ, HR	A closed facility is not affected by flooding. Flooding during operation can connect the water body at the surface / connected with repository (shafts) bypassing aquifer and clay. However, most disposal gallery seals are in place, which, in combination with the facility layout, will limit the water flow potential (**AA1**, **AS1**, and **AGr1**). The PA-model can assess increased advective transport through the clay if parameter values are provided.

FEP Id	FEP name	Scenario /AC	Relevant compartment model	PA treatment
1.3.03	Sea-level change	NES AES	BIO, AQ BIO shortcut with repository	NES: A closed facility is not affected by sea level changes. See level changes can lead to flooding, see FEP 1.2.12.01.
1.3.05	Local glacial and ice-sheet effects	NES AES	BIO, AQ BIO, AQ, HR	BIO and AQ effects are included in PA model NES and AGl2: Travel time [OPERA-PU-DLT621] Impact of intensified glaciation on host rock is considered in **Agl1**, **AGl3** and **SGC1**.
1.3.10	Geomorphological response to climate changes	NES	BIO, AQ	PA model NES: Change from infiltration to exfiltration can impact the travel time [OPERA-PU-DLT621].

4.6.1. Subsurface processes

Regional uplift and subsidence (1.2.01.01/02)
In the western part of the Netherlands subsidence is caused by compaction of peat whereas the uplift in the eastern part is caused by the isostatic response after the retreat of the ice after the latest glaciation. The duration of the compaction of peat is finite and strongly depends on the groundwater level. If all peat would have been oxidized, the subsidence would amount to about 7 metre. Peat compaction is mitigated through appropriate drainage measures.

A marine flooding as a consequence of peat compaction is considered to be unlikely in the Normal Evolutions Scenario. Subsidence could play a role in the Abandonment Scenario, though.

Movement along faults (1.2.01.03)
Active faults can act as preferential fluid migration paths. The integrity of the Boom Clay is not affected if proper characterisation shows that no important faults are transecting the repository. The creation of new faults within 10^4 to10^6 years is not likely because the subsurface stress field is changing only very slowly.

Fault movement is not included in the Normal Evolution Scenario. A dedicated Altered Scenario does consider the presence of a fault.

4.6.2. Surface processes

1.2.12.01 Flooding

On a time scale of 10^2 to 10^6 years flooding has realistic probability, in particular considering the human influence on global climate. Flooding is to be considered in the Normal Evolution Scenario (see (Veen & Dario, 2015), (Valstar & Goorden, 2016) and (Verweij, Nelskamp, Valstar, & Govaerts, 2016).

1.3.03 Sea-level change

Sea level rise can lead to flooding, which is discussed in 1.2.12.01 Flooding. Also a lowering of the seal level is relevant in the Normal Evolution Scenario: as a consequence the erosion base can be lowered by up to 120 metre, changing the gradients of rivers and groundwater gradients. The integrity of the host rock is not affected. See OPERA-PU-DLT621 (Valstar & Goorden, 2016).

1.3.05 Local glacial and ice-sheet effects

According to the Milankovitch Theory and without considering the effects of anthropogenic climate change the next glacial period is expected to start after 55 ka from now. Part of the Netherlands might be covered by ice by then (Veen & Dario, 2015). The emission of greenhouse gases by mankind, in particular CO_2, is expected to delay the next glaciation by up to 500 ka. A glaciation of the Netherlands in the next 100 ka is unlikely (Veen & Dario, 2015, p. 18).

Due to climate cooling permafrost will be formed which may reach to depths of up to several hundreds of meters (Veen & Dario, 2015, p. Appendix Numerical simulation Permafrost Depth). The presence of an ice sheet leads to hydromechanical loading of the subsurface and the production of meltwater. As a consequence of ice loading clay compacts and formation water is expelled which influences the isolation capacity of clay. In OPERA-PU-TNO421_2 (Verweij, Nelskamp, Valstar, & Govaerts, 2016) the effects on the near-field boundary conditions and the residence times have been assessed.

Deep subglacial valleys may be formed below ice sheets like were formed in the geological past. These valleys could reach a maximum depth of about 500 m (Veen & Dario, 2015), down to the top of a repository in the Dutch disposal concept for the Boom Clay. This depth however can only be reached during several consecutive glaciations. In the CORA Programme a maximum depth of 300 m to 400 m was assumed (CORA, 2001, p. 40).

The Normal Evolution Scenario should consider the presence of permafrost in the subsurface after a period of more than 100 ka. An ice sheet with a maximum thickness of about 200 m results in modest loading effects and in the infiltration of glacial meltwater in the subsurface.

The alternative Intensified Glaciation Scenario considers the presence of a massive ice sheet with the formation of a subglacial valley of up to 500 m.

1.3.10 Geomorphological response to climate changes

The glacial processes discussed under “1.3.05 Local glacial and ice-sheet effects” do lead to geomorphological changes. The changes in landscape operate in the very shallow subsurface.

For the Normal Evolution Scenario this implies that the landscape will have changed during and after a future glaciation. These changes have to be considered in the biosphere and aquifer (overburden) compartments. There is no specific case identified for Altered Evolution Scenarios.

4.6.3. Summary "Geology and hydrogeology"

Table 13 Summary "Geology and hydrogeology"; for an explanation of the abbreviations see

Table 12

Process expert finding	Implementation in PA-model Clay
N1 The repository may be influenced by hydromechanical loading of the subsurface and the production of meltwater.	**N1** Reduce clay transport distance by the compaction displacement length for a moderate ice sheet thickness. Melt water will not influence the repository and the host rock, see Section 4.4.
N1 a broad spectrum of climates and geomorphologic conditions must be considered in the geohydrology studies	**N1** A geohydrological process model for screening Mediterranean, moderate, periglacial and boreal climates has been developed. The results are implemented in the PA model.
N1 a broad spectrum of climates and geomorphologic conditions must be considered in the biosphere studies	**N1** Biosphere model assumes a relative small community that lives in a closed agricultural society near the discharge area of the aquifer, which could be a natural discharge point or a human built well. For these conditions, the transfer of nuclides through the biosphere to individuals is at its maximum, and is assumed to cover the large variation in climates. Uptake in this community has been determined for temperate, Mediterranean and boreal climate. Boreal climate uptake coefficients can also be used as an upper estimate for the periglacial climate.
AGl2 subglacial valley of up to 500 m.	**AGl2** Main impact is in the PA-aquifer model and biosphere model: represent transport through glacial valley to nearest possible human inhabited area, exposure by usage of river and lake water from the glacier in a periglacial climate. **AGl2** In the present outline of the disposal facility, the waste is emplaced at 500 m depth, and the top of the Boom clay is at 450 m depth. This would mean that if in this scenario the clay cover above the waste is removed, the waste is in direct contact with the melting water flowing through the "erosion valley".
N1 The Normal Evolution Scenario should consider the presence of permafrost in the subsurface after a period of over 100 ka.	**N1** Exposure in a periglacial or boreal climate.

5. Conceptual models for different scenarios

This chapter combines the description of the OBM in Chapter 3 and the results of the discussions between the process experts and the PA experts as described in Chapter 4 and applies this combination with the narratives of the scenarios and Assessment Cases as identified in OPERA-PU-NRG7111 (Grupa, Hart, & Wildenborg, Description of relevant scenarios for the OPERA disposal concept, 2017).

The most important observation concerning the OBM is that the discussions with the experts have further strengthened the OBM. On the one hand the expert elicitations have allowed the PA experts to better describe the model concepts taken from the process models and on the other hand they allowed the process experts to better understand how their results are further processed, and how their findings are treated in the safety assessment.

5.1. Overview

Table 14 summarizes a list of conceptual models needed to evaluate the Assessment Cases identified in OPERA-PU-NRG7111. For many cases the OBM is adequate, for some cases the OBM needs to be extended, and for a few scenarios an alternative model concept with a different approach is needed.

This description of the OBM was already presented in Chapter 3. For some of the other Assessment Cases the OBM can be used with specific parameter values that represent that case. For other Assessment Cases an extension to the OBM is needed, e.g. advective transport in addition to the diffusive transport in the clay.

Table 14 Overview of the conceptual models for the various Assessment Cases; see below for explanation of the conceptual models

Scenarios and Assessment Cases		**Conceptual model**
	Normal Evolution Scenario	
N1	Central Assessment Case	OBMd
N2	Radioactive gas transport case	OBM and GAS
N3	Gas pressure build-up case (normal range)	GAS
N4	Early canister failure case (normal range)	OBMd
N5	Deep well Assessment Case	OBMd
	Abandonment Scenario	
AA1	Abandonment	OBM
	Poor sealing scenario	
AS1	Poor sealing	OBM
	Anthropogenic Greenhouse Scenario	
AGr1	Flooding of the site	OBM
	Fault scenario	
FS1	Undetected fault scenario	OBM

Scenarios and Assessment Cases		Conceptual model
	Intensified glaciation scenario	
AGl1	Deep permafrost case	OBM + Aquifer-permafrost
AGl2	Deep subglacial erosion case	OBM + Aquifer glacial valley
AGl3	Glacial loading case	OBM + Clay compaction
	Human Intrusion Scenarios	
AH1	Penetration by drilling or mining	Direct exposure
AH2	Deep well scenario - extreme case	OBMd
	What-If Cases	
EEC1	Excessive Early Container Failure	OBMd
EGC1	Excessive Gas generation	GAS
EFD1	Fast and radical dissolution of the waste	OBMd
ECC1	Criticality event	OBM
EHP1	Excessive heat production	OBM
SGH1	Study of hydraulic effects of climate change	OBMd
SGC1	Study of compaction of the Boom Clay and resulting flow	OBM and Clay compaction
SHE1	Study of deep excavation and groundwater flow	OBM
SBM1	Study of microbiological effects on the EBS and host rock	Microbiology
SAT1	Study of additional transport modes	Transport

OBM
The OBM contains the diffusion-advection equation for radionuclide transport through the clay. The conceptual description is given in Chapter 3, as confirmed and strengthened by the discussion with the process experts. The OBM is described in more detail including the mathematical equations in the reports OPERA-PU-NRG7212 (PA model 'Clay'), OPERA-PU-GRS7222 (PA model 'Aquifer') and OPERA-PU-SCK631-NRG7232 (PA model 'Biosphere').

OBMd (OBM, diffusion in the host rock)
In the NES and some other scenarios, only diffusion occurs in the clay; this mode of using the OBM is addressed as OBMd. OBMd was originally implemented for the NES, i.e. only diffusive transport through the clay.

GAS
The OBM does not include the impact of gas production on the PA. The build-up of gas volumes and the impact of gas pressure must be addressed in process studies. A discussion of the GAS model is presented in Section 5.3.

OBM and GAS
In some cases GAS can result in an advective flow potential, which can be assessed in OBM or in OBM and Advection (see Section 5.3).

OBM and Aquifer-permafrost
Permafrost has a strong impact on the PA modules 'Aquifer' and 'Biosphere' (see Section 5.5).

OBM and Aquifer glacial valley
Glacial erosion can have a strong impact on the PA models 'Aquifer' and 'Biosphere', see Section 5.5.

OBM and Clay compaction
The weight of a massive ice cover will cause compaction of the clay layer and subsequent water movements to accommodate the compaction (see Section 0).

Direct exposure
Some human action scenarios, and also extreme glacial erosion may lead to uncovering (parts of the) repository, and consequently direct exposure (see Section 5.6).

OBM and Hydraulic effects of various climates
Hydraulic effects of various climates can be reflected in the residence time in the aquifer (see OPERA-PU-DLT621 and Section 5.7).

Microbiology
The impact of microbiological activity (e.g. gas production) is discussed in Section 5.9.

Transport
Additional transport modes (in addition to diffusion and advection) are discussed in Section 5.9.

5.2. OBM scenarios and Assessment Cases

The OBM was already presented in Section 3. In short, it consists of 4 compartments with the following PA models

- Repository compartment
  Mixing tank model including the waste inventory (per waste section), dissolution rate and solubility limits, and with a diffusive connection to the clay compartment
- Host rock Clay compartment
  Diffusive transport including adsorption for most species, a diffusive connection to the aquifers directly above and below the clay layer.
- Aquifer compartment
  Dilution in and mainly horizontal advective transport through the aquifers, and gradual transport in vertical direction to the biosphere, and an advective connection to the biosphere waters.
- Biosphere compartment
  Small agricultural community in a biosphere that uses water from the aquifer discharge area.

The OBM is directly applicable to the following Assessment Cases:

N1	Central Assessment Case

The central Assessment Case represents the most likely evolution of the system. This Assessment Case includes the most likely range of parameter values for the processes involved. Note that this range can be large for some parameters, e.g. adsorption coefficients can vary 3 orders of magnitude since the precise location of the repository is undecided. Residence times in the aquifer may even vary over 5 orders of magnitude since the precise location is undecided. Very different climate evolutions are considered equally likely, e.g. a glaciation after about 5000 years is equally likely as no glaciations at all in the next 1 million years. This very broad spectrum of possible evolutions is included in the Central Assessment Case and is adequately described by the baseline conceptual model.

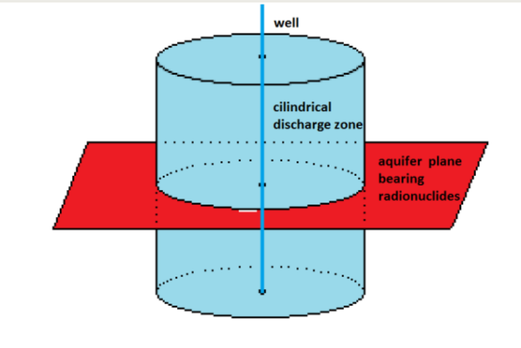
N4	Early canister failure case (normal range)
EEC1	Excessive Early Container Failure
EFD1	Fast and radical dissolution of the waste

It is not unlikely that a small number of OPERA Supercontainers fails during the thermal phase. The case is fully described by the OBM, however the container lifetime value should be modified for a small number of OPERA Supercontainers in N4, a large number of OPERA Supercontainers in EEC1. In EFD1 also the parameter value for the dissolution rate of the vitrified waste is increased. All cases are adequately described by the baseline conceptual model.

N5	Deep well Assessment Case
AH2	Deep well scenario - extreme case

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. The surface geology of The Netherlands is such that wells are sufficiently fed by aquifers at less than 100 m depth. A deep well feeding from an aquifer deeper than 300 m is therefore considered to be very unlikely and is reflected in an alternative evolution scenario AH2.

The geometry of the interface between the well and the radionuclide bearing part of the aquifer is described by a plane with an area of many squared kilometers and a thickness of one or a few meters. The well induces a cylindrical discharge zone with a radius of 50 to 100 m and a height of 100 m.



In this geometry the water from the aquifer is significantly diluted with fresh water. All cases are adequately described by the baseline conceptual model.

5.3. Gas Model scenarios and Assessment Cases

The OBM does not include the impact of gas production on the PA. in most Assessment Cases it is implicitly assumed that gas that is produced in the closed repository is buffered in the pore volume in the EBS, mainly in the backfill materials, and gas is removed from the repository by dissolution of the gas in the pore water and subsequent diffusion of the dissolved gases away from the repository. Alternatively, for the normal evolution it can be acceptable that gas is removed by dilating processes that create microscopic pathways with self-sealing properties at pressures below the lithostatic pressure, if it can be shown that these processes occur without affecting the safety functions of the clay host rock, i.e. nuclide transport in the clay is still diffusion determined.

In the Central Assessment Case it is assumed that gas that is produced (by anaerobic corrosion of metals and degradation of organic materials in the waste) and buffered in the pore volume of the EBS with minor or no impact on the canister lifetime, waste dissolution and radionuclide migration through the clay. This implies a design requirement: the EBS should be large enough to provide this buffer and limit the consequences. In order to show this, Assessment Case N3 was defined.

N3	Gas pressure build-up case (normal range)

The assessment of this case requires some process studies:

1. determination of the gas production rates over time in the various sections of the facility
2. determination of the gas removal capacity of the system by
    a. gas dissolution and diffusion.
    b. dilating processes that must not affect the safety function of the clay
3. determination of the required EBS dimensions to allow sufficient gas buffer capacity

These studies will allow determination of the development of the gas volumes and gas pressures over time in the EBS.

The consequences of such gas volumes in the EBS have to be assessed: does the gas affect the container lifetime, the chemical conditions in the EBS, and the thermal evolution of the HLW section?

The increase of the gas volumes in the EBS must be sufficiently slow to allow water to flow from the (saturated) EBS into the clay without the need for undue large pressures, and the decrease of the gas volume should be slow enough to avoid mechanical instability of the EBS.

The changing gas volumes in the EBS induce a flow of water through the clay, and this should be included in the PA as a mechanism that causes advective transport of radionuclides through the clay. For the N3 case, it should be shown that this advective transport is smaller than the diffusive transport. This assessment requires the addition of advective transport to the OBM (which only describes diffusive transport in the clay), see section 5.4.

N2	Radioactive gas transport case

Some of the radionuclides that are released from the waste are released as gases or may be converted to gas in the EBS. This concerns e.g. the nuclides H-3, C-14 and the Rn isotopes. Based on the estimated inventory of the waste and the radiological characteristics, C-14 may dominate the radioactive gas transport case. Gaseous C-14 in the repository will predominantly exist as CO_2, and, in smaller amounts, methane. Note that the amounts of the radioactive gases themselves (in moles) are too small to induce chemical or mechanical (stress) changes in the system.

If the gases are removed from the EBS by dissolution and diffusion, the OBM is completely adequate. This is studied in the EC CAST project.

If the radioactive gases are mixed with large amounts of non-radioactive gases in the EBS, and are removed from the EBS by dilating processes or other advective processes, this transport mechanism may short cut a large part of the geosphere, and the radionuclides may reach the biosphere much faster than in the case of diffusive transport. This requires process studies on the fate of the gases produced in the repository.

In the Normal Evolution Scenario, it assumed that gas migration through the clay occurs by a dilating process. This process is rather unique in the sense that it requires a rock material that allows this transport mode (relatively soft, plastic behaviour and resealing properties) in combination with a gas source fully enclosed in the rock material, and the inability of the gas to enter the water filled pores (i.e. gas entry pressure about equal to the lithostatic pressure). Once gas starts migrating through the clay rock, some of the dilated gas pathways may reach the aquifer. The aquifer material contains more sand, is less plastic, has a higher permeability and may have a lower gas entry pressure. This may allow the gas to expand, reducing the gas pressure to equal the sum of pore water pressure and the capillary pressure in the more sandy aquifer material.

The most probable gas migration process in the aquifer is two-phase flow, and various effects occur. (a) For the gas to move in the aquifer, the gas entry pressure of the water saturated aquifer pores has to be exceeded. (b) Once the gas is moving, it experiences a larger permeability than water. (c) Since the gas has a lower density than water, it will have a tendency to move upward in the aquifer, and the gas may become trapped in irregularities in the aquitard that is overlying the aquifer. (d) while the gas resides in the aquifer, it will continue to dissolve in the pore water.

Qualitatively it is expected that the gas is not moving significantly faster than the water in the aquifer.

When the gas is migrating by dilating processes (or others, like two phase flow) the gas continues to dissolve in the water. The (maximum) travel distance of the gas depends on the dynamics of these transport processes. Since there have been no quantitative studies with respect to the travel distance of gas in the OPERA disposal concept, it will be assumed indicatively that the gas may travel about 100 m at a maximum), and then migrates as a dissolved species in water.

EGC1	Excessive Gas generation

For this scenario, it is assumed (What-If Case) that high pressurized gas volumes in the EBS have affected the safety function of the EBS and the Clay, i.e. by causing early container failures and inducing advective water flow.
Early container failure can be assessed with the OBM.

Process studies are needed to determine the extent of advective flow potential in the EBS and clay. The radionuclide transport can then be determined by using the OBM plus advective transport, as described in section 5.4.

5.4. Advective transport in the clay host rock

Advective transport in the clay host rock is considered unlikely and therefore only relevant in Altered Evolution Scenarios and What-If Cases. Advective transport may be assessed in the N3 Assessment Case.

In order to achieve advective transport, a water flow needs to enter the repository, the water flow in the repository needs to pick up radionuclides, and the water containing the radionuclides must leave the repository. This water flow pathway must be regarded as part of the natural (or manmade) underground water flow system, i.e. a fraction of the water from one of the Boom Clay surrounding aquifer leaves the aquifer and moves to the repository, than leaves the repository and enters the original or another aquifer in another location.

In the Normal Evolution there is no water flow pathway through the repository that accommodates advective transport. Some Altered Evolution Scenarios contain an event that induces such a new pathway. Once the pathway is described, a process study is needed to determine the amount of water flowing through the new pathway. In the OBM description of radionuclide transport through clay, the transport by a given water flow can be added to the diffusive transport term. The implementation of advective transport in addition to diffusive transport will lead to the diffusion-advection equation, which is a very common instrument in groundwater (pollution) studies.

The approach for scenarios involving advective transport through the clay consists of a three step procedure:
1. an event (e.g. from the FEP list) that induces a water flow through or very near to the repository.
2. a process study involving the hydraulic conditions of the underground in order to determine the magnitude of the water flow through the repository and the locations where this water enters the original aquifer system.
3. calculations with the PA model, where advective transport in parallel to diffusive transport is included.

In the OPERA design of the disposal facility, all wastes are emplaced in dead-end disposal tunnels, each of which is sealed and plugged once all waste is emplaced in the disposal tunnel. Due to this design, a flush flow through the disposal tunnel should be very unlikely, since therefore two independent, unlikely events have to occur: one event is that the seals in the EBS have to fail and the second event has to induce a water permeable pathway though the clay. This requires special attention for "common cause failures" in the scenario identification effort, i.e. one FEP that will cause damage to both independent systems. During the screening (Grupa, Hart, & Wildenborg, 2017) no "common cause" FEPs have been identified, but in the present screening procedure there was no special attention for "common cause failures". In a future safety study, the FEP evaluation procedure should include an explicit mechanism to identify common cause failures.

AA1 Abandonment

It is assumed that the repository is abandoned before proper closure. The waste is emplaced in dead end disposal tunnels, which are sealed once the disposal tunnel is filled. In case of abandonment of the facility, it can be assumed that for each waste section one disposal tunnel is in operation and is unsealed. Also shaft seals and seals that close a waste section have not been build.

After the abandonment the facility will flood slowly (it will take some years), since the underground constructions are not watertight, and the routine pumping operations to remove water from the facility are stopped. Note that, from a mining engineering perspective, it is possible to recover the facility by starting an emergency pumping operation (Grupa J. , Trial Of Formal Use Of Expert Judgement For Scenario Conceptualisation, 2009). For the abandonment scenario, however it is assumed that no recovery operations are attempted, and the flooded shafts and access tunnels form a permeable network through which water will flow. It is also assumed that the water from an aquifer will enter one the shafts, flow through the facility towards the other shaft, and then flows from the shaft into an aquifer. The relevant aquifers may be at a depth of 10 to 50 meters. There will be no flow through the unsealed disposal tunnel, since this is a dead end tunnel.

In the long run (centuries) it is to be expected that the underground structures collapse, and the clay will expand into some tunnel sections, providing in a natural sealing of the flow pathway.

The nuclide migration takes the following course: degradation of the container and waste matrix, dissolution of radionuclides into the flooded disposal tunnel, a short diffusive migration path to the access tunnel, a relatively fast advective transport through the access tunnels and shaft to a shallow aquifer, dilution in the aquifer and mixing with biosphere waters, eventually leading to exposure.

AS1	Poor sealing

It is assumed that one or more of the seals (i.e. the shaft seals, the waste section seals, the disposal tunnel seals) perform poorly because of design or construction failures. In most cases, and after the re-saturation phase, the consequences of such failures are very limited, since the hydraulic gradients are small, and a poor performing seal in the sequence of seals will not lead to a large advective flow.

Calculations performed for SAFIR-2 (ONDRAF/NIRAS, 2001, p. 11.5.4.5.3) indicate that only a very small advection flow (some 5 mm/year) occurs in the poorly sealed galleries. Virtually no water enters the galleries from the Boom Clay because of its low hydraulic conductivity.

For the radionuclide migration there are two variants:

A. The water flows from the aquifer above and beyond the clay layer to the disposal and access tunnels, to the shaft and then to a shallow aquifer.
   The nuclide migration takes the following course: degradation of the container and waste matrix, dissolution of radionuclides into the flooded disposal tunnel, a short migration path to the access tunnel, advective transport through the access tunnels and shaft to a shallow aquifer, dilution in the aquifer and mixing with biosphere waters, eventually leading to exposure.
B. The water flows from an aquifer into the shaft, and flows from the shaft to the access and disposal tunnels, and then through the clay layer to the aquifer above and beyond the clay layer. The radionuclides follow the water flow, but are substantially retarded in the clay because of adsorption.

Variant A may cause the largest exposure in the biosphere.

AGr1	Flooding of the site

Flooding of the site can occur during operations or after closure of the facility.
If flooding occurs during operations, the scenario is similar to the abandonment scenario, although the facility is flooded fast with sea water or fresh water. It is to be expected that eventually the facility can be recovered. If not, radionuclides can be released from the waste.

The nuclide migration starts with degradation of the container and waste matrix, dissolution of radionuclides into the flooded disposal tunnel, a short diffusive migration path to the access tunnel, a relatively fast advective transport through the access tunnels and shaft to a sea, lake or wetlands. This will not lead to larger doses as found for the abandonment scenario.

In case of flooding of the site after closure, the scenario is similar to normal evolution, except that radionuclides are released to a sea, lake or wetlands. This will not lead to larger doses as found for the Normal Evolution Scenario.

FS1	Undetected fault scenario

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. To calculate the migration of radionuclides along the fault plane it was arbitrarily assumed that the hydraulic conductivity K increases by a factor of 20, the diffusion coefficient D_p by a factor of 2 and that the retardation factor R decreases by a factor of 5.

In OPERA, the changes of the clay properties in an undetected fault have not been specified. For the PA, the OBM (including the advective transport term), can be used once the parameter values for the fault zone are available.

Since the water flow is small, no significant effects on container lifetime and waste dissolution rate are expected, although caution must be given to solubility limited processes.

ECC1	Criticality event

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. Early rupture of waste packages and engineered barriers may result from the abovementioned sudden thermo-mechanical effects. A disruption of the integrity of the waste packages, engineered barriers and perhaps also the near field increases the potential for water flow in the EBS. However, it is not likely that this event affects the shaft seals or creates a large fault zone transecting the clay, but this has to be shown.
In order to assess this scenario:

- a heat generation profile for the localized criticality event has to be determined
- a hydro mechanical calculation has to be performed to calculate temperatures and stresses.
- the size of the damage area (due to high temperatures, large stresses and large deformations) has to be determined.

If the damage area is sufficiently large, the water flow has to be determined, and a calculation similar to the poor sealing scenario and/or the undetected fault may be needed. Moreover, the increased heat production may induce a free convection flow through damaged EBS structure, increasing the migration speed of the radionuclides.

EHP1 Excessive heat production

In this What-If Case the consequences of undue high temperatures will be explored. The conceptual model for the calculations is equal to that for criticality event. Moreover, an increased heat production may induce a free convection flow through damaged EBS structure, increasing the migration speed of the radionuclides.

SHE1 Study of deep excavation and groundwater flow

Deep excavations may be created to depths of up to a few hundreds of metres, and may drastically change the hydraulic regime in the overburden. 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.

There are two categories of variants for this scenario:
I. the excavations do not enter the host rock
II. the excavations enter the host rock, but not the repository
A third category, the excavations transect the repository, is treated in another scenario: AH1 - Penetration by drilling or mining.

The excavations of type I can
a) short cut and/or speed up the transport through the aquifer system, or
b) induce a large hydraulic gradient over the clay layer, inducing (vertical) advective transport through the clay.
The excavations of type II can result in the same effects as type I, but also can reduce the effective thickness of the Boom Clay layer.

For the PA, the OBM extended with the advective transport term, can be used once the parameter values for the effective thickness of the clay, the hydraulic gradient over the clay and the reduced aquifer residence times are available.

5.5. Glaciation scenarios and Assessment Cases

AGl1 Deep permafrost case

Direct impacts at repository depth, including possible damage to the EBS, may occur at several locations when deep (200 m - 300 m) permafrost develops. However, even at repository depth (500 m), indirect effects such as brine formation and migration, intrusion of freshwater from melting permafrost or gas hydrate (formed beneath the permafrost layer, and cryogenic pore pressure changes associated with volume change during the water-ice phase transition may affect the integrity of the geological barrier.

Quantitative descriptions of these effects are not available. In general, hydraulic gradients seem to decrease in permafrost conditions. However, the aforementioned effects may cause local hydraulic gradients. The low permeability of the clay host rock seems not to be affected.

In order to assess the scenario:

1. a geological study is needed to more precisely describe the indirect effects of the deep permafrost
2. a hydraulic groundwater model needs to be developed to determine the hydraulic gradient over the clay layer (the potential of advective flow), changes in the salinity of the pore water in the clay, and residence times in the aquifers ("aq-permafrost”).
3. For the PA model, the OBM model seems adequate. However there is a small probability that some additional advective transport occurs in the clay due to large local gradients, and the residence times in the aquifers have to be determined. Changes of the salinity may affect the K_d values of the clay.

AGl2 Deep subglacial erosion case

The expert elicitations with the process experts revealed that present thinking about glacial valleys has changed over the last decades. During the CORA-Research Programme, the potential depth of subglacial erosion was estimated to be 300 to 400 m at maximum. Presently it is stated that a maximum erosion depth of 500 m could be possible as a result of a series of glaciations, where after each glaciation the "erosion valley" is filled with sediments, but with each new glaciation the "erosion valley" is further deepened.

In the present outline of the disposal facility, the waste is emplaced at 500 m depth, and the top of the Boom clay is at 450 m depth. This would mean that in this scenario the clay cover above the waste is removed, and the waste is in direct contact with the melting water flowing through the "erosion valley".

The PA calculations can be performed with the OBM model, assuming that after about 50 000 to 100 000 years the clay cover is removed, and all soluble parts of the waste are carried away by the melting water flowing through the "erosion valley". This water reaches a melting water river, maybe a lake and eventually the sea. Exposures are largest at the nearest possible location for an agricultural community near the melting water river. A screening groundwater model for the "glacial erosion valley" is already described in OPERA-PU-DLT621.

It is also possible that insoluble parts of the waste are picked up in the (mechanical) erosion process and deposit in the melting water river and maybe lakes. This requires special analyses on the spatial distribution of deposits from insoluble parts of the waste. Note that the biosphere sub-model includes exposure to (insoluble) contents in the river and lake sediments.

Depending on the severity of the consequences and the probability of this scenario, a decision has to be made whether a disposal depth of 500 m is sufficient.

AGl3 Glacial loading case

In the case of an intensified glaciation, the stresses in the underground increase significantly due to the weight of the ice layer. As an indication, assume an ice layer of 2 km thickness. The weight of this ice produces an additional stress of 18 MPa in the underground. The lithostatic pressure in the Boom clay would in this scenario increase from 10 MPa to 28 MPa. Since the event will happen after at least 50 000 years, it can be assumed that all EBS elements have failed, but that the whole system has become impermeable due to intrusion of the plastic clay into the failed EBS components. The increasing stress will further compact the remains of the EBS, further decreasing the permeability of the EBS remains.

In OPERA-PU-BGS615(p.36) an indicative value for the bulk modulus of compressibility (K) of 133 MPa is provided for Boom clay. A stress increase of 18 MPa leads to a relative volume reduction of 14%.
For a screening PA-assessment, we may assume that the thickness of the clay layer will reduce from 100 m to 86 m to accommodate the volume reduction of 14%. This is achieved by a reduction of the porosity from about 30% to 16%. This means that about half of the pore water is squeezed out of the clay layer and into the aquifers above and below the clay layer.

Considering the top half of the layer, the thickness decreases from 50 m of saturated clay to 43 m. effectively, there is a layer of 7 m water squeezed out of the clay. However, since the porosity of the clay was about 30%, this layer of 7m of (pure) water was spread out in about 21 m of clay. So, all water in the pores of the top 21 m of the clay layer is squeezed out to the aquifer above the clay layer, due to the compaction of the clay layer. In the lower half of the clay layer, all water of the lowest 21 m of the clay layer is squeezed into the aquifer below the clay layer.

Assuming that the growth of the ice cover is about 2 m per year (presently in NL the precipitation is about 1 m per year), it takes 1000 years to obtain an ice cover of 2 km. The vertical water displacement in the clay during this period is about 0.021 m/year.

The screening PA assessment could be performed with the OBM, assuming a clay layer thickness of 43 m on top of the repository, and introducing a vertical advective pulse of 0.021 m/year in the period from 50 000 to 51 000 years.

This screening approach is based on pragmatic simplifications of the mechanical and hydraulic response to the ice loading. A more concise study is suggested in SGC1 "Study of compaction of the Boom Clay and resulting flow".

5.6. Direct exposure

AH1	Penetration by drilling or mining

The probability that records of a closed facility become incomplete, corrupted or are lost completely increases over time. It can be assumed safely that knowledge of the facility will be in the minds of the local community for a number of generations, so at least 100 to 200 years. A national government can keep the records much longer, at least for hundreds of years, in practise at least as long as the government is stable. This administrative effort to maintain the records is addressed as institutional control.

Technically there is no limit to maintaining records. The oldest written accounts (e.g. the limestone Kish tablet from Sumer with pictographic writing) are more than 5000 years old, and this time span is mainly determined by the time writing was invented. Lost records and corrupted records can often be recovered by historical research.

As long as there is institutional control it is to be expected that no penetration by drilling or mining will occur. The most likely scenario in which institutional control is lost (at least temporarily) is a severe societal disruption. So on the one hand it seems reasonable to assume that institutional control can be lost within 50 to 500 years, while on the other hand records may be maintained or recoverable for more than 5000 years.

If institutional control is lost, accidental penetration by drilling or mining is possible. There are various possibilities for exposure:

1. Workers can be exposed to the radiation either from material that is brought to the surface by drilling or from material that is uncovered in a mine.
2. The waste stream from the drilling or mining operation may contain radioactive materials, which leads to exposure of everybody who is in the vicinity of these wastes.
3. Products made from the mined materials (or the waste) can be contaminated and cause exposure of the persons using these products. This pathway is unlikely because similar clays can be mined easily at the surface.
4. In the direct surroundings of the drilling or mining areas, the permeability of the clay may be increased (e.g. an EDZ) and the hydraulic gradients may be disturbed due to the operations. This may lead to an migration and exposure path comparable to the pathway described for the undetected fault scenario.

For the exposure pathways 1 to 3 an estimate must be made of the range of contamination of mining materials, waste and products, the radiation field must be determined, and the time that a person spends in the neighbourhood of the material must be estimated.

5.7. Climate change

SGH1	Study of hydraulic effects of climate change

A large part of this study has already been performed and reported in OPERA-PU-DLT621 (Valstar & Goorden, 2016). Screening calculations for the following climates have been performed:

- Moderate climate
- Cold climate without ice cover (permafrost)
- Cold climate without ice cover (glaciation)
- Warm climate: Climate Change prediction WH of KNMI
- Warm climate: Mediterranean Climate

Note that OPERA-PU-DLT621 also reports on the Altered Evolution Scenarios: Deep well, Glacial valley, and Fault.

The calculations assume a static climate. It should be noticed that the bandwidth in travel times for a given climate is often larger than the difference between the travel times for different climates.

A gradual change from one climate can be represented by gradual shifts from one set of results to another, e.g. by interpolation. The study must be deepened by improving the more pragmatic assumptions that have been made, reducing conservatisms and identification of potential dynamic effects of climate change that cannot be represented by interpolation.

5.8. Compaction of the Boom Clay

SGC1 Study of compaction of the Boom Clay and resulting flow

This study is meant to create a better basis for the treatment of the glacial loading scenario case, and could include also the impact of the more likely moderate ice loading. The study involves a geomechanical part to calculate the underground deformations and water displacements, a groundwater modelling part to estimate the groundwater flow, residence times and discharge locations, and maybe a chemical part if salinity is considered an issue.

5.9. Additional transport modes

SBM1 Study of microbiological effects on the EBS and host rock

The LILW part of the waste contains organic materials. These are a nutrient to microbes. Anaerobic microbial conversion of the organic materials will lead to the production of gases, mainly CO_2, but also gases such as CH_4 and H_2. The organic remains of the process can also increase the DOM level (amount of dissolved organic material) and there are some speculations that microbial activity may accelerate some of the EBS degradation processes.

The microbial gas production is a key input to the gas scenarios (Wiseall, et al., 2015). Production of gases by anaerobic microbial conversion of organic materials (e.g. paper and plastics) is difficult to model. Coincidental combinations of local concentrations of specific organic materials and the presence of suitable microbe strains provide localized areas in the waste where the microbes can grow. Initially there will be a large growing rate, causing a high but local gas generation rate. However, nutrients are depleted disproportionally, and the population ceases. At a later time, at the same place or nearby, another strain of microbes may develop for which this new condition is a good environment. This creates an irregular pattern of short periods of localised microbial activity followed by longer periods of rest.

From the overview of anaerobic microbial conversion processes given in (Rübel, 2004) it can be estimated that 20 moles of gas can be produced from 1 kg of organic material. The 160 000 LILW containers may contain 100 000 to 500 000 kg of organic material. Assuming a pore fluid pressure of 5 MPa, in total 1000 to 10 000 m^3 gas (at 5 MPa) can be produced. The volume of the LILW disposal section is about 140 000 m^3, the pore volume is about 50 000 m^3. Assuming a pore fluid pressure of 5 MPa, this means that 2% to 10% of the pore volume could eventually be occupied by gas, if the gas is not removed from the EBS.

For large amounts of mixed LILW (Rodwell, 1999), reports an indicative average gas production rate of 0.02 mole CO_2/CH_4 per year per m^3 of waste. The volume of the LILW waste is about 50 000 m^3. So it would take about 200 to 10 000 years (indicative) for the microbes to convert all organic waste.

The purpose of the SBM1 case is to confirm by better calculations and data, that it is to be expected that the gas is removed by dissolution and diffusion, since the volume of the gases is smaller than the buffer volume of the LILW and the generation is on average slow.

SAT1	Study of additional transport modes

The purpose of this scenario case was to consider more speculative transport types than diffusion and advection, such as transport driven by osmosis, or chemical or thermal gradients. These transport modes are described briefly in (Wiseall, et al., 2015, pp. 64-66). Developing a PA-approach, if considered necessary, has been deferred to a follow up of the OPERA Research Programme.

6. Conclusions and recommendations

6.1. Scenario model representation

Twelve experts representing five areas of expertise have analysed close to 50 FEPs in their relevance for the performance assessment of the various scenarios and the way they could be represented in the scenario PA model. The areas of expertise are:

- Geology and hydrogeology
- Gas generation and migration
- (Geo-)chemistry
- (Geo-)mechanics
- Behaviour of waste and container

The OBM has been used as the reference for the evaluation of the expert input. It appears that for most scenario Assessment Cases and What-If Cases the OBM or an extended version of the OBM is applicable (see Table 15). For 8 Assessment Cases an extended version of the OBM is considered to be adequate. The extension of the OBM is related to either the inclusion of an advection term in the clay compartment transport model, glacial phenomena including permafrost, ice loading or subglacial erosion, or clay compaction. In a few cases the OBM has to be substituted by an alternative model for direct exposure, gas migration, microbial interaction or specific transport processes.

Table 15 Summary table with the model representation of the various Assessment Cases; abbreviations of Assessment Cases are explained in Table 14

Model representation	NES	AES	What-If Cases
OBM	N1, N4, N5	AA1, AS1, AGr1, FS1, AH2	EEC1, EFD1, ECC1, EHP1, SGH1, SHE1
Extended OBM	N2, N3	AGl1, AGl2, AGl3	SGC1
Alternative model			AH1, EGC1, SBM1, SAT1

FEP and scenario analysis is labour intensive work. Within the scope of the OPERA Research Programme we have been able to develop a workable method for the identification, characterisation and model representation of scenarios with the help of FEP analysis and to apply this method for radioactive waste disposal in the Dutch Boom Clay. In order to finish the work we recommend to complete and consolidate the scenario analysis in a future continuation of the OPERA research. In future assessments of AES scenarios explicit attention must be given to potential common cause failures, in order to identify FEPs that may results in such failures.

Furthermore, future research should concentrate on the development of dedicated PA models for gas migration and microbial interaction in particular, as there is presently no specific gas module in the OBM.

Experts which have been consulted for the scenario analysis advised to have a closer investigation of transient conditions, like changes in salinity as most work in the performance assessment is studying equilibrium conditions. Particular attention should be directed to changes in salinity, from fresh to brine and vice versa, and their effect on RN speciation, colloid transport, sorption, osmosis, permeability, coupled flow and density-driven flow. Further analysis is necessary to identify situations where non-equilibrium conditions are of importance.

6.2. Methodology

The development of PA models in OPERA is a two track process. The first track, which is the main ingredient of this report, starts with the scenario narratives, and is based on experts' determination which processes need to be addressed quantitatively in the scenario model. The second track uses the available mathematical models developed in previous research programmes, which haves been further refined during the OPERA Programme. In a way, the first track is a bottom-up process, while the second track is a top-down approach.

The deployed method for scenario analysis as laid out in OPERA-PU-NRG7111 and in the current deliverable OPERA-PU-TNO7121 has its merits in terms of comprehensiveness, transparency and verifiability but also is very labour intensive which sometimes is perceived to be tedious. For involved experts the safety-function based FEP method applied in OPERA is not always intuitively understandable. To overcome this one of the experts suggested to evaluate FEPs as follows:

1. Describe intuitively how the disposal system works specified for the various barriers and related safety functions
2. Evaluate FEPs in two classes:
    a. FEPs that support the safety functions of the disposal system
    b. FEPs that threaten the safety functions of the disposal system

The PA experts partly followed this approach in evaluating the impact of the FEPs on the safety functions in the various scenarios. The method we have applied did not focus on the FEPs that support one or more the safety functions.

As was said before the scenario analysis requires a big effort to assure the comprehensiveness and the required level of detail in the analysis of factors influencing the safety performance of a repository in the Boom Clay and to register the underlying argumentations in a transparent and verifiable manner. Yet, a substantial additional effort is necessary to complete the exercise. The work done represents a solid start in the evaluation of FEPs and their representation in the PA model, and it gives a good impression of what the scenario analysis entails in practice. The scenario analysis and model representation as integral parts of the performance assessment require continuous attention and possible action during the lifetime of a repository until closure.

Furthermore, it is suggested to use the FEP database as a means to check the completeness of the process model and PA model concepts. In this way the model developers have the freedom to develop their models and related codes first without too much interference from the scenario analysis. In a second step the model concepts can be challenged on their completeness by targeted questions resulting from the FEP and scenario analysis. In this way the work done by the model developers, their modelling approaches in particular, is thought to be better respected. Requiring that the scenario analysis should be the main starting point for model development would be more cumbersome.

The scenario analysis should primarily be directed to the identification of factors which may influence the safety functions of the various barriers of the disposal concept and its driving forces.

A solid FEP and scenario analysis is an important prerequisite for developing and maintaining the safety case throughout the phases of site characterisation, construction, operation, closure and release from institutional control. It can and should serve as a reference for future R&D work.

IGSC Scenario development

The 2015 IGSC Scenario Development Workshop (Appendix 2) major outcome is that most, or perhaps all, practical scenario development methods involve certain common steps, even though there remain many programme-specific details and differences in terminology. There are two distinct aspects to this description: (1) the safety concept and the safety functions of the disposal system, which is often considered primarily the responsibility of safety assessors and (2) a phenomenological description based on the available scientific and technical knowledge concerning FEPs and their interactions, developed primarily by scientific and technical experts. Bringing these two distinct elements together requires, but can also promote, communication between safety assessors, scientists and engineers.

This outcome is clearly reflected in the present report, where the PA baseline model has been developed by the safety assessors, while a phenomenological description based on the available scientific and technical knowledge has been brought into play by organising communication between safety assessors, scientists and engineers.

Another important finding of the 2015 IGSC workshop is that all scenario development methods make use of expert judgement. Recognising that for the present study expert judgments have been used in abundance (possibly somewhat hampered due to budget and time limitations), even very large research programs will fall back on expert judgment when it comes to scenario development.

6.3. Final conclusion

A firm step towards a solid safety case has been achieved by identifying and screening the normal evolution and possible risk factors in a comprehensive, transparent and verifiable manner.

Scenario analysis and model representation require continuous attention and possible action during all steps of the safety case evolution, i.e. from first generic repository design until repository closure.

References

Arnold, P., Vardon, P. J., Hicks, M. A., Fokkens, J., & Fokker, P. A. (2015). *A numerical and reliability-based investigation into the technical feasibility of a Dutch radioactive waste repository in Boom Clay*. OPERA-PU-TUD311.

Bremmer, C. (1996). *Kartering slecht-doorlatende laagpakketten Tertiaire formaties*. RGD GB 2514 (CORA15).

CORA, C. O. (2001). *Terugneembare berging, een begaanbaar pad?* Ministerie van Economische Zaken.

Dobrev, D., Stammose, D., Pellegrini, D., & Vokla, A. (2013). *Experimental Studies on Hydrogen Generation by Corrosion*. FORGE report D2.5-R.

Filby, A., Deissmann, G., & R., W. (2016). *LILW degradation processes and products*. OPERA-PU-IBR512.

Grupa, J. (2009). *Trial Of Formal Use Of Expert Judgement For Scenario Conceptualisation*. NRG-21952/09.97222 .

Grupa, J. (2014). *Report on the safety assessment methodology*. OPERA-PU-NRG2121.

Grupa, J., & Houkema, M. (2000). *Terughaalbare opberging van radioactief afval in diepe zout- en kleiformaties. Modellen voor een veiligheidsstudie*. NRG 21082/00.33017 (CORA04).

Grupa, J., Hart, J., & Wildenborg, T. (2017). *Description of relevant scenarios for the OPERA disposal concept*. OPERA-PU-NRG7111.

Grupa, J., Hart, J., & Wildenborg, T. (2017). *Scenario model representation - Part A: Main report*.

Grupa, J., Hart, J., Meeussen, H., Rosca-Bocancea, E., Sweeck, L., & Wildenborg, A. (2017). *Migration and uptake of radionuclides in the biosphere PA-model 'Biosphere'*. OPERA-PU-SCK631&NRG7232.

Grupa, J., Meeussen, J., Rosca-Bocancea, E., Buhmannn, D., Laggiard, E., & Wildenborg, A. (2017). *Migration of radionuclides in Boom Clay, PA model 'Clay'* . OPERA-PU-NRG7212.

Grupa, J., Meeussen, J., Rosca-Bocancea, E., Wildenborg, A., Buhmann, D., & Laggiard, E. (2017). *Migration in the formations surrounding the host rock - PA model 'Aquifer'* . OPERA-PU-GRS7222.

Hart, J. (2015). *Report on the determination of the inventory*.

Hart, J., Meeussen, J., & Grupa, J. (2015). *Reference set of model parameters for all scenarios* . OPERA-PU-NRG7122.

Meeussen, J., & Rosca-Bocancea, E. (2014). *Determination of the inventory: part B matrix composition*. OPERA-PU-NRG1112B.

OECD-NEA. (1999). *Nirex methodology for scenario and conceptual model development. An international peer review*. Paris: NEA Radioactive Waste Management.

ONDRAF/NIRAS. (2001). *SAFIR 2 - Safety Assessment and Feasibility Interim Report 2*. NIROND 2001–06 E.

Rijkers, R. (1998). *Inventarisatie eigenschappen van Tertiaire kleipakketten*. TNO NITG 98-90B (CORA16).

Rodwell, W. (1999). *Gas migration and two-phase flow through engineered and geological barriers for a deep repository for radioactive waste* . EUR 19122.

Rosca-Bocancea, E. S. (2017). Reference set of model paramters - Normal evolution scenario.

Rübel, A. (2004). *Konzeptioneller Umgang mit Gasen im Endlager*. GRS-205.

Schelland, M., Hart, J., Wildenborg, A., & Grupa, J. (2014). *OPERA FEP-database*. OPERA-PU-TNO2123A.

Schröder, T. H. (2017). *Report on model parameterization - Normal evolution scenario*.

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

Veen, J. t., & Dario, V. (2015). *Future evolution of the geological and geohydrological properties of the geosphere*. OPERA-PU-TNO412.

Verhoef, E., & Schröder, T. (2011). *Research Plan*. OPERA-PG-COV004.

Verhoef, E., Neeft, E., Deissmann, G., Filby, A., Wiegers, R., & Kers, D. (2016). *Waste families in OPERA*.

Verhoef, E., Neeft, E., Grupa, J., & Poley, A. (2011). *Outline of a disposal concept in clay*. OPERA-PG-COV008 .

Verweij, H., Nelskamp, S., Valstar, J., & Govaerts, J. (2016). *Definition of the future boundary conditions for the near-field model*. OPERA-PU-TNO421_2.

Wildenborg, A., Grupa, J., & Hart, J. (2017). *Scenario model representation Part B: FEP Decomposition*. OPERA-PU-TNO7121B.

Wildenborg, A., Orlic, B., & a.o. (2000). *Transport of radionuclides disposed of in clay (TRACTOR)*. TNO NITG 00-223-B (CORA19).

Wiseall, A., Graham, C., Zihms, S., Harrington, J., Cuss, R., Gregory, S., & Shaw, R. (2015). *Properties and Behaviour of the Boom Clay formation within a Dutch Repository Concept* . OPERA-PU-BGS615.

Appendix 1 OPERA Research Programme Results (excl. WP1&WP7)

Safety	
OPERA-PU-COV004	Research plan
OPERA-PU-COV014	Towards a safety strategy
Design	
OPERA-PG-COV008	Outline of disposal concept in clay
OPERA-PU-TUD311	Report on technical feasibility of a Dutch repository in Boom Clay
OPERA-PG-COV020	Cementitious materials in OPERA disposal concept in Boom Clay
OPERA-PG-COV023	Report on the waste families in OPERA
Geology	
OPERA-PU-TNO411	Report on geological and geohydrological characterization
OPERA-PU-TNO412	Report on the future evolution of the geosphere properties
OPERA-PU-TNO421-1	Report on the present boundary conditions for the near-field model
OPERA-PU-TNO421-2	Report on the future boundary conditions for the near-field model
EBS and host rock evolution	
OPERA-PU-IBR511A	Report on the dissolution behaviour of HLW glasses
OPERA-PU-IBR511B	Report on the corrosion behaviour of spent research reactor fuel
OPERA-PU-IBR512	LILW degradation processes and products
OPERA-PU-SCK513	Report on assessment of the corrosion behaviour of carbon steel waste packages
OPERA-PU-SCK514	Report on degradation processes of the cementitious EBS components
OPERA-PU-SCK515	Report on the geochemical performance of the EBS
OPERA-PU-UTR521	Report on the geochemical characterization of Boom Clay
OPERA-PU-TNO521-1	Report on mineralogical and geochemical characterization of Boom Clay
OPERA-PU-TNO521-2	Report on the composition of deep groundwater in the Netherlands
OPERA-PU-TNO521-3	Autonomous geochemical development of the Boom Clay: Literature review and modelling (draft available)
OPERA-PU-TNO522	Geochemical interactions and groundwater transport in the Rupel Clay. A generic model analysis. (draft available)
OPERA-PU-BGS523	Thermo-hydro-mechanical behaviour of Boom Clay (in preparation)
Radionuclide migration	
OPERA-PU-UTR611-1	Report on determining redox properties of clay-rich sedimentary deposits
OPERA-PU-NRG6121	Report on model representation of radionuclide sorption in Boom Clay
OPERA-PU-NRG6122	Reference database with sorption properties
OPERA-PU-NRG6123	Final report on radionuclide sorption in Boom Clay
OPERA-PU-NRG6131	Model representation of radionuclide diffusion in Boom Clay
OPERA-PU-NRG6132	Reference database with diffusion properties
OPERA-PU-SCK614	Presence and mobility of colloidal particles
OPERA-PU-BGS615	Properties and Behaviour of the Boom Clay Formation within a Dutch Repository
OPERA-PU-BGS616	Report on gas migration in the EBS and in Boom Clay (in preparation)
OPERA-PU-DLT621	Report on hydrological transport in the surrounding rock formations

Appendix 2 2015 IGSC Scenario Development Workshop

2015 IGSC Scenario Development Workshop
Issy-les-Moulineaux, France
1-3 June 2015

The scenario development process involves the collection and organisation of the important scientific and technical information necessary to assess the long-term performance or safety of radioactive waste disposal systems. The process involves the identification of the relevant features, events and processes (FEPs), the synthesis of broad models of scientific understanding, and the selection of cases to be calculation. Scenario development provides the overall framework in which the cases and their calculated consequences can be discussed, including biases or shortcomings due to omissions or lack of knowledge.

The NEA 1999 workshop on scenario development in Madrid had the objective of reviewing the development methodologies of scenarios and their applications. Since then, scenario development approaches used has evolved considerably. To reveal the latest methodologies for scenario development, the NEA Integration Group for the Safety Case (IGSC) organised a workshop in 2015 near Paris.

The objectives of the 2015 IGSC Scenario Development workshop were:

- To provide a forum to review and discuss methods for scenario development and its contribution to the development of recent safety cases (since 1999);
- To examine the latest methods and compare their scope, consistency and function within the overall safety assessment process, based on practical experience of applications;
- To provide a basis for producing a report summarising the current status of scenario methodologies, identifying where sufficient methods exist and any outstanding problem areas.

The proceedings have been published in March 2016 as NEA/RWM/R(2015)3 *Scenario Development Workshop Synopsis* and can be downloaded from www.oecd-nea.org.

Directly relevant to this work are the following quotes from Section 6.2 *Common features and differences in current approaches* of NEA/RWM/R(2015)3:

- *"All methods for scenario development also involve the use of FEP lists and/or FEP databases, which have become more comprehensive over time. These FEPs are screened to exclude those that are inapplicable to the disposal system at hand or are ruled out by regulations, as well as those that can be argued to have negligible impact and/or a very low likelihood of occurrence.*
- *The use of expert judgement, e.g. to assess the likelihood of occurrence of FEPs, is another feature of all scenario development methods, as well of other aspects of the safety case such as model development and data selection. Expert judgement can take a number of forms, including specialists working together on specific topics, panel discussions, and external peer review.*
- *In all cases, expert judgement implies that there is a degree of subjectivity in the decisions that are made.*
- *Thus, transparency and traceability of decisions made by expert judgement is of paramount importance. Formal, systematic methods are available that can be used to provide transparency and traceability in how the experts arrive at their judgements."*

and from Section 8. *Summary and conclusions*:

> *"Further development may be helpful in areas including communicating the role and choice of scenarios between experts within a waste-management programme and also to wider audiences;"*

Appendix 3 Expert elicitation reports

OPERA PA Scenario Representation (Task 7.1.2)
Expert elicitation report on FEPs related to with experts on waste and container behaviour in the OPERA disposal concept
11 March 2016, 14:00 to 15.30 CEST, (via Skype)
Interviewees: Guido Deissmann, André Filby (Brenk), Bruno Kursten (SCK.CEN)
Interviewers: Jacques Grupa (NRG); Ton Wildenborg (TNO)

Introduction
In Task 7.1.2 it is evaluated how the selected FEPs can be represented in the PA model concepts for the Normal Evolution Scenario, the various Alternative Evolution Scenarios and the what-if Assessment Cases.

The key objective of the expert elicitation is to arrive at *a common understanding of the representation of selected FEPs related to the behaviour of waste and containers in the PA modelling*, in order to gain an understanding of the relevance of the selected FEPs and to arrive at a practical representation of the FEPs in the PA modelling.

Prior to the meeting the PA-modellers forwarded a number of specific questions to the experts. Subsequently, a total of 11 FEPs were selected, 3 of which by the PA modellers, and an additional 8 by the experts (see also Table 4). The FEPs were discussed under the hood of 2 different themes:

Theme I: Container (+overpack) lifetime

- OPERA FEP 2.2.01 Containers
- OPERA FEP 2.2.02 Overpack
- OPERA FEP 2.3.03 Mechanical processes
- OPERA FEP 3.2.04 Chemical processes
- OPERA FEP C3 Corrosion – causes / processes
- OPERA FEP M1 Cracking

A) Discussion about the LILW containers and lifetime
B) Discussion about the OPERA HLW containers + overpack+ concrete shield + steel envelope (lifetime)

Theme II: Waste Matrix durability

- OPERA FEP 2.3.04.06 Dissolution (waste package)
- OPERA FEP 2.3.01.01 Radiogenic heat production and transfer (temperature in the SF section)
- OPERA FEP R1 Inventory/source term (amount of fissile material in research reactor fuels)
- OPERA FEP R5 Criticality (In-container criticality SF)
- OPERA FEP 2.3.4.05 Polymer degradation (2.3.4.05)

A) discussion about LILW waste:
  - Inventory/source term
  - Dissolution (waste package)
  - Polymer degradation (2.3.4.05)
  - Corrosion causes/processes

B) discussion about HLW

- 2.3.01.01 Radiogenic heat production and transfer (temperature in the SF section)
- R1 Inventory/source term (amount of fissile material in research reactor fuels)
- R5 Criticality (In-container criticality SF)
- Dissolution/leaching rates

Expert elicitation summary

Theme I: Container (+overpack) lifetime
A) Discussion about the LILW containers and lifetime

In the PA usually no credit is given to the containment provided by the LILW container. However, for the process studies in WP5 (as reported in OPERA-PU-IBR512) some estimates have been made.

Assuming uniform corrosion and oxic conditions, the corrosion rate of steel could be as high as 0.1 µm/year to 1 µm/year. Most LILW drums have a wall thickness of 1 mm: the container then would not fail within 100 years, but will certainly fail within 1000 years. The Konrad type drums have a wall thickness of 3 mm, and would fail in 300 to 3000 years. It is expected that within 10 years after closure, the disposal galleries will be saturated with water, and the chemical condition changes to anoxic. Corrosion rates in anoxic conditions are much lower.

One expert later added better estimates (taken from pages 98-99 of OPERA-PU-IBR512 and findings of Kursten 2015: the re-saturation should take place in one to five years. After that time, anoxic conditions can be expected. The data of Kursten 2015 which are cited in OPERA-PU-IBR512 give maximum values of the corrosion rate of carbon steel in oxic high alkaline environments of 2.2 µm/a (experts range). The maximum corrosion rate in anoxic, alkaline media is 0.2 µm/a (experts range; see OPERA-PU-IBR512. p. 99). Thus, the Konrad containers will fail at a far later point in time.

During the oxic conditions, pitting corrosion may occur due to the high chloride content of the pore water in the OPERA disposal concept. A container could fail within months if pitting corrosion occurs.

Mechanical integrity of the LILW containers under underground conditions has not been considered in OPERA. After closure, the pressure can increase to about 10 MPa (lithostatic pressure at 500 m depth), which will probably lead to mechanical failure of the LILW-canisters.

Figure 3 of the OPERA Research Plan suggests that the LILW must be confined for 100 years. It is unlikely that this confinement can be provided by the LILW canisters. It was suggested that this graph in figure 3 was intended for a surface disposal facility.

Theme I: Container (+overpack) lifetime
B) Discussion about the OPERA HLW containers + overpack+ concrete shield + steel envelope (lifetime)

All HLW and the high active fraction of the LILW will be disposed of in OPERA Supercontainers, which are similar to the NIRAS/ONDRAF Supercontainers.

The OPERA outline report gives the following provisional properties for the OPERA Supercontainer: The HLW canister is placed in an 3 cm carbon steel overpack, which is surrounded by 50 to 60 cm concrete, which is surrounded by a 4 mm stainless steel envelope.

In the Belgium concept, the concrete is saturated with water to 80% to ensure sufficient heat conduction.

The concrete passivates the carbon steel, which virtually does not corrode under these circumstances, leading to a container lifetime of at least 75 000 years.

Failure of the Supercontainer occurs in five stages:

1. Steel envelope is intact, the carbon steel is passivated by the concrete, virtually no corrosion.
2. Steel envelope has failed. Pore water with 'aggressive' species intrudes into the concrete. the concrete buffers the 'aggressive' species. The carbon steel remains passivated by the concrete, virtually no corrosion.
3. Concrete buffer becomes exhausted, aggressive species reach the carbon steel. the corrosion rate of the carbon steel increases to a value in the range of 0.1 μm/year to 1 μm/year. The overpack will not fail as long as the steel thickness is more than 14 mm - at 200 m depth. (See the discussion on mechanical integrity below.) This phase will last between 16000 and 160 000 years.
4. The overpack fails and the HLW container will start to corrode. The waste is still confined by the HLW container.
5. The HLW container has failed, radionuclide bearing species will leach from the waste and start migrating.

It is expected that the Supercontainer condition will gradually flow from one stage to the next, rather than as a sudden change in the system.

It is relevant that in the OPERA concept the clay pore water contains much more 'aggressive' species than in the Belgium reference concept, in particular much more chlorides. If the chloride reaches the steel overpack during the oxic stage, pitting corrosion may occur and the overpack may fail within months. This could occur as a result of leakage of the steel envelope, intrusion of chloride containing pore water from the clay, chloride is not buffered by the concrete Supercontainer, there is a sufficient amount of oxygen available for pitting corrosion of the overpack.

Mechanical structural integrity of the Supercontainer has not been treated in OPERA. For the Belgium concept, Belgatom(?) has performed mechanical analyses to show that the container can endure the underground pressure. In the OPERA design, the containers are disposed of at much larger depth and therefore the pressure is much larger. Mechanical integrity of the Supercontainer system at 500 m depth has still to be shown, and it is unclear whether 14 mm of steel can withstand the pressure at 500 m depth[b].

Theme II: Waste Matrix durability
A) discussion about LILW waste

In the PA no credit is given to (partial) immobilisation of radionuclides because of the waste and cement matrix. It is however important to determine the chemical form in which the radionuclides are released from the waste, since the absorption by the clay and solubility in the clay pore water depends on the species that carry the radionuclide. Degradation products of the cement, and organic material from the cement and the clay, will complex some of the radionuclide bearing species. In many cases these complexes are equally or less mobile than the original species. In some case the complex can be more mobile than the original species.

Cement and cement degradation products may adsorb anionic species better than the clay. Some of the degradation products are 'aggressive' to other parts of the EBS.
Organic material and metals in the LILW will be a source of gas.

Theme II: Waste Matrix durability
B) discussion about HLW

a) Spent fuel of research reactors.
There is not much known about the durability of Al-based spent fuel plates in cementitious and underground clay conditions. Generally, aluminium metal will corrode quickly under cementitious conditions under oxic and anoxic conditions. Under anoxic conditions H_2 gas is generated.

For the fission products in the fuel plates, an almost instantaneous release can be assumed. For Al-U alloys (HEU), it is expected that the U will precipitate as amorphous U-oxide. If there is a specific area in the disposal cell where precipitation preferentially occurs accumulation of U is possible, an criticality should be addressed. Amounts of U-235 in the wastes are not clear to experts.

b) other HLW
This waste is not addressed in OPERA WP5. Instantaneous release can be assumed. There is interest in:
1) the chemical form of the U in the U filters
2) C-14 from the caps and claddings (CAST)
c) vitrified waste
It is acceptable to assume congruent dissolution of the waste and glass. Glass dissolution rate depends on the glass surface evolution and pH. At extremely high pH (pH > 13) the

[b] Note by Jacques Grupa: In CORA 18, appendix B, it is estimated that a steel lining of 25.4 mm can endure the lithostatic pressure at 500 m depth of about 10 MPa with a safety factor of 1.7. Since engineering practise requires a minimum safety factor of 1.5, the minimum thickness of the steel lining at 500 m depth is 22.5 mm. At an initial thickness of 30 mm, and a maximum corrosion rate of 0.1 to 1 μm/year, the duration of stage 3 of the OPERA Supercontainer-evolution is at least 7500 to 75000 years.

glass dissolution rate may increase by a factor 10 to 1000. Species containing Ca and K may alter the dissolution rate.
Data will be published in OPERA-PU-IBR511A (vitrified waste) and OPERA-PU-IBR511B (spent fuel)

Evaluation of the expert elicitation
PA of the Normal Evolution:
All waste containers other than the OPERA Supercontainer can be assumed to fail immediately. All wastes other than vitrified waste will can be assumed to be released instanteneously.
The performance of the OPERA Supercontainer is inconclusive.
1. It would be helpful to set up an oxygen balance to evaluate the potential and probability of failure of the overpack because of pitting corrosion.
2. the uniform corrosion rate of the OPERA overpack in anoxic conditions is not clear
3. the mechanical integrity of the OPERA Supercontainer has not been addressed

Leaching of vitrified waste has been addressed.
1. the leaching occurs as a congruent dissolution process
2. glass dissolution is always slow, but there is a large uncertainty in the actual dissolution rate.
3. there are no processes identified, that will lead to a fast dissolution of the glass.

There is sufficient information to allow estimation of the bandwidth of adsorption and precipitation parameter values of the radionuclide bearing species in the clay.

With respect to the AES:
1. fast dissolution of all waste remains a what-if Assessment Case. For all wastes other than the vitrified waste this is the Normal Evolution. For vitrified waste, no processes have been identified that lead to very fast dissolution
2. criticality remains an issue
3. degradation products and gases from the LILW section may have an impact on the HLW section, but for such scenarios there are no story lines identified.

OPERA PA Scenario Representation (Task 7.1.2)
Expert elicitation report on FEPs related to with experts on mechanical behaviour of concrete and Boom Clay
5 November 2015, 12:00 to 15.00 CEST, at CITG, TU Delft
Interviewees: Phil Vardon - PV and Michael Hicks – MH (TUD); Rob Wiegers – RW (IBR)
Interviewers: Jacques Grupa – JG and Jaap Hart – JH (NRG); Ton Wildenborg – TW (TNO)

Introduction
In Task 7.1.2 it is evaluated how the selected FEPs can be represented in the PA model concepts for the Normal Evolution Scenario, the various Alternative Evolution Scenarios and the what-if Assessment Cases.
The key objective of the expert elicitation is to arrive at *a common understanding of the representation of selected FEPs related to the mechanical behaviour of concrete and Boom Clay in the PA modelling*, in order to gain an understanding of the relevance of the selected FEPs and to arrive at a practical representation of the FEPs in the PA modelling. Prior to the meeting the PA-modellers forwarded a number of specific questions to the experts. Subsequently, a total of 9 FEPs were selected, 4 of which by the PA modellers, and an additional 5 by the experts (see also Table 6). The FEPs were discussed under the hood of 4 different topics:

Topic 1: Can the system deal with elevated temperature effects? > Thermal effects
- T1 – Thermal evolution
- T2 – Thermal effects – physical/mechanical
- 2.3.01 Thermal processes (waste package)
- 3.2.06 Radiological processes (repository)

Topic 2: Can the system deal with gas generation and transport? > Gas effects
- C14 – Gas generation
- H12 – Gas transport
- M7 – Mechanical disturbance of components of the EBS

Topic 3: Can the system reduce water flow to acceptable levels? > Hydraulic effects
- H1 – Hydraulic properties
- D6 – Backfill/supports – dimensions and properties
- D9 – Host-rock EDZ – thickness and properties

Topic 4: Will stress changes cause issues? > Mechanical effects
- D9 – Host-rock EDZ – thickness and properties
- M2 – Creep
- M7 – Mechanical disturbance of components of the EBS.

Expert elicitation outcomes

<u>**Topic 1**</u>: Can the system deal with elevated temperature effects? > Thermal effects
The following FEPs are connected with this topic:

T1	Thermal evolution	THM	The variation in temperature with time and place in the EBS.	Temperatures within the EBS will vary as different heat sources (e.g. radioactive decay of waste elements, exothermic reactions, geothermal gradient) vary with time. Thermal evolution may affect mechanical, hydrological and chemical properties and processes - see related FEPs T2, T3 & H3.
T2	Thermal effects – physical / mechanical	THM	Differential thermal expansion and other changes in the physical characteristics of EBS components owing to the presence of time-varying thermal gradients within the EBS.	These effects could lead to changes in stress and potentially to cracking of EBS components or to the enhancement of pathways through the EDZ. Thermal effects on material properties (e.g. permeability, porosity) could also affect EBS evolution.

These items also relate to the following FEPs:

2.3.01	Thermal processes (waste package)	THM	2.3.01.01	Radiogenic heat production and transfer
3.2.06	Radiological processes (repository)	THM	3.2.06.05	Criticality

Boom Clay

- TUD has calculated a significant increase of the pore pressure in the Boom Clay following the temperature increase resulting from the heat output from the heat-generating waste containers but temperature increase is thought to be modest, max. 60 to 70 °C.
- This pore pressure increase lowers the effective stress and may cause mechanical damage, more specifically shear failure, in the Boom Clay at a large scale 10s of metres from the heat producing waste (see PRACLAY experiment). This observation imposes potential concerns for the long-term safety, and should be investigated further.
- The expansion of Boom Clay pore water may extend the EDZ and potentially cause preferential pathways to occur. Moreover, it is possible to increase radial stresses on the lining and cause collapse.
- A restriction to this observation is that for these preliminary scoping calculations TUD applied generic parameters for the Boom Clay Models which may not be best-estimate.
- Since this calculated phenomenon significantly depends on the temperature evolution in the Boom Clay, it is crucial to accurately describe the heat output from

the emplaced heat-generating waste containers, and the temperature development in the surrounding Boom Clay.

Concrete

- RW mentioned that elevated temperatures (i.e. the range above 60-80 ºC) may induce problems with concrete backfill: Due to the fact that the mechanical strength of concrete and other cementitious materials depends up to a high extend to the so-called cement stone (hardened cement) and this cement stone is for a large part CSH (calcium silicate hydrate) the thermal stability of the CSH is relevant in case of elevated temperatures.
- (RW:) Moreover, at temperatures of approx. 100-110 ºC the solubility of quartz is increasing and of $Ca(OH)_2$ is decreasing (the production of calcium silicate bricks is based on this phenomena). So, at elevated temperatures (> 100 ºC) several aspects have to be considered. One is the crystal structure of the CSH which can undergo transformation/re-crystallisation due to exposure to elevated temperatures and the re-crystalized CSH (e.g. from tobermorite to (maybe) traumasite) has different and not necessarily better properties.
- RW also mentioned that concrete would not suffer from temperature effects below 50 ºC. Additionally, cracks are practically inevitable in concrete.
- After some time saline fluids will intrude the repository; will this cause significant effects?
- Concrete hardening itself also produces some heat. It is however judged that this effect is negligible compared to the heat output from the waste containers.

- <u>In conclusion</u> it is judged that the increase of the Boom Clay pore pressure is the most significant process to occur as a result of heat output from the emplaced waste containers into the Boom Clay.

Topic 2: Can the system deal with gas generation and transport? > Gas effects

The following FEPs are connected with this topic:

C14	Gas generation	THM	Gas production within the EBS from corrosion and degradation of waste or EBS materials (e.g. H_2), microbial activity (e.g. CO_2, CH_4 and H_2S), and radiation effects (He from alpha decay and H_2 and O_2 from radiolysis).	Gas production may change local chemical and hydraulic conditions, and the mechanisms for radionuclide transport (i.e. gas-induced and gas-mediated transport).
H12	Gas transport	THM	Diffusion, advection, microbial activities, storage availability affect whether gases are reduced, dissolved, cause clay dilation etc. Different wastes and components will have different behaviours.	It is likely that the diffusive capacity will be exceeded.
M7	Mechanical disturbance of components of the EBS/Gas impact on stability	THM	Gas will pressurize components of the repository, e.g. pore pressures (or total stresses on the lining if well sealed).	

- Gas production may occur from corrosion and degradation of waste or EBS materials (e.g. H_2), microbial activity (e.g. CO_2, CH_4 and H_2S), and radiation effects (He from alpha decay and H_2 and O_2 from radiolysis). Some scoping calculations would be useful to understand the importance of these processes (see also BGS work and the H2020 MIND project).
- Gas production may change local chemical and hydraulic conditions, and the mechanisms for radionuclide transport (i.e. gas-induced and gas-mediated transport).
- Diffusion, advection, microbial activities, storage availability affect whether gases are reduced, dissolved, cause clay dilation etc.
- Gas, if generated in sufficient quantities, will pressurize components of the repository, e.g. pore pressures, or total stresses on the lining if well sealed.
- Gas, if generated in sufficient quantities, may potentially generate pathways in the EBS and/or Boom Clay, potentially resulting in enhanced radionuclide transport.
- Hydrogen, generated as a result of metal corrosion, may, when released in pore water, result in acidification of the pore water.
- On the other hand, concrete which is present as buffer and lining has a quite large buffering capacity, both chemically (e.g. pH buffering), and physically (gas buffering) due to its high porosity (approx. 40%).

- The system (EBS and host rock) must be able to absorb gas that is generated in the waste. In the normal evolution, parts of the EBS will be filled with gas, meaning that the water from pores and voids in the concrete will be pushed into the clay. The gas cannot enter the clay because of the high gas entry pressure of the clay, but the gases will gradually dissolve at the gas/clay-water interface.
- The question is whether gas pressures can equalize in the repository and what the mechanical effects would be. It is judged that due to the high air entry value, once the diffusive capacity is exceeded, pressures near the repository will increase. In SAFIR-2 gas generated by corrosion is transported by diffusion. More recent studies indicate that more gas is being produced than can be transported. On the other hand only a small proportion of RNs is volatile.
- In case of the formation of preferential pathways resulting from high gas pressures, gaseous nuclides can potentially move a large distance.
- In the vicinity of plugs and seals gas may bypass the plugs through any formed EDZ preferential pathway, e.g. around the outside of the bentonite backfill.
- Concerning the rates and amounts of gas generation, it is judged that gas generation from vitrified HLW containers will occur at a constant and slow rate as a result of corrosion induced by pore water. It this case H_2 is the main gas species.
- For LILW the uncertainties related to gas are larger: more and earlier gas production may occur, and additional gas species may be formed (H_2, CO_2, CH_4) compared to vitrified HLW. On the other hand the amount of volatile radionuclides present in LILW is less than in HLW.
- It is mentioned that the chemical buffering capacity of concrete is important in assessing the contribution of gas to the overall repository safety.

- <u>In conclusion</u>, it can be stated that gas may have a relatively small impact on the safety functions of the repository system – both chemically and physically, it may enhance the transport of volatile radionuclides, but its contribution to the overall transport of radionuclides is judged relatively small. An uncertainty in this respect is the gas generation rate, especially from LILW. Probably it is not an issue for HLW.

Topic 3: Can the system reduce water flow to acceptable levels? > Hydraulic effects

The following FEPs are connected with this topic:

H1	Hydraulic properties	THM	The hydraulic properties of the EBS and the EDZ, particularly hydraulic gradient, conductivity, porosity, permeability, and fracture properties.	The hydraulic properties will control groundwater flow.
D6	Backfill / supports - dimensions and properties	THM	The thickness and properties of backfill emplaced between the Supercontainer envelope and the tunnel lining. Must also consider the dimensions and properties of supports on which the Supercontainer is set.	Backfill properties affect the time for host rock porewaters to arrive at the surface of the Supercontainer and the importance of this pathway.
D9	Host-rock EDZ – thickness and properties	THM	That part of the host rock damaged by construction of the repository.	The extent of this excavation damage zone (EDZ) along tunnels and shafts will depend on the host rock and construction methods used. EDZ properties affect the rate of repository resaturation and radionuclide transport from the EBS to the host rock.

- Relevant hydraulic properties of the EBS and the EDZ are the hydraulic gradient, conductivity, porosity, permeability, and fracture properties.
- The hydraulic properties will control groundwater flow. However, groundwater flow will not be present/be very limited in a Boom Clay hosted repository due to the absence of driving forces. The travel time to the top of the host rock is estimated at 10 to 20 ka (e.g. for Iodine).
- Backfill properties affect the time for host rock pore water to arrive at the surface of the emplaced containers and the relevance of this pathway.
- The extent of the EDZ along tunnels and shafts will depend on the host rock and construction methods used. EDZ properties affect the rate of repository re-saturation and radionuclide transport from the EBS to the host rock.
- After closure the repository will be re-saturated in say five to fifty years. As a consequence of the influx of fluids the bentonite – if that material is going to be used - will swell resulting in a permeability which is lower than of the host rock. Influx might be reversed through gas pressurisation.
- One of the main safety functions of the EBS is to suppress water transport through the EBS, the EDZ and the host rock (i.e. the "near field"). The hydraulic properties of the EBS are therefore important aspects. They can be influenced by design; the overcut of the tunnel sections must be limited to the very minimum.
- Limited water flow may occur, with larger flows (albeit still limited) in the EDZ and in the backfilled repository galleries. Plugs and seals can be designed in such a way to limit any flow in the repository.

- It would be easier to build the repository by having ‘straight through’ tunneling. This would however require more plugs.
- Concerning the question discussion how large water flows would be “acceptable” inside a repository, it is judged that advective water flow rates should be smaller than diffusive flow rates.
- The question is whether advective flow will be possible at all, taking into account the lack of a hydraulic gradient. In principle, a (very small) hydraulic gradient may occur resulting from dynamic effects during glaciation periods. In the OPAP performance assessment glaciation is one of the scenarios under consideration.

- In conclusion, it can be stated that (advective) water flow will be of negligible importance in the EBS and the Boom Clay. Design measures like the placement of plugs and seals may even further reduce any suspected water flow. Only in case of dynamic forces on the repository system, e.g. resulting from glaciation, water flow might have a contribution to the overall transport rate, although it is judged small. No overall endangerment of the geological safety from the repository itself except maybe for the gas related FEPs.

Topic 4: Will stress changes cause issues? > Mechanical effects

The following FEPs are connected with this topic:

D9	Host-rock EDZ – thickness and properties	THM	That part of the host rock damaged by construction of the repository.	The extent of this excavation damage zone (EDZ) along tunnels and shafts will depend on the host rock and construction methods used. EDZ properties affect the rate of repository re-saturation and radionuclide transport from the EBS to the host rock.
M2	Creep	THM	Slow plastic deformation of solids in response to deviatoric stress.	For example, creep may occur in metals used in the Supercontainer overpack or envelope, or in the EDZ as a result of stress relief in the host rock arising from tunnel excavation.
M7	Mechanical effects	THM	Mechanical disturbance of components of the EBS.	The EBS could be mechanically disturbed by physico-chemical degradation of the buffer, external forces (e.g. tunnel roof or lining collapse, rock creep or faulting in near-field rock), volume increase of corrosion products, and/or the build-up of internal gas pressure. These disturbances could cause processes such as cracking, and movement of the overpack through the buffer.

- The extent of the EDZ along tunnels and shafts will depend on the host rock properties and construction methods used. EDZ properties affect the rate of repository re-saturation and radionuclide transport from the EBS to the host rock.

- Slow plastic deformation of solids in response to deviatoric stress may be relevant. For example, creep may occur in metals used in the Supercontainer overpack or envelope, or in the EDZ as a result of stress relief in the host rock arising from tunnel excavation. The question however is whether this effect would compromise the long-term safety.
- The EBS could be mechanically disturbed by physico-chemical degradation of the concrete buffer, external forces (e.g. tunnel roof or lining collapse, rock creep or faulting in near-field rock), volume increase of corrosion products, and/or the build-up of internal gas pressure. These disturbances could cause processes such as cracking, and movement of the overpack through the buffer.
- Stress evolution in the near and far field will cause properties to change. Creep will cause sealing of the EDZ, but also increases stresses on the tunnel lining. Additionally, creep can also impact the permeability further away from the local failure, following local tunnel collapses.
- It is judged that short-term effects of stress changes are quite well understood. However the long-term effects of altering stresses are less well understood. The short-term is in years to decades and long-term is in decades to centuries. The long-term effects are creep (mainly in the Boom Clay) and long term evolution of the engineered parts of the barrier, e.g. tunnel stiffness (from e.g. cracking concrete).
- Concerning the concrete parts of the EBS, it is apparent that cracks will always occur after some decades (30-50 years). The question is whether such cracks in the EBS would impact the long-term safety.

- <u>In conclusion</u>, it can be stated that stress changes will occur in the repository system following the excavations. It is judged that stress changes apply for the most part in the short term (several decades), and that the process understanding is quite well understood. Long-term stress changes (centuries, millennia) are less well understood, but the consequences on the long-term safety would be judged as relatively small since the dynamic processes following the excavations will have become extinct.

Appendix A Preliminary treatment of mechanical behaviour in scenario analysis (quoted from deliverable M7.1.1.1)

Normal Evolution Scenario

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

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 and the HLW for 1,000 years in the waste container.*

……

*The **far field** includes the formations outside the near field. Due to the disposed waste or repository materials, chemical and mechanical effects, and to a lesser extent thermal effects, might occur in the far field, but these should not significantly alter the characteristics of the far field.*

Fault Scenario

Site characterization must carefully screen for the presence of faults transecting the repository. 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, an existing non-detected fault may transect the repository and continue 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 in the fault zone compared to those of the undisturbed clay.

….

The mechanical disturbances that may accompany the formation of faults may influence the stable conditions normally present in the Boom Clay host rock.

Intensified glaciation scenario

Within the next 100 to 1,000 ka climatic deterioration is to be expected, leading to cooling, lowering of the seal level and permafrost formation, aspects of which will be included in the Normal Evolution Scenario. For the Normal Evolution Scenario it is assumed that mid-latitude ice sheets are formed but do not cover the repository area. The alternative evolution may be that cooling is accompanied by the formation of an ice sheet covering a larger part of the Netherlands. Mechanical and hydraulic effects connected with the ice sheet may influence the disposal system. Cooling and melt-water influx change the stability fields of dissolved and precipitated minerals. Deep subglacial valleys can be formed due to subglacial erosion.

Appendix B Pre-selected FEPs and questions about "Geomechanical behaviour", in relation to OPERA Performance Assessment

<u>**FEPs of interest (P Vardon and M Hicks)**</u>

*For discussion with the experts (5/11/2015 - TU Delft -room **2.62** in the CiTG building 12.00 - 15.00)*

Topic 1: Can the system deal with elevated temperature effects

T1	Thermal evolution	THM	The variation in temperature with time and place in the EBS.	Temperatures within the EBS will vary as different heat sources (e.g. radioactive decay of waste elements, exothermic reactions, geothermal gradient) vary with time. Thermal evolution may affect mechanical, hydrological and chemical properties and processes - see related FEPs T2, T3 & H3.
T2	Thermal effects – physical / mechanical	THM	Differential thermal expansion and other changes in the physical characteristics of EBS components owing to the presence of time-varying thermal gradients within the EBS.	These effects could lead to changes in stress and potentially to cracking of EBS components or to the enhancement of pathways through the EDZ. Thermal effects on material properties (e.g. permeability, porosity) could also affect EBS evolution.

Experts are convinced that (extremely) high temperatures exceeding 80°C can be avoided, with the exception of critical events. However, mechanical stability from pore pressure increases (due to temperature increase and expansion of the water, which cannot escape due to low pore pressures), is a potential problem.

This will extend the Excavation Damaged Zone (EDZ) and potentially cause preferential pathways to occur. Moreover, it is possible to increase radial stresses on the lining and cause collapse.

Experts think the timescales where this is most critical are within the first 50 years of operation.

Topic 2: Can the system deal with gas generation and transport?

C14	Gas generation	THM	Gas production within the EBS from corrosion and degradation of waste or EBS materials (e.g. H_2), microbial activity (e.g. CO_2, CH_4 and H_2S), and radiation effects (He from alpha decay and H_2 and O_2 from radiolysis).	Gas production may change local chemical and hydraulic conditions, and the mechanisms for radionuclide transport (i.e. gas-induced and gas-mediated transport).
H12	Gas transport	THM	Diffusion, advection, microbial activities, storage availability affect whether gases are reduced, dissolved, cause clay dilation etc. Different wastes and components will have different behaviours.	It is likely that the diffusive capacity will be exceeded.
M7	Gas impact on stability	THM	Gas will pressurize components of the repository, e.g. pore pressures (or total stresses on the lining if well sealed).	

The system must be able to remove gas that is generated in the waste. In the normal evolution, parts of the EBS will filled with gas (i.e. the water from pores and voids in the concrete will be pushed into the clay). The gas cannot enter the clay (because of the high gas entry pressure of the clay), but the gases will gradually dissolve at the gas/clay-water interface.

Can gas pressures equalize in the repository – and what are the mechanical effects. Due to the high air entry value, once the diffusive capacity is exceeded, pressures will increase. How will gas move after this point? Quickly/slowly, could radionuclides be ‘carried’ by gas. Preferential pathways can mean that a gas moves a large distance.

Topic 3: Can the system reduce water flow to acceptable levels?

H1	Hydraulic properties	THM	The hydraulic properties of the EBS and the EDZ, particularly hydraulic gradient, conductivity, porosity, permeability, and fracture properties.	The hydraulic properties will control groundwater flow.
D6	Backfill / supports - dimensions and properties	THM	The thickness and properties of backfill emplaced between the Supercontainer envelope and the tunnel lining. Must also consider the dimensions and properties of supports on which the Supercontainer is set.	Backfill properties affect the time for host rock porewaters to arrive at the surface of the Supercontainer and the importance of this pathway.
D9	Host-rock EDZ – thickness and properties	THM	That part of the host rock damaged by construction of the repository.	The extent of this excavation damage zone (EDZ) along tunnels and shafts will depend on the host rock and construction methods used. EDZ properties affect the rate of repository re-saturation and radionuclide transport from the EBS to the host rock.

One of the main safety functions of the EBS is to suppress water flows through the EBS, the EDZ and the host rock (i.e. the "near field"). The hydraulic properties of the EBS are crucial. Limited water flow will occur, with larger flows (albeit still limited) in the EDZ/EdZ and in the repository galleries. Plugs and seals can be designed in such a way to limit flow at various times in the repository lifetime.

It would be easier to build the repository by having ‘straight through’ tunneling. This would require more plugs.

A discussion could address:

. What flows remain acceptable?

. what would be the lifetime of the EBS system?

. can we distinguish natural processes that would take over from a gradual degrading EBS?

Topic 4: Will stress changes cause issues?

D9	Host-rock EDZ – thickness and properties	THM	That part of the host rock damaged by construction of the repository.	The extent of this excavation damage zone (EDZ) along tunnels and shafts will depend on the host rock and construction methods used. EDZ properties affect the rate of repository re-saturation and radionuclide transport from the EBS to the host rock.
M2	Creep	THM	Slow plastic deformation of solids in response to deviatoric stress.	For example, creep may occur in metals used in the Supercontainer overpack or envelope, or in the EDZ as a result of stress relief in the host rock arising from tunnel excavation.
M7	Mechanical effects	THM	Mechanical disturbance of components of the EBS.	The EBS could be mechanically disturbed by physico-chemical degradation of the buffer, external forces (e.g. tunnel roof or lining collapse, rock creep or faulting in near-field rock), volume increase of corrosion products, and/or the build-up of internal gas pressure. These disturbances could cause processes such as cracking, and movement of the overpack through the buffer.

Stress evolution in the near and far field will cause properties to change. Creep will cause sealing of EDZ/EdZ, but also increases in stresses on the tunnel lining. Creep can also mean that local tunnel collapses could cause impact to permeability further away from the local failure.

OPERA PA Scenario Representation (Task 7.1.2)
Report of expert elicitation with experts on FEPs related to geochemical behaviour of Boom Clay
20 October 2015 10:00-12:30: TNO Princetonlaan 6, Utrecht
Interviewees: Thilo Behrends (UU); Jasper Griffioen (TNO); Hans Meeussen (NRG)
Interviewers: Jacques Grupa and Jaap Hart (NRG); Ton Wildenborg (TNO)

Introduction

In Task 7.1.2 it is evaluated how the selected FEPs can be represented in the PA model concepts for the Normal Evolution Scenario, the various Alternative Evolution Scenarios and the what-if Assessment Cases.

The key objective of the expert elicitation is to arrive at *a common understanding of the representation of selected FEPs related to the geochemical behaviour of Boom Clay in the PA modelling*, in order to gain an understanding of the relevance of the selected FEPs and to arrive at a practical representation of the FEPs in the PA modelling.

Prior to the meeting the PA-modellers forwarded a number of specific questions to the experts with a list of 27 preselected FEPs that may need treatment in the expert elicitations (see table *Pre-selected FEPs* at the end of this expert elicitation report). After iterations with the experts, a total of 9 FEPs were selected for discussion. In addition one extra item was added by one of the experts related to changes or gradients in salinity and their effect on permeability, osmosis, coupled flow etc. (see table below).

Shortlist with selected chemical FEPs		19-10-2015				
				JG	TB	HM
2.3.07	Gas generation (waste package) (2.1.12)	2.3.07.02	Organic degradation (waste package)			
2.3.07	Gas generation (waste package) (2.1.12)	2.3.07.06	Gas dissolution (waste package)			
3.2.04	Chemical processes (repository) (2.1.09)	3.2.04.02	Redox conditions (repository)			
3.2.04	Chemical processes (repository) (2.1.09)	3.3.02.05	Speciation and solubility (repository) (3.2.02)			
4.3.02	Water-mediated transport (geosphere) (3.2.07)	4.3.02.06	Speciation and solubility (geosphere) (3.2.02)		~sal	
4.3.02	Water-mediated transport (geosphere) (3.2.07)	4.3.02.07	Sorption and desorption (geosphere) (3.2.03)			
4.3.02	Water-mediated transport (geosphere) (3.2.07)	4.3.02.09	Colloid transport (geosphere) (3.2.04)			
4.1.09	Current geochemical state (2.2.08)		Geosphere; Changes relate to possible current geochemical disequilibrium state, future changes in p, T, Eh and pH conditions due to climate change and repository construction and waste emplacement		~sal	
4.2.04	Geochemical processes (geosphere) (2.2.08)		Effects of repository, climate change, ...			
x.x.xx	Salinity change/gradients (added by Thilo Behrends)		Permeability, osmosis, coupled flow, density-driven flow & RN speciation			

The FEPs were discussed under the hood of 5 topics:

1. General FEP approach
2. Gas generation and gas dissolution
3. Chemical processes: redox condition, speciation and solubility
4. Water mediated transport
5. Geochemical changes

Expert elicitation outcomes

Topic 1. General FEP approach

One of the experts is of the opinion that the (safety function based) FEP method applied in OPERA is not intuitively understandable. As an alternative he suggested to evaluate FEPs as follows:

1. describe intuitively how the disposal system works specified for the various barriers and related safety functions
2. evaluate FEPs in two classes:

-- a. FEPs that support the function of the disposal system

-- b. FEPs that threaten the function of the disposal system

Comment from the PA-expert: This is actually what we have done by evaluating the impact of the FEPs on the safety functions. However, it should be recognised that the safety functions also need to be understood in other scenarios than the Normal Evolution Scenario, and the impact of the FEPs must also be evaluated in the context of these other scenarios.

The method we have applied does not focus on those FEPs that support the safety function,

Topic 2. Gas generation and gas dissolution

FEP 2.3.07.02 Organic degradation (2.3.07 Gas generation)

Gas can be generated by the degradation of organic material like paper in the LLW and ILW. The gaseous and non-gaseous degradation products are often smaller organic molecules CO_2, H_2, CH_4, and complex organic substances that can affect the mobility of radionuclides. Microbial activity is necessary for organic material to deteriorate.

Comment from the PA-expert: Regarding the production of non-gaseous dissolved organic material, this may be relevant for clays that have a low natural amount of organic material. Boom clay contains a high amount of organic material. The effect of extra dissolved organic material is covered by the considered uncertainty bandwidth of the natural dissolved organic material content of the Boom clay. Quantitative estimates of products from organic degradation with large uncertainties are available.

Could gas pressure lead to "fracking" as used in shale gas production?

FEP 2.3.07.06 Gas dissolution (2.3.07 Gas generation)

Comment from the PA-expert: After fracking, the rock containing the shale gases contains large fractures (aperture in the order of 1 cm), allowing production of the shale gas. The expert elicitation with the gas experts reveals that as a result of the gas pressure micro-fractures may be formed in the Boom Clay, and that there is no evidence to suggest that features would coalesce into one or more 'large' fractures which then interact with the continuum stress field. Dilating processes create microscopic pathways with self-sealing properties and may occur already at pressures below the lithostatic pressure. One even observes a hardening effect as the pressure often needs to be higher with the next gas pressure pulse. In that sense in Boom Clay these dilating processes do not create a preferential pathway for future RN groundwater transport.

Gas production leads to pressure build up which could induce fracturing. Effects of deformation have been studied in experiments at Mol; BGS did some scoping calculations in OPERA (Jon Harrington).

Production and dissolution of organic acids increases RN mobility.

Topic 3. Chemical processes: redox condition, speciation and solubility

FEP 3.2.04.02 Redox conditions (3.2.04 Chemical processes)

What happens if large amounts of UO_x enter the clay?

- ➔ Dependent on porewater composition, presence of sulphides/sulphate and effect on pH which determines solubility of Si-oxides (glass dissolution rate).
- ➔ Is there a solubility limit for the concentration of dissolved UO_x in the EBS and/or the clay? Cement has an immobilizing effect on Uranium.
- ➔ High pH generally reduces anaerobic corrosion rates.

Mixing of materials from different waste compartments may affect the EBS and the near field.

The materials in the EBS cause a CDZ (chemically disturbed zone) in the clay. Can the EDZ increase the size of the CDZ, compared to considering 'chemical diffusion' only?
Comment from the PA-expert: It is expected that the EDZ will heal quickly once the gallery support is constructed, or after the galleries have been backfilled (i.e. once the dilatant stress field component has reduced to zero). Experts judge that the healed EDZ is not a preferential flow pathway for water, but may be a preferential flow path for gases, i.e. a healed EDZ may be less resistant to microcracking than undisturbed clay. Therefore, it is expected that the size of the CDZ is determined by diffusion, and not by the size of the EDZ.

The intrusion depth of oxygen from the galleries into the clay is very limited because the oxygen rapidly reacts with the pyrite in the Boom clay. During operational phase oxidation of pyrite in the Boom Clay may occur via dilatation fractures. It is important to know the dimensions of the plastic deformation. Effects depend also on the concentrations of limestone influencing pH and pyrite. After closure anaerobic conditions will prevail. Will this always be the case?

FEP 4.3.02.07 Sorption and desorption (4.3.02 Water-mediated transport)

Some clays have small Ca-content, and will not buffer the pH.

Iodine may react with calcium (lime) causing retardation and maybe irreversible retention.

Topic 4. Water mediated transport

FEP 4.3.02.09 Colloid transport (4.3.02 Water-mediated transport)

Colloids: there are two definitions:

1: A colloid, in chemistry, is a mixture in which one substance of microscopically dispersed insoluble particles is suspended throughout another substance.

2: Colloids are particles in the nanometre to micrometre size range which can form stable suspensions in a liquid phase.

Most colloid particles are practically not mobile, but a small fraction of the colloid particles can be mobile and act as a carrier of nuclides that are immobile in the absence of these colloids.

For advection conditions, colloids can be assumed to travel at the same rate as water and dissolved ions. For diffusion conditions, colloids diffuse/migrate much slower than free ions, mainly because the diffusion coefficient of colloids is smaller than the diffusion coefficient of free ions (because of their size) and (to a lesser extent) because the colloid accessible pore volume is smaller than the free ion accessible pore volume.

The mobility of radionuclides that strongly adsorb to these colloids will not become larger than the mobility of these colloids. Attention should be given to glaciation and the glacial valley scenario, where the salinity of the groundwater changes, which changes the geochemical properties of the clay.

Permeability of the clay depends on the salinity. At higher salt concentrations diffuse double layers of clay become thinner and clay becomes more porous.
Osmotic effects during a transition could increase migration.

Topic 5. Geochemical changes

Geochemical changes can be caused by glacial valleys and permafrost. The reaction zone will normally be limited to a few dm; deeper penetration is not likely. Effects might be stronger when a deep subglacial channel is in direct contact with the Boom Clay. During glaciations one may expect changes in salinity due to influx of glacial meltwater.

Most geochemical systems are in a metastable equilibrium because the system contains chemical buffers which can become exhausted.
However the rate of change for most processes is determined by diffusion of chemical substances (alkalinity, salt, acidity, oxygen etc.). These diffusion rates are very low for Boom clay systems.
Boom clay is reduced and buffers against oxidising conditions. A salinity front may cause geochemical changes.
Salinity front should be added as a FEP. (However, the salinity front will not move faster than conservative mobile trace elements, so the maximum rate of change will be slow).
Comment PA-expert: Now geochemical changes are is only implicitly accounted for in FEP 4.1.09 Current geochemical state (2.2.08) and 4.2.04 Geochemical processes (geosphere); Geochemical effects of climate change (geosphere).

Particular attention should be directed to transient situations, e.g. changes in salinity, from fresh water to brine and vv. And their effect on RN speciation colloid transport and sorption, osmosis, permeability, osmosis, coupled flow, density-driven flow. Further analysis is necessary to identify situations where non-equilibrium is of importance. These non-equilibrium situations are represented in the range of the retardation factor. The question then is whether this range is always representative.

Pre-selected FEPs

List of FEPs preselected by the PA-modellers

4.3.02	Water-mediated transport (geosphere) (3.2.07)	C	4.3.02.06	Speciation and solubility (geosphere) (3.2.02)
4.3.02	Water-mediated transport (geosphere) (3.2.07)	C	4.3.02.07	Sorption and desorption (geosphere) (3.2.03)
4.3.02	Water-mediated transport (geosphere) (3.2.07)	C	4.3.02.08	Complexation (geosphere) (3.2.05)
4.3.02	Water-mediated transport (geosphere) (3.2.07)	C	4.3.02.09	Colloid transport (geosphere) (3.2.04)
4.3.02	Water-mediated transport (geosphere) (3.2.07)	C	4.3.02.05	(3.2.01)
2.3.04	Chemical processes (waste package) (2.1.09)	C	2.3.04.04	Corrosion (waste package)
3.2.04	Chemical processes (repository) (2.1.09)	C	3.2.04.01	pH conditions (repository)
3.2.04	Chemical processes (repository) (2.1.09)	C	3.2.04.02	Redox conditions (repository)
3.2.04	Chemical processes (repository) (2.1.09)	C	3.2.04.06	Mineralisation (repository)
3.2.04	Chemical processes (repository) (2.1.09)	C	3.2.04.07	Precipitation reactions (repository)
3.2.04	Chemical processes (repository) (2.1.09)	C	3.3.02.04	(3.2.01)
3.2.04	Chemical processes (repository) (2.1.09)	C	3.3.02.05	Speciation and solubility (repository) (3.2.02)
3.2.04	Chemical processes (repository) (2.1.09)	C	3.3.02.07	Complexation (repository) (3.2.05)
3.3.05	Human-action-mediated transport (repository) (3.2.	C		
4.1.09	Current geochemical state (2.2.08)	C		disequilibrium state, future changes in p, T, Eh and pH
4.2.04	Geochemical processes (geosphere) (2.2.08)	C		Effects of repository, climate change, ...
2.3.07	Gas generation (waste package) (2.1.12)	C	2.3.07.01	Metal corrosion (waste package)
2.3.07	Gas generation (waste package) (2.1.12)	C	2.3.07.02	Organic degradation (waste package)
2.3.07	Gas generation (waste package) (2.1.12)	C	2.3.07.06	Gas dissolution (waste package)
2.3.07	Gas generation (waste package) (2.1.12)	C	2.4.01.02	Dissolution (waste form) (3.2.01)
2.3.07	Gas generation (waste package) (2.1.12)	C	2.4.01.04	Speciation and solubility (waste form) (3.2.02)
3.2.03	Mechanical processes (repository) (2.1.07)	C	3.2.06.05	Criticality (2.1.14)
3.2.04	Chemical processes (repository) (2.1.09)	C	3.3.02.06	Sorption and desorption (repository) (3.2.03)
3.2.04	Chemical processes (repository) (2.1.09)	C	3.3.02.08	Colloid transport (repository) (3.2.04)
4.1.06	Current geothermal state (2.2.10)	C		Geosphere

OPERA PA Scenario representation (Task 7.1.2)
Expert elicitation report on Gas-related FEPs with BGS experts
22 July 2015, 10.30 to 12.20 CEST
Interviewees: Richard Shaw and Jon Harrington (BGS)
Interviewers: Jaap Hart (NRG) and Ton Wildenborg (TNO)

Introduction

In Task 7.1.2 it is evaluated how the selected FEPs can be represented in the PA model concepts for the Normal Evolution Scenario, the various Alternative Evolution Scenarios and the what-if Assessment Cases. To date two Assessment Cases have been identified with relevance for gas generation and migration, which are the NES Assessment Case N3 Gas pressure build-up case (normal range) and the what-if Assessment Case EGC1 Excessive gas generation (see *Preliminary treatment of gas generation and migration in scenario analysis* at the end of this elicitation report).

The key objective of the expert elicitation is to arrive at *a common understanding of the representation of the selected gas-related FEPs in the PA modelling*. This can be split in two parts: to gain an understanding of the relevance of the FEPs and to propose a practical representation of the FEPs in the PA modelling. A number of specific questions for the experts were defined (Appendix B, p. 101).

In total 10 FEPs were selected, 6 of which by the experts and 4 of which (between brackets) by the PA-experts:

Waste package

- (2.3.07.01 Metal corrosion (waste package))
- (2.3.07.07 Gas-induced failure)

Repository

- 3.2.07.08 Gas-induced dilation (repository)
- (3.3.03 Gas-mediated transport (repository))

EBS

- 11 Gas flow and transport
- 12 Gas-induced flow and transport
- 14 Preferential pathways
- (6 Corrosion – gases)

Geosphere

- 4.2.07.05 Gas-induced dilation (geosphere)
- 4.3.03 Gas-mediated transport (geosphere)

Expert elicitation outcomes
Richard Shaw was the coordinator of the FORGE project and has 24 years of experience in UK (and European) RWM programmes.
Jon Harrington works in radioactive waste management since 1992 and is a specialist in multi-phase flow and associated hydromechanical coupling in low-permeability media.

Waste package

- *(2.3.07.01 Metal corrosion (waste package))*
- *(2.3.07.07 Gas-induced failure)*

EBS

- *(6 Corrosion – gases)*

In analysing gas generation one should distinguish between the various waste streams. LLW and ILW hold a lot of biodegradable cellulosic material (e.g. paper, cotton, ….) which can result in significant volumes of CH_4 and CO_2 in the first millennia after disposal. Gas production because of bioprocesses result for a big part in the formation of methane. This process occurs relatively quickly, i.e. within hundreds to ~1000 years after disposal, and may result in a “gas pulse”.

HLW in contrast will potentially generate far less gas: anaerobic metal corrosion (and smaller contribution by radiolysis which is dissociation of molecules by ionising radiation) will be the main source of gas (H_2) after the Supercontainer has degraded in thousands to 10,000 years. Bacterial interaction may transform H_2 into CH_4. This is especially the case if a source of carbon is present, which includes calcium carbonate.

Gas production by ***radiolysis*** is significantly smaller than by metal corrosion and organic biodegradation, although this needs to be confirmed for the OPERA waste inventory. Considering that, radiolysis may be insignificant in OPERA due to shielding by the concrete Supercontainer, unless water reaches the surface of the SF+HLW waste containers.

Metal corrosion and associated H_2 generation are fairly well understood. One of the FORGE reports addresses these topics: FORGE 2.5-R “*Synthesis of experimental processes governing gas generation*”. Rates of corrosion are well established with generally high initial rates which drop off later on (see also OPERA Tasks 5.1.1 to 5.1.5). Release of C-14 comes from activated steel and is in the form of methane and CO_2. C-14 is the topic of the EC project CAST. Also in the UK there is a specific C-14 project going on. In the Dutch waste C-14 is almost solely present in SF from the research reactors, and in vitrified HLW residues (CSD-C containers).

Although the fraction of biodegradable material in LLW/ILW is high, the degradation will be determined by the availability of water in the Boom Clay which is expected to be low.

Repository

- *3.2.07.08 Gas-induced dilation (repository)*
- *(3.3.03 Gas-mediated transport (repository))*

EBS

- *11 Gas flow and transport*
- *12 Gas-induced flow and transport*
- *14 Preferential pathways*

Current French research work is examining the impact of gas on their repository. Management and mitigation will be dependent on the predicted impact of the gas. The UK policy is trying to manage this gas pulse by venting of LILW containers. This also implies that water ingression would be possible. Accommodating a gas pulse by any mitigating measure, such as dispersion within the repository volume depends on several issues e.g. permeability of Boom Clay versus engineered barriers (seals, plugs). Accessible voidage within the repository into which the gas can flow and accumulate will also impact the rate of gas pressure build-up. Excessive gas generation may be mitigated to some extent by designing a "co-located" repository, where separate sections for different types of waste share e.g. the same shafts/entries, but are located several kilometres away from each other. This does not necessarily mitigate the generation of gas but can help manage its impact.

'Leaky' galleries and plugs/seals may be an effective way of dispersing generated gases and allowing this dissolution and dilution while not potentially leading to development of a free gas pathway providing a direct route to the biosphere.

After closure of repository volumes (e.g. disposal galleries) any trapped air inside will partly be consumed in the corrosion process (O_2), and partly dissolve into Boom Clay pore water (N_2).

Geosphere

- *4.2.07.05 Gas-induced dilation (geosphere)*
- *4.3.03 Gas-mediated transport (geosphere)*

Gas entry pressure for Boom Clay: a rough estimation is that about 1-2 MPa (depending on orientation of the clay) in excess of the pore pressure can result in gas entry at a depth of 220m. At greater depths (~500m) excess gas breakthrough pressures increase. Measurements by BGS indicated peak pressure is sensitive to the state of stress. Latest unpublished data which will be reported back to Covra at the end of 2017, suggest gas entry in longer samples occurs at higher pressures close to lithostatic stress. Compare for the Dutch disposal concept in Boom Clay at 500 m depth: pore water pressure is about 5 MPa and confining pressure about 10 MPa; therefore actual gas breakthrough pressures likely to be around 7.5 to 8.5 MPa.

The "peak pressure" largely depends on the gas production rate. It would be interesting to distinguish between slow versus fast gas production rate. This has been explored in EBS tests on compact bentonite but little data exists for Boom Clay.

As a result of the gas pressure micro-fractures may be formed in the Clay, though there is no evidence to suggest features coalesce into one or more 'large' fractures which then interact with the continuum stress field. However, the complex interaction of the gas with the stress field on all scales remains unclear, as do the number, distribution and aperture functions of the resulting pathways. Additional work is required to assess the role of dilatancy in a Boom Clay hosted repository at depths considered in the Dutch disposal concept.

Dilating processes create microscopic pathways with self-sealing properties and may occur already at pressures below the lithostatic pressure. One even observes a hardening effect as the steady state pressure often needs to be higher with the next gas pressure pulse. In that sense it is not creating a preferential pathway for future radionuclide (RN) groundwater transport. The “dilation effect” seems significant in Boom Clay at 500 m depth. As it is coupled with the local stress field, and since it is a dynamic process, it is still complicated to understand and to model under in-situ conditions. After a “gas pulse”, which has to be confirmed for the OPERA disposal concept, rock properties may have changed. However, the effects on the Boom Clay permeability would be limited as gas pockets can serve as a blockage for water flow and diffusion (in pore water). Considering the previous point, from a PA-perspective it would not be necessary to model two separate parallel paths for RN diffusion (pore water) and gas-induced flow as the accessible porosity may change between pre- and post-gas injection samples as may the fabric. However, the degree of any change remains unclear.

From (only a few) experiments (performed by SCK on iodine), it appears that RN-migration by gas transport is probably limited compared to diffusive transport in pore water due to the fact that gas flow is strongly localized. However, the localisation of flow may result in greater transport distances of a small amount of RNs as flux may be concentrated through a small number of pathways. Modelling is required to confirm or reject this hypothesis. Gas-driven transport would only be applicable if the pathways are there, but this gas flow would be localized.

Concluding on gas migration in OPERA PA

Depending on geology (control of groundwater availability) and gas generation rates it is possible that a gas phase may form even in a 'normal' case (and certainly in the 'Excessive gas' case) dilatant pathways and their longevity may be locally important.

Since the last 15 years there is now quite a body of evidence for gas migration through dilatant pathways which partially can re-seal after episodic gas pulse flow. Subsequent gas flow events may develop new pathways or follow previous ones. Modelling is difficult and bulk porous models for bulk flows may be adequate *but this would need to be confirmed for each scenario/case/FEP*. Organisations who model gas in the repository use continuum flow codes based on two-phase flow concepts, assigning parameters for each component of the repository (e.g. EDZ, seals, host rock etc.). The applicability of such approaches to dilatant flow (if present) is however open to question. Experimental data indicate that gas entry into Boom Clay occurs at gas pressures below lithostatic pressure.

It is recommended to model gas-related topics in the OPERA PA. Previously, this was ignored from PA, mainly because a lack of process understanding. Nowadays, processes are better understood, and “Gas” is becoming more and more important.

It is not the intention of BGS’s project to explicitly model gas-related issues for the PA model. The BGS report intends to compare migration models: Two modelling approaches are briefly mentioned in the text. There are merits and weaknesses with each. At this stage it is not known if any constitutive model exists that is able to represent the time-dependent formation, propagation and distribution of dilatant pathways within clay/mudrock. Additional data is required on the coupling of gas flow to the fabric, mineralogy, stress field etc.

Episodic gas flow and diffusion needs to be assessed in future research as these are possible sinks for the generated gas. In an analysis of corrosion and radiolysis rates a first assessment of gas volumes can be calculated and from an estimate of the percentage of gas that can be accommodated and the pressure build-up can be computed.

<u>NES N3 Assessment Case and what-if EGS1 Assessment Case</u>
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)*.

Excessive gas generation may happen under the assumptions of maximal biodegradation and metal corrosion, and sufficient water availability, and result in an <u>early</u> gas pulse. However, for Boom Clay the assumption of *sufficient water availability* is perhaps overly conservative, since water in Boom Clay is less-mobile.

Considering the complex coupled processes in the case of excessive gas generation, this "What-If" case may not be simulated in the present OPERA Programme. Additional testing and modelling efforts would be needed for a better understanding.

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 compounds and/or between these compounds and the ambient materials (Boom Clay, pore water).

It is at present not clear if 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, although this has not been demonstrated. Therefore it has been proposed to study the effects of excessive gas generation in a What-If Case.

<u>Preliminary treatment of gas generation and migration in scenario analysis</u>

<u>Normal Evolution Scenario</u>
Near field serves "*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.*"

<u>"FEP 2.3.07.07 Gas-induced failure</u>
Has the FEP an effect on a safety function?
Yes, it can negatively affect the 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.

Motivation
Large amounts of gas can be produced from metal and organic materials in the LLW and ILW sections of the disposal system. Small and medium amounts of gas can be removed from the disposal system by dissolution of the gas in the pore water and subsequent diffusion. Larger amounts of gas will lead to high gas pressures in the disposal facility. If the gas pressure reaches a critical pressure, the gas will be able to enter and widen pores

in the clay. There are observations that this "slug" flow does not impair the clay permeability, i.e. the clay recovers from it after the gas has been removed and the pressure has decreased. However, the observations are from relatively small scale experiments, so to which extent this applies to repository size phenomena is uncertain. Therefore, the expert judgment is to consider this FEP is considered in a What-If Case.

Gas Assessment Case
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. Excessive gas generation and excessive gas effects can be treated this case.

It is not clear if these excessive effects actually disturb the Normal Evolution Scenario, since the clay seems capable of parsing the gas without losing its safety functions, although this has not been fully demonstrated. Therefore it has been proposed to study the case in a what-if scenario: what happens if excessive amounts of gas are produced in the facility?

What-If Case
EGC1 Excessive Gas Assessment Case

Questions about "Gas", in relation to OPERA Performance Assessment
J. Hart, 21 July 2015
Production of gas
Processes involved in the production of gas (SAFIR-2, Section 11.3.6.5.2

- Biodegradation; The gases produced by anaerobic respiration are mainly CO_2 and CH_4
  + Conversion of hydrogen by methane forming bacteria

- Radiolysis

- Anaerobic corrosion of metals

[Q] What production rates can we expect for respectively (1) Biodegradation vs (2) radiolysis vs (2) anaerobic corrosion of metals?
NOTE: Radiolysis may be insignificant (shielding by Supercontainer)
[Q] Build-up of pressure? How large can gas pressures become? In the disposal galleries, the transport galleries? (Dilation?)
[Q] Reactivity of H_2? Does this counteract the H_2 production rate due to corrosion?
[Q] What about the existing volume of air, trapped inside the repository? What happens with that (significant?) volume after closure?
[Q] What can justify an "Excessive gas generation" scenario? (One of the identified scenarios)

Transport of gas
[Q] Preferential migration pathways: would they be created when the gas pressure exceeds the lithostatic pressure locally?
(OPERA TUD-311, p.162): *For a tunnel located at 500m depth the total in situ stresses in the horizontal and vertical directions are set to* $\sigma_{h,0} = \sigma_{v,0} =$ ***10*** *MPa and the in situ pore water pressure is set to* $u_{w,0} =$ ***5*** *MPa.*
[Q] How significant is the "dilation" effect at a depth of 500 m in Boom Clay
[Q] How far would the dilatant pathways extend away from the repository into the clay, if they occur?
[Q] How do dilatant pathways affect the radionuclide transport?

Effects of Engineered Barriers
Gas transport through interfaces - **FORGE D1.5R**, Sect. 3.4.2.5, and Sect. 4.3.3 (Interfaces with the EBS) >> <u>preferential pathways</u> (FORGE D1.5R; p.70)
[Q] Is it necessary/feasible/relevant to model gas transport through interfaces (EBS/EDZ)? How important/relevant is this phenomenon?

Gas in Boom Clay
SAFIR-2 Section 11.3.6.5 Formation and transport of gas

- The chemical reaction between hydrogen and Boom Clay can consume 3 µg H_2/g for fresh clay and 30 µg H_2/g for oxidized clay;

- In several experiments it appeared that in the Boom Clay hydrogen was converted into methane; this reduces strongly the generated gas volume.

[Q] Is part of the generated H_2 taken up by Boom Clay? What fraction dissolves/diffuses compared to the H_2 generation rate? Model it by Henry's law? (PAM321, Sect.2.2.2)
[Q] Is there pore water displacement to be expected in Boom Clay at a depth of 500 m? (ONDRAF/NIRAS RD&D Plan, p.174: minimal displacement (<1%)
[Q] Can we expect two-phase flow conditions in Boom Clay, considering the 500 m depth? (see e.g. PAM321, Sect. 2.2.3)

Modelling
(see also e.g. SAFIR-2 Section 11.3.6.5.4.2 Modelling)
[Q] Is it necessary (from PA perspective) to model the cyclicity of opening and closing the preferential pathways?
[Q] If yes, how to model the cyclicity of opening and closing the preferential pathways?
[Q] How far extend the preferential pathways into the clay, if they happen – at a depth of 500 m?
[Q] How to model dilatant pathways? Consideration of alternate porosity/permeability distribution in these pathways?

(The "moral question"):
[Q] Is it necessary/relevant (from OPERA PA perspective) to model "Gas"?

<u>R.Shaw (comment in FEP list):</u>
There is now quite a body of evidence for gas migration through dilatant pathways which can re-seal after episodic gas pulse flow. Subsequent gas flow events may develop new pathways or follow previous ones. Modelling is difficult and bulk porous models for bulk flows may be adequate but this would need to be confirmed for each scenario/case/FEP. Experimental data from 220m depth indicate that gas entry into Boom Clay occurs at gas pressures below lithostatic pressure. Gas entry pressures will increase with depth. Latest unpublished data which will be reported back to Covra at the end of 2017, suggest gas entry in longer samples occurs at pressures close to lithostatic stress.

[Q] Where can we find such a modelling - *bulk porous models for bulk flows*? Are there examples available from other PA exercises? (E.g. <u>PAMINA 3.2.1, Sect 3.4 – GRS model</u>? >> PAMINA 3.2.14). Note: this is a "complicated" TOUGH2 model)
[Q] In the OPERA PA: do we have to distinguish a separate *dilatant pathway?* i.e. additionally to the Boom Clay diffusion model?

Excessive gas generation
During the OPERA 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 compounds and/or between these compounds and the ambient materials (Boom Clay, pore water).
[Q] What can justify an “Excessive gas generation” scenario?

OPERA performance assessment – expert elicitatie 1; 18 november 2014
Johan ten Veen, Jacques Grupa, Ton Wildenborg, Merel Schelland

De besproken FEPs zijn geselecteerd uit het OPERA FEP database.

Doel van de expert elicitatie:

1. Bekrachtigen en preciseren van de beschrijving van het Normale Evolutiescenario (NES) met de nadruk op de Central Assessment Case.
2. Opbouw van het PA model vanuit de FEPs / scenariobeschrijving.
3. Aanknooppunten voor Alternatieve Evolutiescenario's (AES) vaststellen.

Algemeen
In het algemeen lijkt de conclusie geoorloofd te zijn dat de hier besproken fysieke processen (zoals bijvoorbeeld processen die voor diepe erosie zorgen) de Boomse Klei niet gemakkelijk zullen beschadigen. Invloeden op de vloeistofhuishouding daarentegen zijn wel te verwachten en kennis daarvan is daarom van belang voor de performance assessment.

Besproken FEPs
1.2.01 Tectonic movement
Binnen de FEP Tectonic movement zijn meerdere FEPs gedefinieerd (1.2.01.01 Regional uplift; 1.2.01.02 Regional subsidence; 1.2.01.03 Movement along faults; 1.2.01.04 Glaciotectonic movement; 1.2.01.05 Diapiric movement). Tectonic movement kan immers door verschillende processen veroorzaakt worden en verschillende effecten hebben. Van deze vijf zijn er drie nader besproken.

Bodemdaling en –stijging (1.2.01.02 en 1.2.01.01) wordt in Nederland met name veroorzaakt door inklinking van veen in het westen (daling) en een na-ebbende isostatische respons op de terugtrekking van het ijs na de laatste glaciaal in het oosten (stijging). Het inklinkingsproces is eindig (~duizenden jaren); compactie/inklink is sterk afhankelijk van het grondwaterniveau en dus sterk afhankelijk van menselijke interventie. Uitgaande van de huidige snelheid zal al het veen in 2700 jaar geoxideerd zijn; dit gaat gepaard met een daling van ~7 m. Op dit moment wordt de inklinking tegengegaan d.m.v. bemaling; binnen het NES (dus zonder voortijdige abandonment van de berging; zie abandonment AES) is een mariene overstroming van de site binnen de periode van terugneembaarheid (~honderden jaren) niet waarschijnlijk.

Breukbewegingen (1.2.01.03) lijken geen gevaar te vormen voor de integriteit van de Boomse Klei als uit de karakterisering van de locatie blijkt dat geen belangrijke breuken de berging zullen doorsnijden. Actieve breuken vormen wel een risico vanwege hun grotere doorlatendheid voor vloeistofstromen. Het is raadzaam en d.m.v. observatie mogelijk om bij de plaatsing van de berging weg te blijven uit bestaande al of niet actieve breukzones.

Het ontstaan van nieuwe breuken binnen enkele 10.000-en jaren lijkt niet waarschijnlijk daar het spanningsveld in de ondergrond maar heel langzaam verandert.

➔ Binnen het NES wordt Regional subsidence en daarmee Tectonic movement in zijn geheel *niet* beschouwd.

Conclusies:
1. Beschrijving NES: Grote veranderingen in de bovengrond zijn alleen op de lange termijn te verwachten.
2. Performance Assessment NES: Deze FEPs hebben geen invloed op het isolerend vermogen van de klei. Impact op het bovenste deel van de aquifers en de biosfeer kan meegewogen worden.
3. AES: er is een kleine kans op een actieve breuk in (de nabijheid) van de opbergsite. Dit kan leiden tot een verhoogde transportsnelheid door de klei.

1.2.12.01 Flooding (detaillering van 1.2.12 Hydrological/hydrogeological response to geological changes)

Het is belangrijk om flooding en, meer algemeen, sea-level change te koppelen aan de glacio-eustatische bewegingen.

Flooding heeft een zeer reële kans van optreden op de tijdschaal van een miljoen jaar, zeker als de menselijke invloed op het klimaat wordt meegenomen in de beoordeling. Het loading effect van landijs lijkt daarbij niet de grootste invloed te hebben op de veiligheidsfuncties, omdat dat i.h.a. gecompenseerd wordt door sedimentatie. De effecten op de vloeistofhuishouding moeten door Johan ten Veen, Johan Valstar en Hanneke Verweij worden bepaald.

➔ Flooding is deel van het NES en heeft daarin gevolgen voor de fluxen. De bijbehorende getallen volgen uit OPERA-onderzoek.

Conclusies:
1. Beschrijving NES: Er is een kans dat in de toekomst de site gedurende enige tijd onder zeeniveau zal liggen.
2. Performance Assessment NES: Deze FEPs hebben geen invloed op het isolerend vermogen van de klei. Er is een kwalitatieve overweging van de impact op de te verwachten blootstelling in de biosfeer nodig.
3. AES: Evaluatie van flooding als onderdeel van het abandonment AES is nodig.

1.3.03 Sea-level change

Naast zeespiegelverhoging (zie 1.2.12.1 Flooding), is ook zeespiegelverlaging relevant voor het NES. Door verlaging van de zeespiegel kan tijdens een glaciaal de ondergrond worden ingesneden bij een verschuiving van de kustlijn tot ~120m bedragen. De gradiënten van rivieren worden groter, wat grote gevolgen heeft voor de dynamiek van riviersystemen (erosie potentie, avulsie frequentie etc.).

Zeespiegelveranderingen gedurende glacialen en interglacialen hebben grote effecten op de grondwaterstromen. Deze effecten moeten besproken worden met Johan Valstar.

➔ Sea-level change is deel van het NES en heeft daarin gevolgen voor grondwaterstromen, fluxen en landschap.

Conclusies:

1. Beschrijving NES: Er is een kans dat in de toekomst de site gedurende enige tijd onder zeeniveau zal liggen.
2. Performance Assessment NES: Deze FEPs hebben geen invloed op het isolerend vermogen van de klei. Er is een (kwalitatieve) overweging van de impact op de te verwachten blootstelling in de biosfeer nodig.
3. AES: geen.

1.3.05 Local glacial and ice-sheet effects

Volgens de Milankovitch-theorie is het aannemelijk dat er over ~55 duizend jaar een glaciaal zal voorkomen. In hoeverre Nederland daarbij bedekt zal worden door ijs ligt niet vast. Volgens voorspellende studies over van landijsvolumes en -verbreiding (Bergre & Loutre, 2002), zal alleen het noorden van Nederland door ijs bedekt worden. IJskapvorming wordt door allerlei complexe processen beïnvloed en voorspellingen zijn daarmee onzeker. Bovendien speelt de huidige antropogene CO_2 uitstoot een cruciale rol in de mogelijkheid ijskappen te ontwikkelen. Maar liefst 7% van de huidige uitstoot blijft meer dan 100.000 jaar in de atmosfeer, waarmee het hernieuwd optreden van landijsbedekking tot wel 500.000 jaar kan worden uitgesteld.

Onder ijskappen kunnen subglaciale (tunnel)valleien ontstaan. Kijkend naar de bestaande subglaciale valleien is het aannemelijk dat die een maximale diepte van 500m (dus tot de top van de Boomse Klei) kunnen bereiken. Deze diepte wordt in meerdere glaciaties opgebouwd. Daarnaast geldt dat hoe vlakker het landschap is, hoe kleiner de kans op subglaciale erosie is. In het voorgaande Programma OPLA is van een maximale diepte van 350 m uitgegaan.

Ook loading effecten van landijs (en daardoor veroorzaakte drukgradiënten), smeltwaterfluxen en de daardoor veroorzaakte erosie kunnen relevante gevolgen hebben voor het opslagsysteem.

De omvang van de genoemde effecten en de kans op het ontstaan van subglaciale erosie worden nog gecheckt en verder onderbouwd.

➔ Permafrost moet in het NES zeker beschouwd worden; effecten van een ijskapbedekking alleen in het geval dat verder onderzoek een significante kans van optreden oplevert.

Conclusies:

1. Beschrijving NES: Er is een redelijk grote kans dat in de verre toekomst de site gedurende enige tijd onder een ijskap zal liggen.
2. Performance Assessment NES: Ice loading heeft door compactie en uitdrijven van formatiewater invloed op het isolerend vermogen van de klei. Er is een (kwalitatieve) overweging van de impact op de te verwachten blootstelling in de biosfeer nodig.
3. AES: Er is een kleine kans op de vorming van een diepe subglaciale vallei boven de site. Hiervoor zijn minstens twee ijsbedekkingen nodig.

1.3.10 Geomorphological response to climate changes

Alle hierboven besproken glaciale processen hebben ook een geomorfologische respons. Daarnaast veranderen landschapsvormen o.i.v. het klimaat (bijvoorbeeld via winderosie, die gevolgen heeft voor de vegetatie). Deze processen spelen zeer ondiep. In studies van SCK is misschien meer detail op dit gebied te vinden; dit wordt nog gecheckt.

➔ Oppervlakkige geomorfologische effecten van klimaatverandering zijn deel van de biosfeermodellering in het NES.

Conclusies:

1. Beschrijving NES: Na een glaciaal zullen de landschapsvormen boven de site sterk veranderd zijn.
2. Performance Assessment NES: Ice loading heeft door compactie en uitdrijven van formatiewater invloed op het isolerend vermogen van de klei. Voor de geohydrologie en de biosfeer moet een breed spectrum aan klimaten en landschapsvormen verondersteld worden.
3. AES: Geen.

Disclaimer

This report has been prepared at the request and for the sole use of the Client and for the intended purposes as stated in the agreement between the Client and Contractors under which this work was completed.

Contractors have exercised due and customary care in preparing this report, but have not, save as specifically stated, independently verified all information provided by the Client and others. No warranty, expressed or implied is made in relation to the preparation of the report or the contents of this report. Therefore, Contractors are not liable for any damages and/or losses resulting from errors, omissions or misrepresentations of the report.

Any recommendations, opinions and/or findings stated in this report are based on circumstances and facts as received from the Client before the performance of the work by Contractors and/or as they existed at the time Contractors performed the work. Any changes in such circumstances and facts upon which this report is based may adversely affect any recommendations, opinions or findings contained in this report. Contractors have not sought to update the information contained in this report from the time Contractors performed the work.

The Client can only rely on or rights can be derived from the final version of the report; a draft of the report does not bind or obligate Contractors in any way. A third party cannot derive rights from this report and Contractors shall in no event be liable for any use of (the information stated in) this report by third parties.

OPERA

Meer informatie:

Postadres
Postbus 202
4380 AE Vlissingen

T 0113-616 666
F 0113-616 650
E info@covra.nl

www.covra.nl