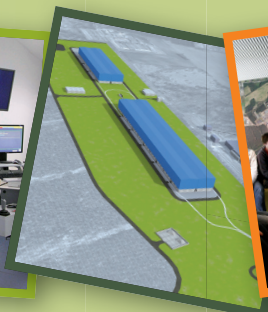
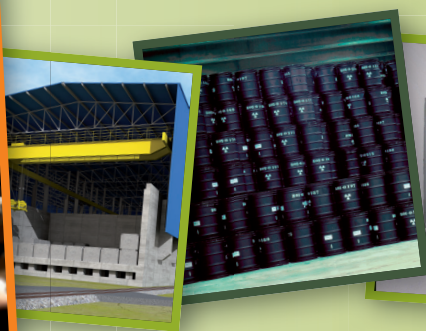


# **ONDRAF/NIRAS Research, Development and Demonstration (RD&D) Plan**

**for the geological disposal of high-level and/or long-lived radioactive waste including irradiated fuel if considered as waste**

**State-of-the-art report as of December 2012**



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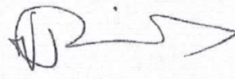


**Belgian Agency for Radioactive Waste and Enriched Fissile Materials**

**NIROND-TR 2013-12 E    December 2013**

This document is the result of extensive team work.

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# 1

## **Part 1**

**The research, development and demonstration plan in the programme for the long-term management of high-level and/or long-lived radioactive waste**



# 1 Introduction

## 1.1 Context of the Belgian programme

In Belgium, the legislature entrusted the management of radioactive waste to a public institution with legal status: the Belgian Agency for Radioactive Waste and Enriched Fissile Materials, known by the French/Dutch acronym ONDRAF/NIRAS. This management must ensure the protection of man and the environment against the risks associated with this waste, and therefore includes an important long-term component. Conditioned short-lived low-level and medium-level waste, called category A waste, presents in fact a risk for man and the environment on a timescale of hundreds of years. A common feature shared by the other conditioned wastes managed by ONDRAF/NIRAS, namely those from the categories B and C, also called B&C waste, which are high-level and/or long-lived wastes, is that they also present a risk, but on a timescale of tens to hundreds of millennia owing to the quantities of long-lived radionuclides that they contain.

The long-term management of radioactive waste is under the exclusive competence of ONDRAF/NIRAS. In accordance with the legal framework, this long-term management must ensure that the waste is disposed of in a long-term management disposal facility without *intention* to retrieve, this disposal facility being then its final destination. However, the fact that the intention is not to retrieve the waste does not necessarily preclude retrieval or controls.

Contrary to the situation for category A waste<sup>1</sup>, no institutional policy has yet been formally approved in Belgium for the long-term management of existing and planned B&C waste, including non-reprocessed irradiated nuclear fuel if declared as waste, as well as excess quantities of enriched fissile materials and plutonium-bearing materials (excluding fuel) if declared as waste.

In accordance with the legal framework, ONDRAF/NIRAS has taken the initiative to compile in a single document, the *Waste Plan*, all elements necessary to enable the Government to make, with full knowledge of the facts, a *decision in principle*, that is a *general policy* decision or a *general guidance* decision, relating to the long-term management of B&C waste (ONDRAF/NIRAS, 2011c). This Waste Plan is based on results from the ONDRAF/NIRAS research, development and demonstration (RD&D) programme in the field of long-term management of B&C waste, which is in line with the corresponding international recommendations.

RD&D in the field of long-term management of B&C waste was initiated in 1974 by the Belgian Nuclear Research Centre (SCK•CEN) and transferred under the responsibility of ONDRAF/NIRAS more than a decade later. The research programme has benefitted since the early 80s from a dedicated underground research facility built in Boom Clay in Mol.

ONDRAF/NIRAS has synthesised the RD&D relating to geological disposal conducted in Belgium in several reports: the Safety Assessment and Feasibility Interim Report or

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1 On 31 January 2013, ONDRAF/NIRAS has submitted the licence application for the surface disposal facility for Belgian Category A waste to the Federal Agency for Nuclear Control or FANC.

SAFIR report (ONDRAF/NIRAS, 1990) and the SAFIR2 report (ONDRAF/NIRAS, 2001b). The interest and the quality of the RD&D activities have been confirmed several times as from 1976 by different commissions and working groups asked by institutional bodies to advise on ongoing studies in the field of long-term management of B&C waste or on energy policy issues and reported in particular in:

- the international peer review of SAFIR2 under the auspices of the NEA, carried out at the request of the Belgian Government (NEA, 2003);
- the report assessing the possible consequences in the Netherlands of geological disposal of B&C waste in the Netherlands, written by Professor Olsthoorn from the Delft University of Technology, commissioned by the Province Noord-Brabant (NL) (Olsthoorn, 2011).

According to these reports, there is no inescapable obstacle for geological disposal of B&C waste in Boom Clay.

However, the direction proposed by ONDRAF/NIRAS for the long-term management of B&C waste — *geological disposal in poorly indurated clay* (in Belgium, Boom Clay or Ypresian clays) — has not been *formally* confirmed at the federal level. According to ONDRAF/NIRAS, a geological disposal facility — progressively developed, realised and closed, if need be after a period of (*in-situ*) controls — is the only management solution ensuring the protection of man and the environment in the long term against the risks associated with B&C waste, and minimising the transfer of the burdens to future generations while leaving them some freedom to choose, in particular regarding controls of the disposal facility, closure planning, possible retrieval of waste and knowledge transfer to the next generations. This solution is in line with international recommendations and foreign practices<sup>2</sup>.

The Waste Plan was adopted by the Board of Directors of ONDRAF/NIRAS on 23 September 2011 and handed over by ONDRAF/NIRAS to its supervisory authority, accompanied by other documents: a strategic environmental assessment or SEA, the declaration<sup>3</sup> (which summarises notably the way in which the SEA and the consultations conducted during the legal procedure have been taken into consideration in the Waste Plan) and the report from the citizens conference organised in late 2009 – early 2010 by the King Baudouin Foundation at the request of ONDRAF/NIRAS and dedicated to the issue of how to decide on the long-term management of B&C waste.

Pending a policy decision on the long-term management of B&C waste, ONDRAF/NIRAS has been mandated by its supervising authority to ensure the continuity of its public service tasks, in particular to:

- *continue RD&D on geological disposal in poorly indurated clay in order to confirm and refine the scientific and technical foundations of this solution and ensure its financing, at the required level, by the producers;*
- *further define the gradual, adaptable, participative, transparent and continuous decision-making process that will take place in parallel with the development and*

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2 The ONDRAF/NIRAS Waste Plan (ONDRAF/NIRAS, 2011c) contains numerous references to international recommendations and foreign practices.

3 The declaration and executive summary of the Waste Plan were published in the Belgian Official Journal of 30 September 2011.

*implementation of the management solution; this process will start a priori with the making of a decision in principle;*

- *develop the societal dimension of the B&C programme and ensure the related financing;*
- *specify, in consultation with all stakeholders, the demands arising from the consultations concerning operational reversibility and retrievability of the waste disposed of, monitoring the proper functioning, transfer of knowledge of the disposal facility, including the memory of its location, and the waste it contains;*
- *follow the developments regarding the management options that were examined in the Waste Plan but were discarded (translation ONDRAF/NIRAS).*

Some general notes on the Belgian RD&D programme:

- The Federal Agency for Nuclear Control – FANC, the Belgian regulator, is currently working on a complete and dedicated regulatory framework for the geological disposal of B&C waste. A dialogue between the regulator and the implementer has been established in order to ensure a common interpretation of international guidance and to inform ONDRAF/NIRAS about the development of FANC regulations.
- The status of irradiated fuel (resource or waste) has not been established. ONDRAF/NIRAS must give equal consideration to the study of the geological disposal of reprocessing waste and of non-reprocessed spent<sup>4</sup> fuel, according to the resolution by the Chamber of 22 December 1993 (Chambre des représentants, 1993).
- The Mol–Dessel area is home to the reference site for RD&D in Boom Clay, with the HADES underground research facility operating since 1982. However, this does not prejudice the site where a disposal facility would potentially be implemented (with the host rock being Boom Clay or Ypresian clays).

## 1.2 Objectives of the document

Considering the above context, ONDRAF/NIRAS has decided to establish a RD&D Plan on geological disposal in poorly indurated clay. It aims to:

- present the status of knowledge regarding the development of geological disposal of B&C waste in poorly indurated clay, as of December 2012. This high-level document refers to numerous references, for more details.
- identify the RD&D needed to support geological disposal of B&C waste in poorly indurated clay. It prioritises the RD&D needs in function of the current level of understanding, of their potential impact on safety or feasibility and of the stage of the disposal programme when they should be catered for.
- integrate societal concerns expressed in the frame of the Waste Plan, e.g., retrievability, controllability and follow-up of long-term management options discarded in the Waste Plan.

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4 Irradiated fuel is called spent fuel when declared as waste.



- illustrate with a few examples the applicability of the safety assessment methodology.

It should be noted that this document:

- contains no safety analysis. The examples only partially illustrate the application of ONDRAF/NIRAS methodologies. It is therefore not a safety case.
- is primarily intended for experts from various disciplines involved in RD&D related to geological disposal.
- focuses on the achievements since 2003, as ONDRAF/NIRAS then re-evaluated its RD&D programme on geological disposal of B&C waste in order to bring it into line with the recommendations of the reviews of the SAFIR2 report. In particular, ONDRAF/NIRAS has refined and formalised the safety strategy and the methodology for the safety assessments and has modified the disposal facility design.
- reflects the state of knowledge at the end of 2012. It is not exhaustive, being a synthesis of knowledge concerning the need to substantiate the Safety and Feasibility Statements, the cornerstone of the safety strategy (Section 2.1).
- focuses on the long-term management of B&C waste, considering only existing and planned (mainly within the scope of the current nuclear power programme) waste. In the rest of the text, "B&C waste" must be understood as also referring to non-reprocessed irradiated nuclear fuel if declared as waste, as well as excess quantities of enriched fissile materials and plutonium-bearing materials (excluding fuel) if declared as waste. The RD&D Plan does not address research for surface disposal and the long-term management of the following waste types: radium-bearing waste mostly present on Umicore's licensed interim storage facilities in Olen and waste resulting from future remediation operations in Olen, of NORM (*naturally occurring radioactive materials*) and of TENORM (*technologically enhanced, naturally occurring radioactive materials*).

ONDRAF/NIRAS intends to develop its geological disposal facility for B&C waste in a cautious, stepwise process, punctuated by the submission of key documents to the relevant authorities providing them with the necessary materials to take a position on the requested decision at each stage. These documents will consist of Safety and Feasibility Cases (SFC). A Safety and Feasibility Case is the synthesis of evidence, analyses and arguments that quantify and substantiate the claim that the disposal facility can be constructed and be safe after closure and beyond the time when active control of the disposal facility can be relied on. ONDRAF/NIRAS is working on the preparation of a first Safety and Feasibility Case (SFC1).

The decision that will be requested with the SFC1 and the precise scope of this document will fundamentally depend on the policy decision on the long-term management of B&C waste yet to be taken based on the ONDRAF/NIRAS Waste Plan. According to ONDRAF/NIRAS's current hypotheses, the SFC1 is intended to ask the competent authorities for the green light to launch the siting process.

Considering these uncertainties, the first Safety and Feasibility Case (SFC1) should in any case focus on:

- testing the safety assessment methodologies;
- refining the design for a disposal facility located in Boom Clay;
- providing a first evaluation of the safety and feasibility of a disposal facility located in Ypresian Clays;
- providing a first integration of societal concerns like retrievability, controllability, etc.

The RD&D Plan identifies the RD&D priorities with a view to establishing this first Safety and Feasibility Case (SFC1). At the end of the sections, a “roadmap” will summarise the disposal-related RD&D needs, sorted into four categories:

- RD&D to be conducted *now*, because its first results are necessary for developing SFC1, to close open questions that need to be addressed *for SFC1*.
- RD&D in progress or to launch before SFC1 but whose final results will be integrated in *later SFCs*. The final results of this RD&D are not required for developing SFC1 because, for instance, SFC1 safety assessments can use conservative assumptions. Later SFCs may rely on more realistic assumptions.
- RD&D to launch during the *siting process or after site selection* (beyond SFC1). Some RD&D is site-specific by nature and can only start during the site selection process or even after selection of the site for geological disposal.
- RD&D carried out for *confidence building*: the knowledge is sufficient for the purpose (current stage of the programme), but further RD&D may reduce remaining uncertainties, provide multiple lines of evidence and/or complete the assessment basis. This concerns topics important for both safety and feasibility. Available results will be integrated in SFC1 and subsequent SFCs.

In some fields, the current knowledge is considered sufficient for the purpose of SFC1.

Given the continued development of a geological disposal facility and its gradual implementation span over several decades, the future RD&D programme needs to be flexible and evolve according to developments in the societal, scientific, technical, economic and regulatory context.

The RD&D programme is essential because the system to be designed has a unique character, in particular because it must provide maximum adequacy between the waste for disposal, the engineered barriers and the host formation. In this respect, ONDRAF/NIRAS has adopted a careful, systematic and stepwise approach aimed at verifying the absence of inescapable obstacles, whether in terms of safety (operational and long-term, classic and radiological) or feasibility.

In practice, ONDRAF/NIRAS defines RD&D activities in terms of long-term management, assigns their execution to scientific partners (universities, research centres, etc.), engineering firms and industrial partners, in Belgium and abroad, and ensures knowledge integration with a view to drafting Safety Cases (Inset 1). Most results are then peer reviewed by experts. The large-scale demonstration projects and the experiments in the underground research facility constructed in the Boom Clay under the

SCK•CEN site were assigned to EURIDICE, the economic interest grouping created by ONDRAF/NIRAS and SCK•CEN in 1995 (known at the time as the PRACLAY economic interest grouping) (Annex A4).

The RD&D Plan comprises seven parts, mainly structured according to the Safety and Feasibility Statements trees, the cornerstone of the application of the safety strategy (Table 1):

- Part 1 contains the strategies and methodologies elaborated in the frame of the RD&D programme guiding the development of a geological disposal facility in Belgium.
- Part 2 reviews the knowledge and understanding of the disposal facility, the Boom Clay and its environment and their development obtained over 30 years of RD&D.
- Part 3 presents the RD&D performed to underpin the feasibility of constructing, operating, closing, and where applicable, decommissioning<sup>5</sup>, the proposed disposal facility design for category B&C (built in Boom Clay).
- Part 4 illustrates the application of the strategies and methodologies used to assess the long-term safety of man and the environment, keeping in mind that the assessment will be provided in SFC1 and not in this document.
- Part 5 presents the measures taken by ONDRAF/NIRAS to insure that the radiological and environmental requirements arising from applicable standards and regulations and conditions resulting from societal concerns will be met.
- Part 6 extends the knowledge basis with information on three fields of RD&D not detailed elsewhere: Ypresian clays, societal aspects and follow-up of management possibilities discarded in the Waste Plan.
- Part 7 collects all the “roadmaps” summarising the disposal-related RD&D needs dispersed throughout the document.

Each part contains one or more chapter(s) with the current status of knowledge, key areas of work and associated key area of uncertainty that need to be addressed, the latter being presented in the form of roadmaps.

This RD&D Plan contains seven annexes. Annex A1 contains the current Safety and Feasibility Statements trees. Annex A2 outlines the origins and characteristics of existing and planned (mainly within the scope of the current nuclear power programme) B&C waste. Annex A3 presents the history of the HADES underground research facility construction while Annex A4 summarises the PRACLAY “Demonstration and confirmation experiments”. Annex A5 lists the projects of the Belgian programme funded by the European Union and by the Nuclear Energy Agency (NEA), complemented by a list with other *in-situ* experiments. Annex A6 and Annex A7 respectively contain a list of acronyms and references.

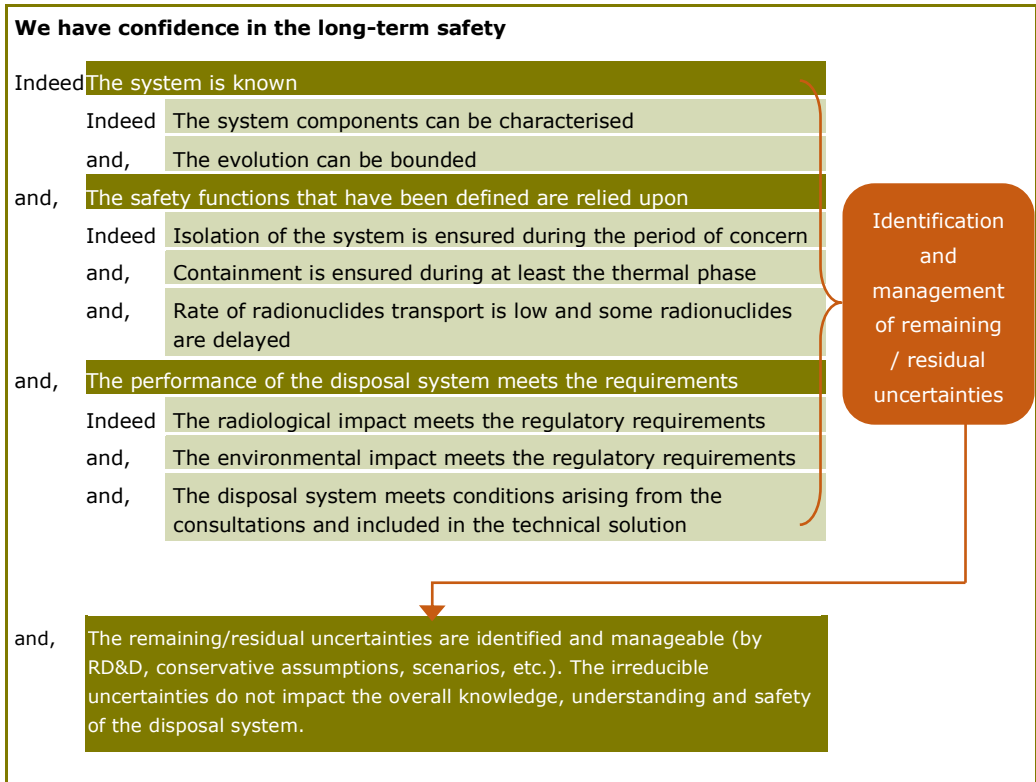
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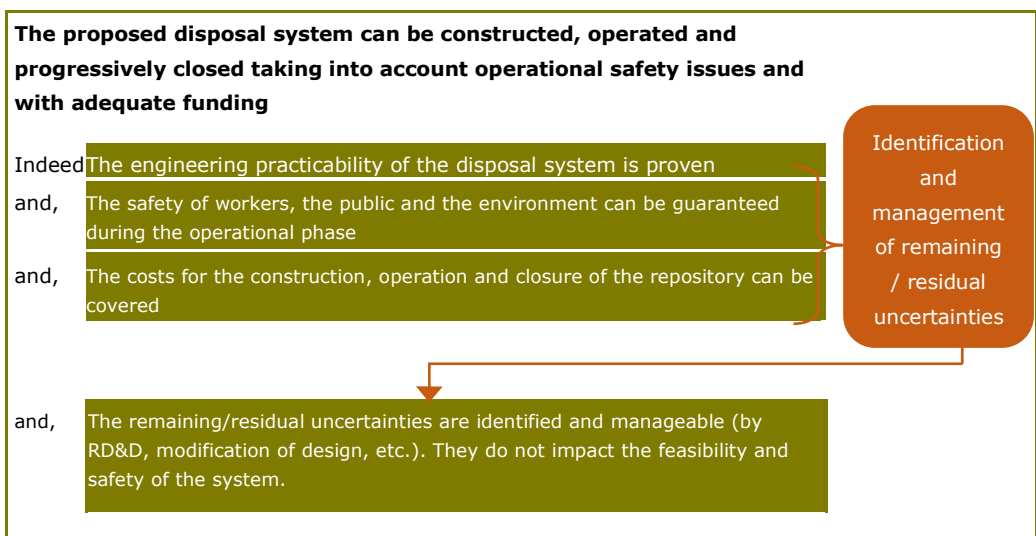
<sup>5</sup> Decommissioning includes dismantling of the facility (IAEA, 2007).

**Table 1** – The Safety (a) and Feasibility (b) Statements trees are cornerstones to applying the safety strategy. They contain a set of claims that must be substantiated, which are arranged hierarchically in a tree structure. Most content of the RD&D Plan is structured according to these trees. This table presents the highest-level statements. Annex A1 contains all current statements.

(a) Safety Statements tree



(b) Feasibility Statements tree



### **Inset 1 – Collaboration for the long-term management of radioactive waste**

Research and development in terms of radioactive waste management across the world, at both the national and international organisation levels, follows an open approach. Knowledge and experience are shared, resources pooled and results published in scientific literature and subjected to peer review. The RD&D Plan is therefore based on scientific and technical knowledge that goes far beyond the knowledge acquired as part of the Belgian programme, as illustrated hereafter.

In addition to its RD&D activities within the Belgian programme, ONDRAF/NIRAS collaborates with other national radioactive waste management agencies. In particular, ONDRAF/NIRAS has signed a trilateral agreement with Andra (France) and Nagra (Switzerland), two agencies that are also studying clay formations as host formations for the geological disposal of radioactive waste. In 2010, ONDRAF/NIRAS signed a research and development agreement with COVRA, its Dutch counterpart, on RD&D regarding disposal in poorly indurated clay, and more particularly Boom Clay, on their respective national territories.

ONDRAF/NIRAS also actively contributes to numerous initiatives at an international level relating to radioactive waste management. Some examples are listed hereafter:

- ONDRAF/NIRAS participates in various projects organised by the IAEA (International Atomic Energy Agency), which potentially lead to IAEA publications, such as:
  - ▶ The “*Intercomparison and Harmonization project on Demonstrating the Safety of Geological Disposal (GEOSAF)*” which led to the publication of an IAEA Safety Standards Series document “*The Safety Case and Safety Assessment for the disposal of Radioactive Waste*” (IAEA SSG-23).
  - ▶ The “*Human Intrusion in Disposal of Radioactive Waste (HIDRA) project*”, which studies the scenarios of human intrusion in radioactive waste disposal and aims to draft an international guidance on human intrusion.
  - ▶ The “*Modelling and Data for Radiological Impact Assessments project (MODARIA)*”, with a particular focus on developing a common framework for addressing environmental changes in long term safety assessments of radioactive waste repositories.
- ONDRAF/NIRAS is directly involved in several working groups and projects of the RWMC (Radioactive Waste Management Committee), the main body advising the NEA (Nuclear Energy Agency, a semi-autonomous body within the OECD) member countries in the area of radioactive waste management, notably:
  - ▶ The “*Integration Group for the Safety Case (IGSC)*”, whose mission is to assist member countries in developing effective Safety Cases supported by a robust scientific technical basis. In addition to the technical aspects in all developmental stages of disposal facility implementation, the group also provides a platform for international dialogues between safety experts to address strategic and policy aspects of disposal facility development.
  - ▶ The “*Clay Club*”, which groups member countries that consider clay as a potential host formation for the geological disposal of radioactive waste.
  - ▶ The “*Sorption project*”, which studies the potential of chemical thermodynamic models for improving representation of sorption phenomena in the long-term safety analysis linked to the disposal of radioactive waste.
  - ▶ The “*Thermochemical Database project (TDB)*”, whose purpose is to make available a comprehensive, internally consistent, quality-assured and internationally recognised chemical thermodynamic database of selected chemical elements in order to meet the specialised modelling requirements for safety assessments linked to the disposal of radioactive waste.

► The "*Preservation of Records, Knowledge and Memory (RK&M) across Generations project*", whose goals are to compare approaches, test potential solutions and build common references in this domain.

► The "*Reversibility and Retrievability project (R&R)*", which led, among others, to the publication of a "retrievability scale", which has proven to be an effective support to communication.

- ONDRAF/NIRAS is an active member of the IGD-TP, the technology platform devoted to the implementation of geological disposal of radioactive waste, supported by the European Commission, launched in 2009. The vision of the IGD-TP is that, by 2025, the first geological repositories for irradiated fuel, high-level waste, and other long-lived radioactive waste will be operating safely in Europe. The platform coordinates and implements the necessary RD&D to realise this objective, involving a wide range of RD&D stakeholders active in this field.
- ONDRAF/NIRAS and its main research partners are also involved in European research projects (Annex A5 presents the list of finished and current projects.) They actively contribute to six projects within the Euratom Seventh Framework Programme for Research and Technological Development from the European Commission.



## **2 ONDRAF/NIRAS develops an approach for the development of a geological repository ensuring safety and feasibility**

For over 30 years, ONDRAF/NIRAS has been studying geological disposal in poorly indurated clay (Boom Clay or Ypresian clays) as a solution for the long-term management of high-level waste and low- and intermediate-level waste, long-lived (HLW/LILW-LL or category B&C waste or B&C waste). In line with international practice, ONDRAF/NIRAS plans its geological disposal facility – or repository – for category B&C waste and its implementation in a cautious, stepwise process, punctuated by the submission of key documents to the government and/or authorities such as the SAFIR2 documents submitted in 2001 and the Waste Plan submitted in 2011 (ONDRAF/NIRAS, 2001b) (ONDRAF/NIRAS, 2011c).

The international peer review of SAFIR2 under the auspices of the NEA acknowledged the maturity of the Belgian scientific programme and endorsed the conclusion of ONDRAF/NIRAS to pursue the research, development and demonstration (RD&D) programme on poorly indurated clay (NEA, 2003). Consequently, the NEA International Review Team invited ONDRAF/NIRAS to move ahead with the programme while elaborating a strategy for setting priorities and a structured approach for managing uncertainties and developing the frame and tools to embed its national programme in a societal dialogue and in a stepwise decision-making plan with key milestones stretching over the next decades towards the licensing process. Next to the scientific aspects, the programme should also integrate the aspects of operational safety, feasibility, cost and environmental impacts and their complex interdependences.

To serve these ends, ONDRAF/NIRAS has reassessed the organisation of its geological disposal programme and developed a (overall) safety approach including a strategy and a series of methodological instruments. The output of the programme stage at hand will be a set of deliverables providing the government with the necessary materials to take position on a requested decision. These documents will consist of Safety and Feasibility Cases (SFC). A Safety and Feasibility Case is the synthesis of evidence, analyses and arguments that quantify and substantiate the claim that the repository can be constructed and be safe after closure and beyond the time when active control of the facility can be relied on. The Safety and Feasibility Case becomes more comprehensive as a programme progresses, and is a key input to decision making at several steps in the repository planning and implementation process. To fulfil this role, the Safety and Feasibility Case encompasses, in addition to the safety arguments and feasibility specifications, the environmental policies of concern and their implementation as well as the mechanisms to ensure the appropriate public information and participation. The Safety Case may also be used as a platform for informed discussion whereby interested parties can assess their own levels of confidence in a project, issues that may be a cause for concern can be identified for further work (after (NEA, 2013)). SFC1 will be the first such Safety and Feasibility Case.



The **disposal system** is the set of components and barriers contributing to the concentration and confinement strategy. It includes the engineered barrier system (EBS) together with, in the case of geological disposal, the natural geological barrier, or host formation, in which it is built.

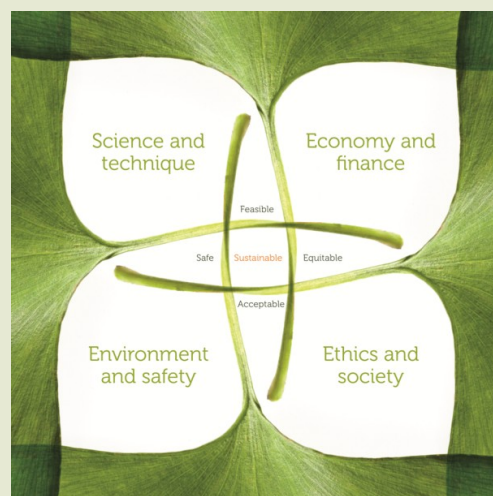
The approach developed for the geological disposal programme consists of three steps, listed hereafter, and developed in the next sections:

- The first step is the definition of the safety strategy, *i.e.*, how it is envisaged by ONDRAF/NIRAS that disposal will be achieved so that it satisfies the safety objective.
- The second step, also at the strategic level, is the definition of the management strategy, *i.e.*, the set of organisational and quality principles, rules and practices, to ensure that the development of SFC1 is safety-driven, is consistent with and according to the safety strategy and leads to a safe disposal system which meets the quality objectives and standards set in advance.
- The third and last step concerns the operational level, through the development and implementation of a management system, which is the set of interrelated and interacting operational (processes) for implementing the management strategy for SFC1. The management system encompasses quality control, quality assurance and quality management. The management system includes the set of deliverables submitted to the government with the request to proceed to the next stage.

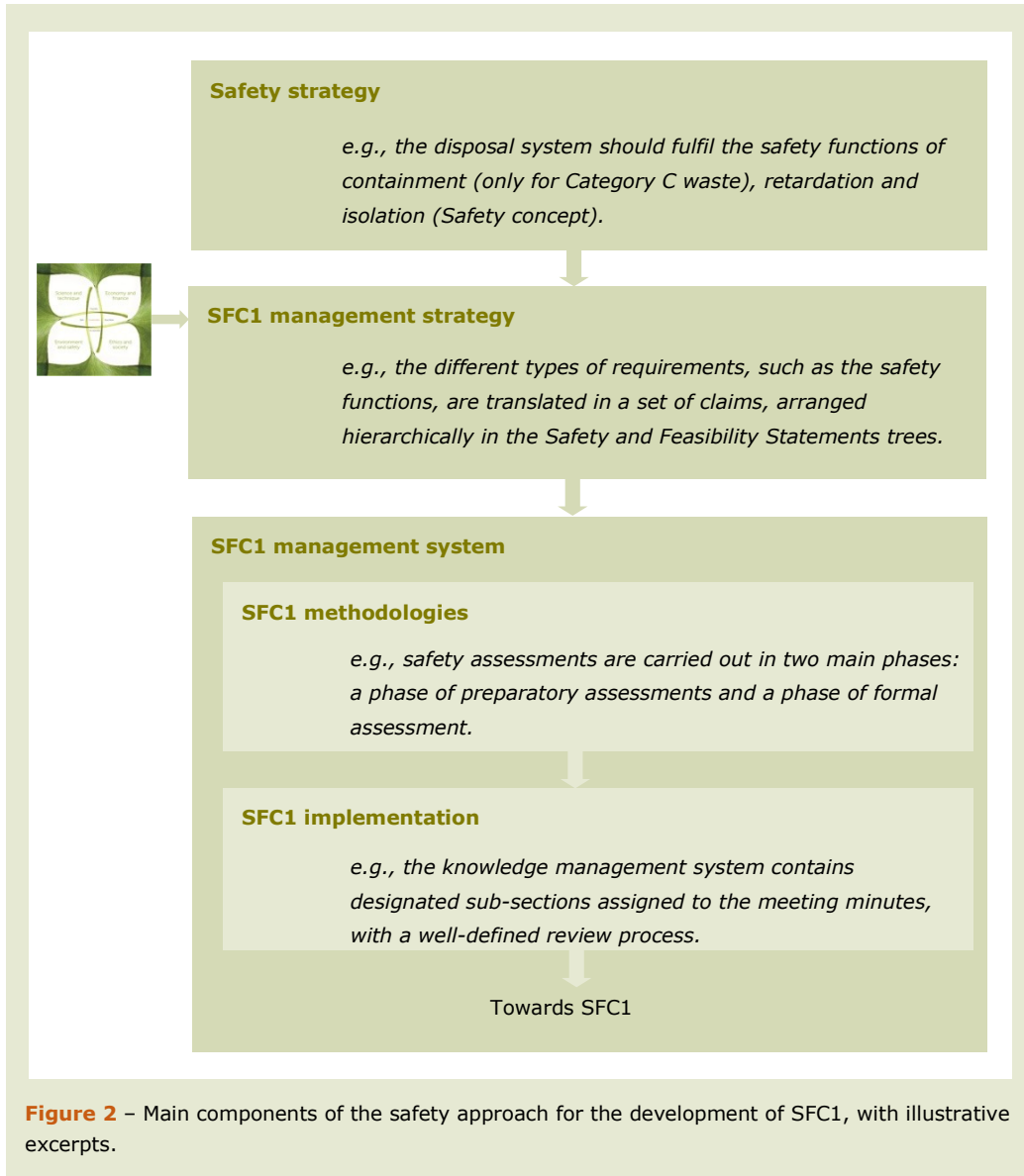
Figure 2 illustrates the main components of the safety approach while Figure 7 details this approach.

The development of SFC1 is carried out in line with ONDRAF/NIRAS integrated management system (IMS), which is defined at the corporate level and integrates the different arrangements and processes necessary to address and achieve the goals of the organisation, in accordance with:

- the international rules and recommendations, in particular the IAEA Safety Standards N° GS-R-3 (IAEA, 2006c);
- the principles and requirements of sustainable management, that means a management based on a balanced consideration of science and technique, economy and finance, environment and safety, and ethics and society (Figure 1).



**Figure 1** – The four dimensions of a sustainable management.



## 2.1 Safety strategy

The commonly accepted and applied strategy for radioactive waste management is that of concentration and confinement of waste, with isolation from the biosphere, as opposed to a strategy of dilution and dispersion of the radioactivity into the environment (IAEA, 1995) (IAEA, 2011b).

The first step in the development of SFC1, and a prerequisite for its realisation, is the definition of the safety strategy, which defines in broad terms how it is envisaged that safe disposal will be achieved. A safe disposal system is one that protects man and the environment now and in the future from the harmful effects of ionising radiation, as well as of any chemically toxic contaminants associated with the waste. Protection must be provided at all stages over the lifetime of a repository, without imposing undue burdens on future generations.

According to the International Atomic Energy Agency (IAEA), the aims of disposal are (IAEA, 2011b):

- “to contain the waste;
- to isolate the waste from the accessible biosphere and to reduce substantially the likelihood of, and all possible consequences of, inadvertent human intrusion into the waste;
- to inhibit, reduce and delay the migration of radionuclides at any time from the waste to the accessible biosphere;
- to ensure that the amounts of radionuclides reaching the accessible biosphere due to any migration from the disposal facility are such that possible radiological consequences are acceptably low at all times”.

ONDRAF/NIRAS has developed a safety strategy based on 30 years of experience, knowledge and understanding acquired in the field of geological disposal in poorly indurated clay and on constraints imposed to ONDRAF/NIRAS by third parties. The safety objective and the main safety orientations and principles, due to their founding nature, will remain stable during the whole process of developing and implementing a safe geological repository. However, some other elements of the safety strategy have to be flexible in order to iteratively integrate changes arising for instance from evolving stakeholder requirements or strategic choices, during SFC1 and the programme stages beyond.

The safety strategy adopted by ONDRAF/NIRAS includes boundary conditions to be met, safety principles to be applied, strategic choices to be made, requirements to be satisfied and the safety concept that sets out in broad terms how it is envisaged that safe disposal will be achieved, as detailed hereafter.

### Boundary conditions

The boundary conditions are imposed to ONDRAF/NIRAS by third parties. Boundary conditions include the international framework in which all geological disposal programmes operate, the Belgian legal and regulatory framework, the institutional policy

and other stakeholder conditions (see (ONDRAF/NIRAS, to be published) for more details):

- The international framework consists of:
  - ▶ International treaties and conventions to which Belgium is a signatory (see Inset 2). (They are later transposed into Belgian legislation.)
  - ▶ European directives: legislative acts of the European Union, which require Member States to achieve a particular result without dictating the means of achieving that result. The directives are translated by Royal Decree into Belgian legislation (Inset 2).
  - ▶ European regulations, which are legal acts, become immediately enforceable as law in all Member states simultaneously.
  - ▶ European decisions, which are legal instruments binding upon those individuals to which it is addressed.
  - ▶ General texts and practice regarding radioactive waste management and disposal by international organisations that are active in nuclear-related matters (such as IAEA, International Commission on Radiological Protection (ICRP), Nuclear Energy Agency (NEA/OECD)), and also, where relevant, guidance observed in other industries.
- The Belgian legal and regulatory framework is essentially composed of all the legal and regulatory items, at the federal and regional levels, relevant to the planning, licensing, construction, operation, closure and post-closure surveillance and monitoring of a repository.
- Institutional policy items are policy-oriented decisions or recommendations made by competent authorities, the Federal Agency for Nuclear Control or FANC (FANC, 2013) but without being incorporated in the legal and regulatory framework (although they may be incorporated later).
- Other stakeholder conditions are those associated with the implementation of a repository that may be set either by a Belgian non-institutional stakeholder or by a foreign institutional stakeholder. For instance, the public consultation performed in the frame of the Waste Plan led to consider retrieval of the waste in the RD&D programme and to pay more attention to the transfer of knowledge to the next generations (see Chapter 9).

**Reversibility** is the technical possibility of safely retrieving waste packages placed in disposal galleries that are not yet sealed using means identical or comparable to those used for their emplacement. Reversibility is strictly related to the operation of the repository: for each waste package, between its disposal and the sealing of the gallery in which it has been placed (ONDRAF/NIRAS, 2011c).

**Retrievability** of waste is the technical possibility of safely retrieving waste disposed of in sealed disposal galleries, if necessary using means other than those used for its disposal. The extreme case for retrievability is the full mining excavation (mining out) of a completely closed repository (FANC, 2007).

### **Inset 2 – International conventions and treaties and European directives**

The main international conventions and treaties to which Belgium is a signatory and that are relevant to radioactive waste management are as follows:

- Treaty establishing the European Atomic Energy Community (called the Euratom Treaty, 1957);
- Treaty on the Non-proliferation of Nuclear Weapons (called the Non-Proliferation Treaty or TNP, 1968);
- Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (called the London Convention, 1972) and its related protocol (1996);
- Convention on Environmental Impact Assessment in a Transboundary Context (called the Espoo Convention, 1991);
- Convention for the Protection of the Marine Environment of the North-East Atlantic (called the OSPAR Convention, 1992);
- Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (called the Joint Convention, 1997) (IAEA, 1997);
- Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters (called the Aarhus Convention, 1998);
- Convention on nuclear safety (IAEA, 2004).

The main relevant European directives in terms of radioactive waste management are as follows:

- Council Directive 85/337/EEC of 27 June 1985 on the assessment of the effects of certain public and private projects on the environment (EU, 1985);
- Council Directive 96/29/Euratom of 13 May 1996 laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionising radiation (EU, 1996);
- Council Directive 97/11/EEC of 3 March 1997 amending Directive 85/337/EEC on the assessment of the effects of certain public and private projects on the environment (EU, 1997);
- Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption (EU, 1998);
- Directive 2001/42/EC of the European Parliament and of the Council of 27 June 2001 on the assessment of the effects of certain plans and programmes on the environment (EU, 2001);
- Directive 2003/4/EC of the European Parliament and of the Council of 28 January 2003 on public access to environmental information and repealing Council Directive 90/313/EEC (EU, 2003);
- Directive 2003/35/EC of the European Parliament and of the Council of 26 May 2003 providing for public participation in respect of the drawing up of certain plans and programmes relating to the environment (EU, 2003b);
- Directive 2011/70/EC of 19 July 2011 establishing a community framework for the responsible and safe management of irradiated fuel and radioactive waste, which the member states are required to bring this directive into force by 23 August 2013 (EU, 2011).

## Safety principles

For safe geological disposal, ONDRAF/NIRAS has adopted the following set of safety principles: robustness, demonstrability, passive safety, defence-in-depth, best available techniques and optimisation of protection (and safety). These principles, detailed hereafter, are based on international standards and recommendations by the IAEA (safety fundamentals, safety requirements, safety guides, etc.) (notably (IAEA, 2006b) (IAEA, 2011b)) and on the basic principles of radiation protection of the International Commission on Radiological Protection publications (ICRP) (ICRP, 2007) (ICRP, 2008) (ICRP, 2013). European directives (such as (EU, 1996b)) and NEA publications (among others in (NEA, 2012)) precise the scope of a few principles.

- **Robustness**  
Robust systems are characterised by a lack of complex, poorly understood or difficult to characterise features and phenomena, by ease of quality control and an absence of, or relative insensitivity to, detrimental phenomena arising either internally within the repository and host formation, or externally in the form of geological and climatic phenomena. They are also characterised by a lack of uncertainties with the potential to compromise safety.
- **Demonstrability**  
Demonstrability requires that safety be provided for by reliable features, for which sufficient evidence has been presented of their feasibility and effectiveness, before construction activities start. Where there is uncertainty, it is taken into consideration in the estimation of safety.
- **Passive safety**  
The principle of passive safety implies that, in the long term, no institutional control or active human action is required to ensure the long-term safety of the man and the environment.
- **Defence-in-depth**  
The defence-in-depth (DiD) principle requires the presence of multiple levels of protection that enhance safety thanks to their diversity and redundancy. The protection is ensured by physical barriers (physical entities, such as the waste form, the disposal package, the backfill or the host formation) and/or by the fulfilment of safety functions. These latest are provided by means of physical or chemical properties or processes that contribute to safety, such as: impermeability to fluids, limited corrosion, dissolution, leach rate and solubility, and retention. Safety is thus not unduly dependent on a single component or control procedure, or the fulfilment of a single safety function or administrative procedure.
- **Best-available techniques (BAT)**  
The IPPC (Integrated Pollution Prevention and Control) Directive of the European Union requires that installations should be operated in such a way that *best available techniques (BAT)* are used to prevent or reduce pollution of the environment (EU, 1996b). ICRP has further refined the definition of BAT to BATNEEC for “best-available techniques not entailing excessive costs”: “*The term best available has usually implied best from the environmental viewpoint, regardless of cost. The addition of not entailing excessive cost brings the concept closer to the Commission’s recommendation to keep doses as low as reasonably*”

*achievable, but involves costs only when they are becoming excessive” (ICRP, 2008).*

- Optimisation of protection (and safety)  
ICRP defines the optimisation of protection and safety as *“the process of determining what level of protection and safety makes exposures, and the probability and magnitude of potential exposures, as low as reasonably achievable, economic and societal factors being taken into account (ICRP, 2013).”* An optimal solution means balancing the political and acceptance issues and any other boundary conditions imposed by society, with the need to use resources efficiently. It is therefore a learning process, and as such can contribute to building confidence in the Safety and Feasibility Case by the demonstration of ongoing learning across the organisation. Optimisation occurs at each stage of the development programme of the repository, and is therefore forward looking rather than focussed on re-examining past decisions. It should be about the right way forward at each stage, making the best decisions to move forward from the present situation based on current knowledge and understanding (NEA, 2012).

### **Strategic choices**

The strategic choices are high-level choices made by ONDRAF/NIRAS regarding repository planning and the broad features that a repository should have in order to meet the safety objective of protecting man and the environment from the risks associated with category B&C waste (Inset 3). Strategic choices are based on a priori knowledge and understanding and are constrained by the boundary conditions. Some of them are hypotheses that ONDRAF/NIRAS has had to make in order to be able to plan and carry out its B&C Programme in a focused way, pending for the formal approval of an institutional policy for the long-term management of B&C waste. Strategic choices reflect a certain level of ONDRAF/NIRAS own freedom and are grounded in the working hypotheses made at a previous programme stage and confirmed during the programme stage at hand by ONDRAF/NIRAS, or even by third parties outside ONDRAF/NIRAS, such as the Federal Government, the Federal Agency for Nuclear Control (FANC) and local partners. The strategic choices may in turn further be confirmed, elaborated, modified or rejected as a result of the deliberations of these parties. The current strategic choices include demands expressed during the societal consultations organised by ONDRAF/NIRAS around the Waste Plan publication (ONDRAF/NIRAS, 2011c).

### **Inset 3 – Strategic choices of the B&C programme**

1. The long-term management of category B&C waste requires a solution on the national territory.
2. The potential host formations for a geological repository are limited to poorly indurated argillaceous formations (Boom Clay or Ypresian clays).
3. Waste types shall be divided into groups to be emplaced in separate sections of the repository.
4. There are preferences for permanent shielding of the waste and for minimisation of operations in the underground.

Taking into account the societal consultations around the Waste Plan, ONDRAF/NIRAS is committed to (ONDRAF/NIRAS, 2011c):

5. Ensure reversibility during the operational phase.
6. Consider provisions to facilitate potential retrievability of the waste after closure of the disposal (partial or total) for certain duration to be defined.
7. Consider the transfer of knowledge to the next generations: it concerns knowledge of both the waste and the facility to be transferred from one generation to the next.
8. "Controllability" of the repository, including monitoring, surveillance and inspections measures, both prior to its closure and afterwards, during the surveillance and control phase.

## **Requirements**

Boundary conditions, safety principles and strategic choices are translated into requirements related to the disposal system as a whole, to subsystems or to individual components of the system. These requirements can be either general or specific, and cover a wide range of domains, such as long-term safety, feasibility, which is taken to include operational safety and costs, knowledge of the waste to be disposed of, awareness of uncertainties and aspects of quality assurance. Examples of requirements are the minimum required duration of the containment phase for category C waste and the composition of a filling material.

## **Safety concept**

Based on existing knowledge and understanding and of the requirements on the system and some of its subsystems, the safety concept is defined by the B&C programme as the integrated description of the elements on which the passive long-term safety of the proposed disposal system rests. This description, which is given at a level of detail appropriate to the stage of disposal system development, includes:

(1) the safety functions provided by the main components of the disposal system and its geological coverage. These are functions that the disposal system should fulfil to achieve its general safety objective of providing long-term safety through concentration and confinement strategy (IAEA, 2011b). A number of engineered and natural barriers, fulfilling different safety functions, are placed between the contaminants and the accessible environment. A possible release of radionuclides is spread far in time so that



radioactive decay can decrease the radiological hazard and so that the eventual releases to the environment are below the regulatory limits.

(2) features of the system and its implementation providing robustness and reliability by ensuring that each of the safety functions will be fulfilled over at least the assigned time frames, despite irreducible uncertainties. Evidence, arguments and analyses relevant to long-term safety are acquired or progressively developed as the RD&D programme progresses, and are used to refine and elaborate or confirm the initial description provided by the safety concept to form a key component of the Safety and Feasibility Case.

The safety functions provided by the disposal system are illustrated in Figure 3 and detailed hereafter:

1. *Engineered containment (C)* (only for category C waste) consists of preventing the release of contaminants from the waste disposal package during the thermal phase, where the thermal phase is the time frame during which the temperature of the host formation is expected to lie above the range of temperatures within which nominal migration properties can be relied upon, by using one or several engineered barriers. The component contributing to this safety function is a part of the engineered barrier system called the supercontainer (Section 3.2.3.1).

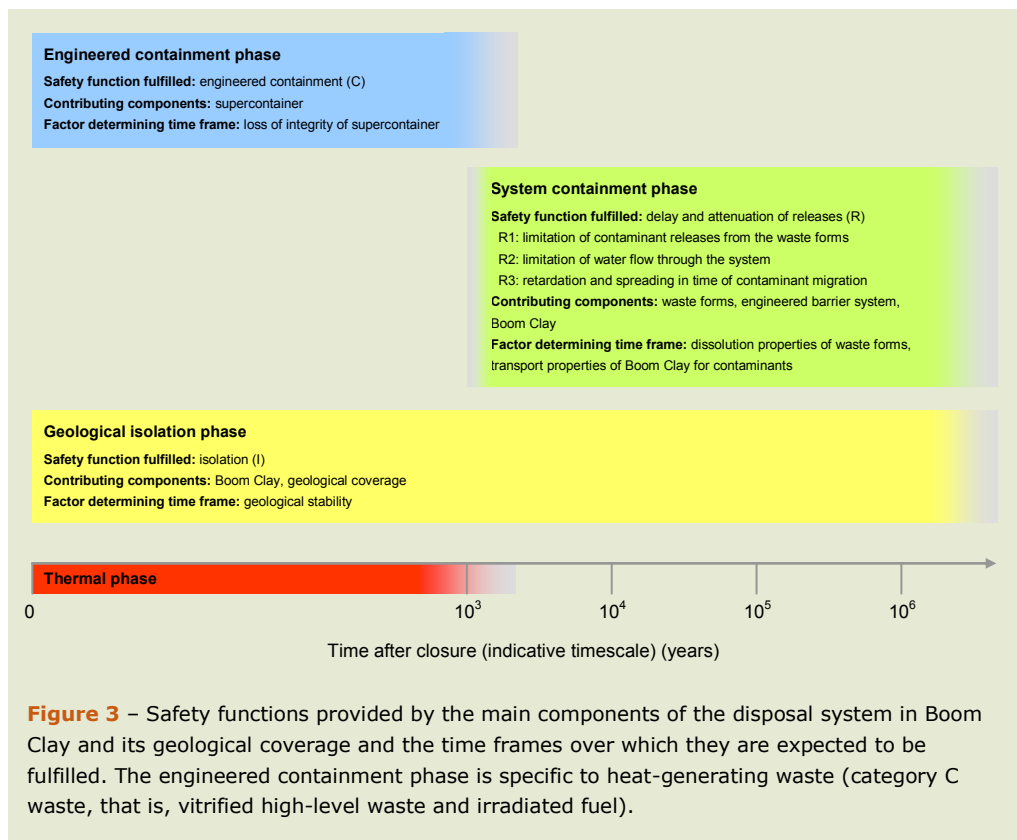
2. *Delay and attenuation of the releases (R)* in order to retain the contaminants for as long as required within the disposal system. The components contributing to this safety function are the waste forms, the engineered barrier system and the host formation. Three sub-functions are defined:

- limitation of contaminant releases from the waste forms (R1): The R1-function consists of limiting and spreading in time the releases of contaminants from the waste packages.
- limitation of the water flow through the disposal system (R2): The R2-function consists of limiting the flow of water through the disposal system as much as possible, thus preventing or limiting the advective transport to the environment of the contaminants released from the waste packages.
- retardation of contaminant migration (R3): The R3-function consists of retarding and spreading in time the migration to the environment of the contaminants released from the waste packages.

3. *Isolation (I)* of the waste from man and the environment for as long as required, by preventing direct access to the waste and by protecting the repository from the potential detrimental processes occurring in its environment. The host formation and its geological coverage provide this safety function. Two sub-functions are defined:

- reduction of the likelihood of inadvertent human intrusion and of its possible consequences (I1): The I1-function consists of limiting the likelihood of inadvertent human intrusion and, in case such intrusion does occur, of limiting its possible consequences in terms of radiological and chemical impact on humans and the environment.
- ensuring stable conditions for the disposed waste and the system components (I2): The I2-function consists of protecting the waste and the engineered barrier system from changes and perturbations occurring in the environment of the

facility, such as climatic variations, erosion, uplifting, seismic events or relatively rapid changes in chemical and physical conditions.



The primary component of the disposal system from the point of view of long-term safety is the host formation.

The poorly indurated clay studied in Belgium, the Opalinus clay investigated in Switzerland and the Callovo-Oxfordian clay chosen in France for the disposal of high-level and long-lived radioactive waste present similar characteristics. Thanks to their properties, they are efficient natural barriers to the migration of radionuclides and chemical contaminants towards the surface environment:

- They have a very low permeability. There is therefore practically no water movement in these clays. As a result, transport is essentially diffusive, which means species migrate under the influence of their concentration gradient, not under the influence of the pore water movement.
- They have a strong retention capacity for many radionuclides and chemical contaminants (sorption capacity, favourable geochemical properties, etc.). Their migration through the clay is thus considerably delayed.
- They have a capacity of self-sealing. For instance, fractures such as those induced by excavation works seal within weeks in Boom Clay and Ypresian clays.

Consequently, ONDRAF/NIRAS considers that its safety concept and repository design are valid for disposal in Boom Clay and Ypresian clays. However, the assumptions need

to be validated for the Ypresian clays, whose knowledge is limited. The safety concept and repository design will be adapted, if necessary.

The engineered barrier system (EBS) fulfils three main functions: next to operational safety aspects, it limits perturbations of the host formation by repository construction, operation and closure and it contains the category C waste during the thermal phase. Furthermore, it also contributes to the delay and attenuation of the releases. Finally, the presence of backfill and seals will ensure that transport within the repository after closure will be diffusion-dominated.

## **2.2 Management strategy**

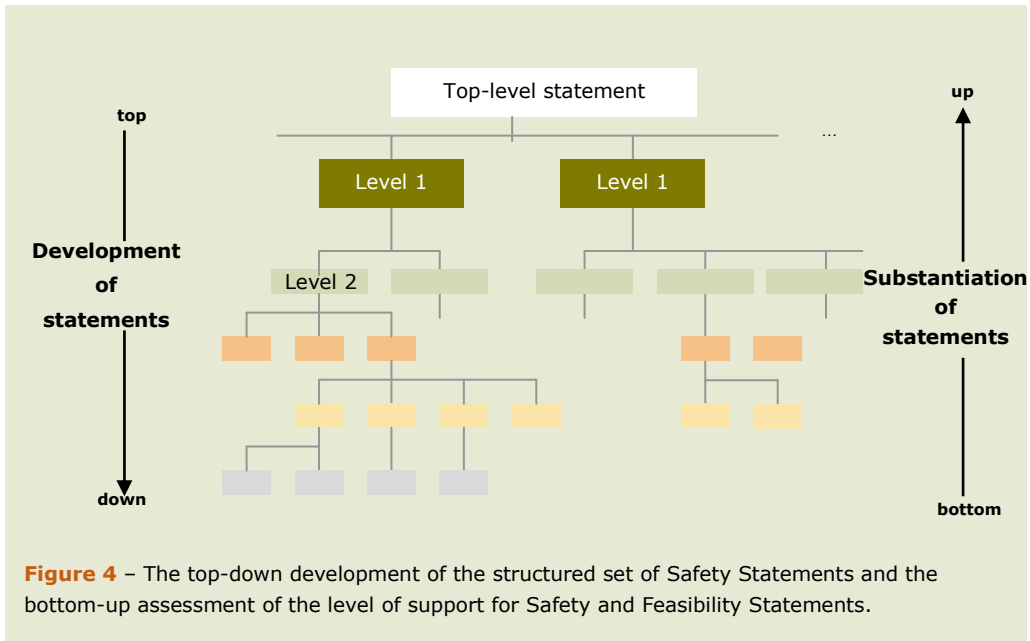
Whereas the safety strategy defines in broad terms how it is envisaged that safe disposal will be achieved, the management strategy defines how the activities for the implementation (realisation) of the safety strategy should be managed to ensure that the boundary conditions, strategic choices and safety principles therein are respected and that there is a high level of confidence in the results and the quality of the SFC1. The management strategy is expressed through a set of management principles and high-level management choices and the resulting principles, rules and practices to be applied at the operational level.

The management principles are derived from the safety principles, the (corporate) integrated management system and the quality requirements, the latter being based on the experience ONDRAF/NIRAS has gained from previous stages of the programme and on the best practices followed by other national programmes.

The high-level management choices are set by ONDRAF/NIRAS. Of major importance for the RD&D is that all SFC1-related activities are driven by the safety functions, which the repository has to fulfil. The safety functions must be translated into a set of more pragmatic requirements to be used for implementation. ONDRAF/NIRAS has chosen to formulate and organise these requirements as a set of claims regarding what the system does and the properties that it has, arranged hierarchically in a tree structure, called the Safety and Feasibility Statements trees. The introduction of statements in the ONDRAF/NIRAS RD&D programme on geological disposal has resulted in significant changes in the programme management. In particular, reorganisation of the RD&D programme around the need to substantiate the statements has led to a more efficient and pertinent prioritisation of the issues.

The statements are structured in a top-down manner, starting with the most general (high-level) statement and progressing to increasingly specific (lower-level) statements (Figure 4). The top-level statements define the main objectives of the safety and feasibility assessment of the Safety and Feasibility Case at hand, namely demonstrating that the disposal system can provide long-term safety and that it is feasible to implement. The substantiation of the Safety and Feasibility Statements, with the multiple lines of evidence and their associated uncertainties generated from the RD&D programme, is performed bottom-up. The need to obtain arguments to substantiate the lowest-level Safety and Feasibility Statements and to address any open issues guides the RD&D programme, ensuring that focus is maintained on the upper claims. At this stage of the programme, two trees are under development, one focused on long-term safety (Section 2.3.1) and the other one on feasibility and operational safety

(Section 2.3.2). These trees will merge at a later stage. The derivation of the tree statements is part of the management system.



## 2.3 Management system

The implementation of the management strategy leads to the SFC1 management system. The development of SFC1 is performed within ONDRAF/NIRAS integrated management system that is defined at the corporate level and integrates the different arrangements and processes necessary to address and achieve all the goals of the organisation (Chapter 1).

As defined by IAEA, the main aim of the management system is to achieve and enhance safety by: i) bringing together in a coherent manner all the requirements for managing the organisation; ii) describing the planned and systematic actions necessary to provide adequate confidence that all these requirements are satisfied; and iii) ensuring that health, environment, quality and economic requirements are not considered separately from safety requirements, to help preclude their possible impact on safety (IAEA, 2008). Safety is paramount within the management system.

The management system encompasses quality control, quality assurance and quality management. The management system includes the set of deliverables submitted to the government with the request to proceed to the next stage. The need for effective management systems applied to organisation, responsibilities, resources, processes and quality is set out in the generic technical guidance from the Federal Agency for Nuclear Control or FANC (FANC, 2013). The management system also includes methodologies and processes specifically developed for SFC1. The management system is detailed in the management strategy report of ONDRAF/NIRAS (ONDRAF/NIRAS, to be published).

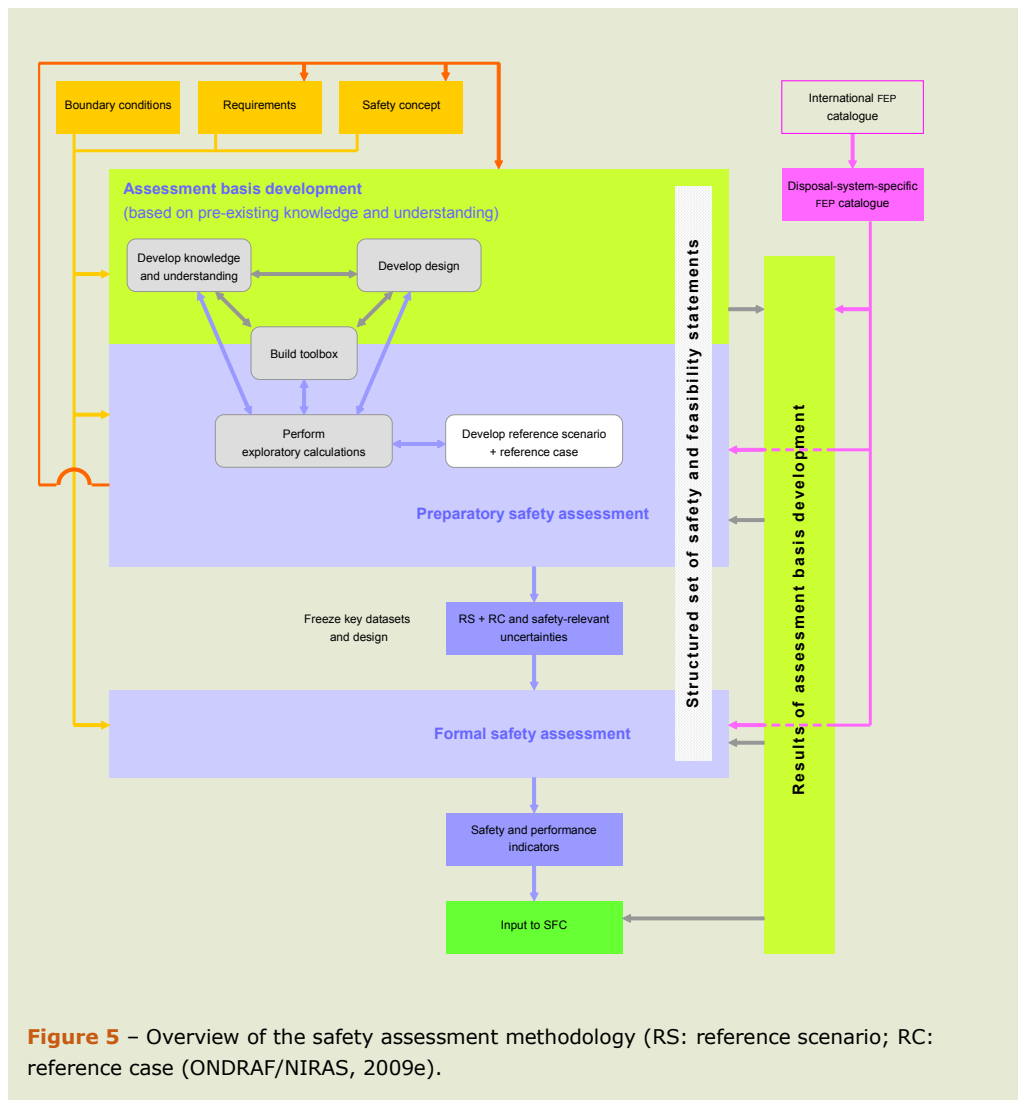
This section presents three elements of the management system: the safety assessment methodology (Section 2.3.1), the feasibility assessment methodology (Section 2.3.2) and the quality assurance (Section 2.3.3). Three insets illustrate the implementation of the management system at the end of the section.

### 2.3.1. Safety assessment methodology

This section presents the methodology that ONDRAF/NIRAS follows for assessing the long-term safety of geological disposal in poorly indurated clay. It currently focuses on radiological aspects, but it is expected to be applicable to non-radiological aspects as well. It is based on ONDRAF/NIRAS own evaluation of the strengths and limitations of its SAFIR2 methodology, in particular regarding the treatment of uncertainties, on the conclusions and recommendations from the peer review of SAFIR2 (NEA, 2003) and, more generally, on recent international discussions and developments in safety assessment methodology. Recently, the ONDRAF/NIRAS methodology has in turn contributed to set methodological principles and best practices in various international projects (NEA, 2013) (NEA, 2012c), (MODERN, 2011).

Safety assessment in a Safety and Feasibility Case is the process of systematically analysing the hazards associated with a disposal facility and assessing its ability to provide for the fulfilment of safety functions and to meet technical requirements as well as those from the regulatory body. The safety assessment methodology, illustrated in Figure 5, describes the processes (arrows) and interactions (loops) as well as the steps and main activities (boxes) that are followed for the evaluation of the long-term safety of the proposed disposal system. The major milestones are summarised hereafter. More

information is available in the long-term safety assessment methodology document (ONDRAF/NIRAS, 2009e).



Practically this process of safety assessment takes the form of a quantitative assessment of the safety and the performance of the disposal system through a large spectrum of *selected scenarios and calculation cases*. The results of the safety assessment provide key-input to the demonstration supported by the Safety and Feasibility Case that the disposal system will perform safely if built as intended. They also highlight the residual uncertainties and outstanding issues to be tackled in the next programme stage. The term “uncertainties” encompasses uncertainties bound to expected processes, on the level of models and parameters, and all perturbing features, events and processes (FEPs) of low expectation (e.g., geologic events).

## Scenarios

In the ONDRAF/NIRAS safety assessment methodology, scenarios include a reference scenario, based on the safety concept, several altered scenarios and human intrusion scenarios<sup>6</sup>.

A scenario is a set of high-level descriptions of possible evolutions of the disposal system, in a simplified, abstract form. These high-level descriptions share a common time-deployment of the safety functions. In the reference scenario, safety functions are deployed such as described in the safety concept while for the altered-evolution scenarios, one or more safety functions are considered as partially or fully impaired. Thus, the reference scenario takes account of processes and events likely to occur and assumes that (1) there are no unexpected or significant undetected features in the environment surrounding the disposal system (such as geological structures) that could significantly perturb its performance, and (2) intrusion into the repository or its immediate geological environs by humans does not occur within the period covered by safety assessment. This definition is in line with the common understanding of the reference scenario (Nagra, 2010b) (NEA, 2012c).

On the relevant high-level descriptions of the possible evolutions of the disposal system within a scenario rest the so-called assessment cases. An assessment case is a specific realisation of how the disposal system might evolve and perform over time assuming a particular set of assumptions, design or natural features, processes and parameters values. Ultimately, the outcomes of the different assessment cases are expressed in terms of radiological impact (safety calculations). Besides, the results give insights on the impact of various uncertainties and provide guidance to expert discussions and future RD&D.

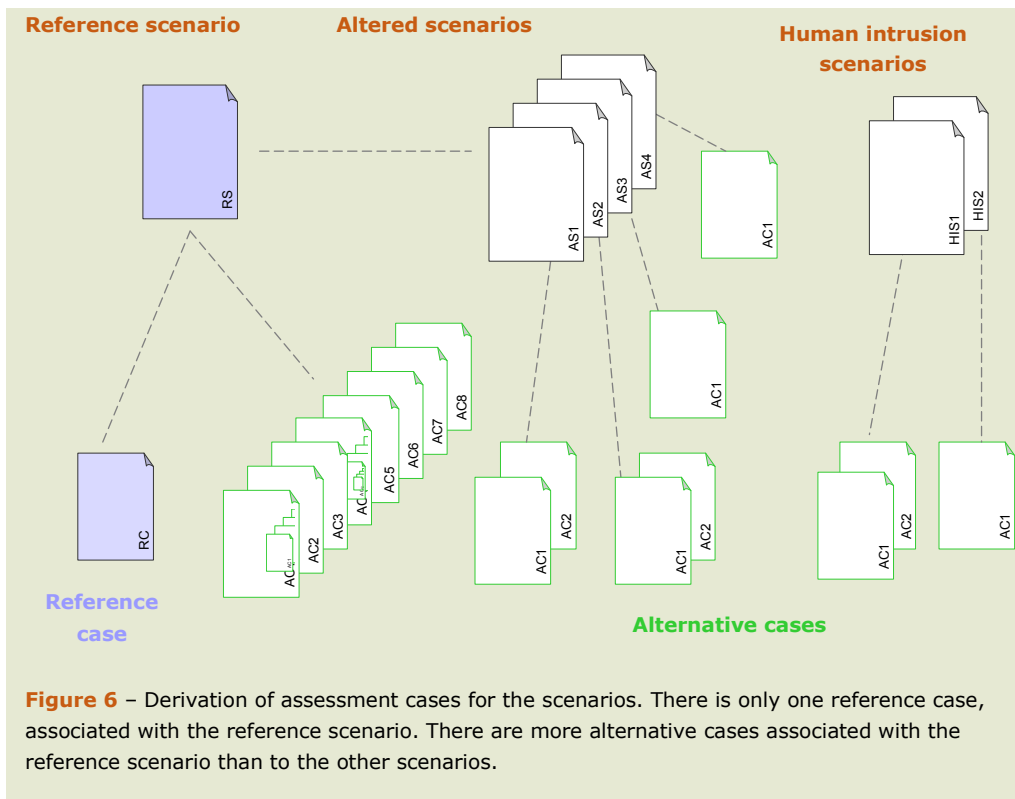
The reference scenario includes the so-called reference case and multiple alternative cases that adopt different assumptions (Figure 6). In the reference case, the system is assumed to be implemented according to the specified design. The assumptions behind this case tend to be conservative. The development of the reference case is an iterative process, with the definition of successive working versions. The first working version is based on the existing knowledge from the previous Safety and Feasibility Case. In subsequent iterations, assumptions are refined making better use of acquired knowledge and understanding of the system. Working versions integrate the most recent RD&D results (Depaus and Capouet, 2012).

Alternative cases within the reference scenario are defined to elucidate the impact of uncertainties on evolution, models and parameters or are used to evaluate the impact of design options. The use of alternative assessment cases is valuable, for example, to show that different model assumptions lead to similar results or, for those uncertainties that are potentially amenable to reduction or mitigation by future RD&D, to focus RD&D on the uncertainties to which safety and performance are most sensitive. Comparing the results of the evaluation of alternative cases with those of the reference case also provides an indication of the degree of conservatism introduced in the reference case and, hence, of the safety margins. In addition to cases of lower probability of occurrence than the reference case, alternative cases may also be considered for treating evolutions

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<sup>6</sup> These scenarios also include human action scenarios.

of the system with the same probability of occurrence as the reference case, such as climatic evolutions. The alternative cases are added in the course of the programme.



In addition to the reference scenario, the B&C programme distinguishes two other categories of scenarios, whose impact can be compared with that of the reference one (Figure 6):

- Altered scenarios represent alternative futures of the disposal system with a lower probability of occurrence than the reference scenario and which result from events or processes other than human actions that may significantly impair one or more safety functions. The altered scenarios are derived from a systematic examination of the perturbing phenomena and associated uncertainties potentially affecting the validity of the Safety Statements, and consequently, by upward propagation of these uncertainties from one statement to another, up to the top-level statements representing the safety functions. In addition to this bottom-up approach of scenarios development, completeness checks can be performed with other methodologies (e.g., PROSA (ONDRAF/NIRAS, 2001), storyboards, etc.)
- Human intrusion scenarios represent alternative futures of the disposal system resulting from future human actions. Their probability of occurrence cannot reliably be quantified over the time frame covered by safety assessment, but in line with the safety concept, it is kept low by siting and design measures. For each of these scenarios, one of several calculation cases will be developed. The human intrusion scenarios will be developed in interaction with the Federal Agency for Nuclear Control or FANC.



### Organisation of RD&D activities around three poles of expertise

A key management measure of the safety assessment methodology is the organisation and structuring of all RD&D activities around three poles of expertise, with clearly defined responsibilities and roles, the “phenomenology”, the “technology” and the “safety assessment” poles:

- The pole “phenomenology” concerns the development of scientific understanding of the disposal system and the events and processes that affect its evolution and performance. Phenomenological studies include laboratory tests, process models, *in-situ* site characterisation studies, full-scale tests and studies of natural and anthropogenic analogues. Experts in phenomenology consider the evolution of the disposal system including all its interactions (thermal, hydraulic, mechanical, biological and chemical) and pursue the goal of continuously refining the description and the understanding of the evolution of the system through an iterative RD&D programme.
- The pole “feasibility” concerns the development of a repository design and the means for its implementation, including feasibility assessments, which includes operational safety assessments. It provides design specifications, and thus defines the engineered barrier system to be developed.
- The pole “safety assessment” concerns the analyses of the proposed disposal system related to long-term safety, both radiological and non-radiological. The analyses may be partial or more comprehensive and systematic. In addition, the pole develops the strategies as well as the methodologies followed in order to elaborate the Safety and Feasibility Case (*e.g.*, safety strategy, management strategy, safety assessment methodology, monitoring strategy, data clearance, etc.)

Interactions between the three poles of expertise are important to ensure that the phenomenological and technological uncertainties are understood and correctly abstracted in the scenarios.

### Assessment basis

The assessment of the safety and feasibility of a geological disposal system requires a detailed knowledge base and adequate analysis tools: these form the assessment basis, whose development, through an iterative and stepwise process, is a major objective of the RD&D programme. More specifically, the assessment basis includes the following:

- the description of the design of the proposed disposal system and, depending on the stage of planning and development, implementation procedures: this aspect of the assessment basis falls within the scope of the “feasibility pole” of the RD&D programme;
- the scientific bases that are relevant to the assessment of the safety and feasibility of the disposal system under consideration, including relevant process models and computer codes, a description of the expected phenomenological evolution of the system, and the scientific knowledge and understanding underlying this description, including associated uncertainties: this aspect of the assessment basis falls within the scope of the “phenomenology pole” of the RD&D programme;

- the various methods, models, computer codes and datasets for assessing safety and feasibility, including the safety assessment methodology and the feasibility assessment methodology: this is termed the “toolbox” by ONDRAF/NIRAS.

### Safety assessments

Safety assessments are carried out in two main phases: a phase of preparatory assessments and a phase of formal assessment, according to the safety assessment methodology and in line with recent international trends.

Preparatory safety assessments, the first phase of safety assessments, aim to identify potential safety-relevant uncertainties, to provide partial, quantitative assessments of their impact on system performance, and to confirm the definitions of the reference scenario and the reference case in order to provide a suitable starting point for formal safety assessment. Preparatory safety assessments must give reasonable assurance to safety assessors, prior to the formal safety assessment being undertaken, that their findings will provide adequate support to the required Safety and Feasibility Case.

Preparatory safety assessments are carried out simultaneously with works on repository development and system understanding. They include *safety and exploratory calculations*.

Safety calculations model the migration of the contaminants throughout the disposal system to the biosphere. They give a quantitative assessment of the performance and safety of the disposal system with the use of safety and performance indicators, such as dose and risk. Their results are compared with regulatory limits or guidelines.

All other calculations carried out during preparatory safety assessments are called exploratory calculations. They are quantitative analyses aimed to study the sensitivity of the long-term safety of the disposal system to parameter and model assumptions. They serve a range of purposes, such as:

- Evaluating the impact of a particular process or uncertainty on system performance and hence determine its relevance to safety and in turn, to steer the RD&D. For example, exploratory calculations estimating the gas generation and removal rates for B&C waste have highlighted the need for further RD&D in this field for the disposal of category B waste only (thus not for category C waste). Conversely, exploratory calculations may also allow to identify which uncertainties have negligible impact on system evolution and performance and do not, therefore, need to be addressed by RD&D as a matter of priority and to be carried forward in formal safety assessment of the reference scenario.
- Testing the robustness of a system, particularly with respect to uncertainties that are difficult to quantify or bound. For example, the sensitivity of safety indicators to the lifetime of irradiated fuel is an analysis commonly performed to understand the importance of this parameter for long-term safety.
- Bounding the extent of perturbations. For example, exploratory calculations carried out using simplified and conservative models provided an upper limit of the extent of oxidised zone in Boom Clay.

Once the level of support available for the statements and the knowledge of the impact of uncertainties are judged sufficient, given the objectives of the programme stage at hand, for proceeding with formal safety assessment, the key datasets within the assessment basis the design, and consequently the boundary conditions, strategic choices and requirements, are formally frozen for the formal assessment.

Formal safety assessments, which form the second phase of safety assessments, aim to demonstrate in a formal, quantitative way, that the disposal system can ensure the safety of the man and the environment despite the existence of residual uncertainties, in compliance to regulations and other requirements included in the safety strategy. They are quantitative and as exhaustive as possible, and are conducted only every few years, shortly before the planned compilation of a Safety and Feasibility Case.

A formal safety assessment typically considers several scenarios and different assessment cases for each scenario, which are evaluated to illustrate the impact of the various uncertainties. A formal safety assessment may also include specific calculation cases imposed by the regulator.

Formal assessments also aim to illustrate by a wise selection of calculation cases and indicators, the robustness and the defence-in-depth of the system with regard to various evolutions with respect to the reference case.

The results of the evaluation of assessment cases, expressed in terms of safety indicators such as dose and risk, are compared with regulatory limits or guidelines. Should the formal safety assessments not confirm the safety of the system, then the formal phase would be stopped and the safety strategy of the geological programme would need to be adjusted. This is however not expected, as the programme progressively proceeds from one stage to the next.

Both preparatory safety assessments and formal safety assessments can focus the work of phenomenology by identifying the key safety-relevant phenomena and can lead to the specification of safety requirements on key components that technology should aim to meet. The formal safety assessments prioritise the previously identified uncertainties as input to the next programme stage.

As part of the quality assurance of safety assessments, completeness checks are conducted during both preparatory assessments and formal assessments by comparison with the international FEP list compiled by the NEA (in order to verify that the FEPs identified in other national programmes and potentially relevant for the Belgian programme have been adequately taken into account or screened out in the assessments) (NEA, 2000).

From a phenomenological point of view, experts have to consider the applicability of their data under the conditions prevailing in a real disposal system, at a chosen site, over the course of the whole assessment period. In other words, they need to consider the applicability of the data gained from a reference site for RD&D in Boom Clay to a (larger) zone in the same host rock (through upscaling, evolving conditions and transferability) and to a zone in Ypresian clays (through transposability), as detailed hereafter:

- Upscaling refers to the applicability of the phenomenological data collected at the scale of the laboratory over relatively short intervals of space and time to a larger

spatial scale of interest in the safety assessment. (Upscaling refers for instance to the short duration of the experiment, small size of samples, artefacts due to the type of experiments, etc.)

- Evolving conditions refers to the impact on the phenomenological data obtained today of phenomena occurring over time that may affect the disposal system, such as phenomena triggered from within the disposal system or external events (ONDRAF/NIRAS, 2009e).
- Transferability typically addresses the transfer of parameters values from boreholes to the whole Boom Clay zone (e.g., hydraulic parameters). Because the raw data come from boreholes (amenable to a vertical view simplification), the variability concerned here is a horizontal variability between two points, from one borehole to another or from one borehole to a larger area.
- Transposability is a measure of the extent to which the knowledge obtained in one host rock (parameter, technique, process understanding, conceptual model or high-level conclusion) can be used as proxy in another host rock. This methodology is based on the comparison of basic properties and prevailing conditions and lead to the conclusion that they do not have, at first sight, to be studied again, or, on the contrary, cannot be applied as equivalent and need additional investigation.

The main driver behind the transferability/transposability approach is the different stage of development of specific research programmes, allowing the knowledge base to be expanded during early stages of research as well as allowing a comparison of particular aspects at different situations during a more advanced stage of research, possibly giving rise to confidence building in the case of convergent results or give rise to new research question and guide future research in the case of divergent results (Mazurek *et al.*, 2008). The transferability/transposability approach might also accelerate the research if existing conceptual models and investigation techniques can be recycled (Mazurek *et al.*, 2008).

### **Safety statements**

The Safety Statements tree has evolved with time. Initially (since SAFIR2) Safety Statements were derived top down from safety functions. They were later revised progressively in the light of increasing knowledge from the ongoing RD&D programme addressing wider aspects of system understanding. The Safety Statements thus evolved from being strictly “safety-assessment oriented” to “safety-case oriented”, able to provide next to the safety, a synoptic view of all aspects linked to the implementation of a disposal system. These changes were mainly driven by the iterative interactions between the three poles during the early preparatory phase of SFC1.

At the time of SAFIR2, the focus of the safety assessment was on safety assessment calculations. A Safety and Feasibility Case such as SFC1 is broader in scope, drawing together the diverse and growing body of evidence that supports the assertion that the system envisaged is both safe and technically feasible. Experience has shown that, as the programme has gained in maturity, the focus of the RD&D programme has tended to shift towards a quest for more general understanding of the system and its evolution beyond the narrower objective of supporting the assumptions of, and providing input parameters for, safety assessment calculations. This shift in focus is consistent with the

emphasis in broader aspects of safety and confidence in safety that will be addressed in SFC1.

Table 2 presents the current version of the high-level Safety Statements, which is used to structure this document (the Annex A1 presents the whole tree). It comprises four branches supporting the assertion that we have confidence in the long-term safety:

- The branch “*the system is known*” comprises the knowledge basis acquired in 30 years of research about the waste, the disposal system, its evolution (which can be bounded) and its environment (in which the impact of the system is assessed), as detailed in Chapters 3 and 4.
- The branch “*the safety functions that have been defined are relied upon*” aims to show that the proposed disposal system will provide passive safety over the long-term. The substantiation of this branch is under way and will be developed for SFC1.
- The branch “*the performance of the disposal system meets the requirements*” includes information about the definition and calculations of the relevant performance and safety indicators and comparison with regulatory requirements, the environment impact of a disposal system and other external requirements. It is under development (see Chapters 7, 8 and 9).
- The branch “*residual uncertainties*” includes statements explaining that there are no uncertainties that call into question the capacity of the system to fulfil the requirements and that there are good prospects that future RD&D will enable safety-relevant uncertainties to be reduced or even avoided. It will be developed for SFC1. Inset 4 presents the NEA’s way to treat the uncertainties, for information.

**Table 2** – Current version of the high-level Safety Statements.

<b>We have confidence in the long-term safety</b>	
Indeed,	The system is known
Indeed,	The system components can be characterised
and,	The evolution can be bounded
and,	The safety functions that have been defined are relied upon
Indeed,	Isolation of the system is ensured during the period of concern
and,	Containment is ensured during at least the thermal phase
and,	Rate of radionuclides transport is low and some radionuclides are delayed
and,	The performance of the disposal system meets the requirements
and,	The remaining/residual uncertainties are identified and manageable (by RD&D, conservative assumptions, scenarios, etc.). The irreducible uncertainties do not impact the overall knowledge, understanding and safety of the disposal system.

The major ideas behind this structure include:

- The (repository) site is chosen in order to limit the number of external perturbations to be considered in the whole evolution of the system (link to optimisation).
- The effects of external perturbations unavoidable by site location do not compromise the functioning of the disposal system.
- The design of the repository is optimised in order to limit internal perturbations (perturbations due to the repository and the waste).
- The effects of internal perturbations (unavoidable by design) do not compromise the functioning of the system.

The tree and its substantiation include all category B&C waste types, upscaling, evolving and transferability conditions linked to the reference scenario.

**Inset 4 – How to treat uncertainties (extract from (NEA, 2013))**

“Strategies of treating uncertainties within the safety assessment are well established. Generally, these fall into one or more of the following five strategies:

- Demonstrating that the uncertainty is irrelevant to the safety assessment.
- Addressing the uncertainty explicitly, for example through a probabilistic approach or through a series of sensitivity studies.
- Bounding the uncertainty, for example by making a number of simplifying assumptions taking a conservative view, *i.e.* assumptions are made such that the calculated safety indicators such as dose rate or radiological risk will be overestimated.
- Ruling out the event or process being uncertain, for example ruling out uncertain events on the basis of very low probability or very low consequence.
- Using an agreed stylised approach to avoid addressing the uncertainty explicitly, for example, biosphere uncertainties and uncertainties regarding future human behaviour patterns may be addressed used a stylised “reference man” and an agreement that the assessment should be based on present day conditions and technologies.”

### 2.3.2. Feasibility assessment methodology

The feasibility assessment methodology is based on the Feasibility Statements, organised in a tree structure, defined in a top-down manner in analogy with the Safety Statements (ONDRAF/NIRAS, 2011e). At this stage of the programme, both types of statements evolve on their own. The top-level statement states that:

*"The proposed disposal system can be constructed, operated and progressively closed, taking into account long-term safety requirements and operational safety requirements, at a cost that is commensurate with available funding."*

This general statement is underpinned by three more specific (Level 1) Feasibility Statements relating to:

- Engineering practicability: The engineering practicability of the disposal design is proven.
- Operational safety: The safety of workers, the public and the environment can be guaranteed during the operational phase.
- Cost: The costs for the construction, operation and closure of the repository (including the monitoring period) can be covered.

Lower-level Feasibility Statements relating to the different components of the disposal system are then derived from these high-level FS, as shown in Table 3 and in excerpts of the FS hierarchy provided in subsequent sections of this chapter on feasibility and in Annex A1.

Substantiation of the FS is performed in a bottom-up fashion, starting with the most detailed Level 4 FS and working upwards. The approach to acquire evidence and build a complete set of arguments supporting feasibility includes the following steps (Wacquier *et al.*, 2011):

- Review of the current status of knowledge and understanding relating to each FS and synthesis of the "state-of-the-art".
- Identification of uncertainties or gaps in knowledge and understanding, referred to as open questions, which need to be addressed in order to demonstrate that every activity forming part of the category B&C disposal design is feasible.
- Prioritisation of open questions based on the potential impact of each one on the feasibility of the category B&C disposal programme, and on the level of uncertainty that exists.
- Design and scheduling of a series of RD&D studies that will address remaining open questions, in order to provide sufficient evidence to underpin feasibility for SFC1.
- Undertaking the RD&D studies.
- Reviewing the outputs from RD&D studies, and using new evidence to update the arguments substantiating feasibility.

This process is iterative: as new information becomes available, it is used to progressively strengthen the evidence underpinning feasibility, but also to identify where

uncertainties still remain, and therefore to define the scope of subsequent RD&D studies, until a sufficient level of confidence in feasibility is achieved.

Within the feasibility RD&D programme, there is a focus on engineering practicability because of the unique nature of the Belgian disposal design, which may require tailored design and engineering solutions. However, the implications of construction and operational activities on worker and public safety, and environmental impacts are also being evaluated. Other factors influencing feasibility such as cost and scheduling are also considered.

**Table 3** – High-level Feasibility Statements

<b>FS The proposed disposal system can be constructed, operated and progressively closed taking into account operational safety issues and with adequate funding</b>	
<b>Indeed,</b>	<b>FS 1 The engineering practicability of the disposal system is proven</b>
Indeed,	FS 1.1 The disposal waste packages can be fabricated
and,	FS 1.2 The repository for category B&C waste can be constructed
and,	FS 1.3 The repository for category B&C waste can be operated
and,	FS 1.4 The repository for category B&C waste can be closed
and,	FS 1.5 The performance of the disposal system can be monitored
<b>and</b>	<b>FS 2 The safety of workers, the public and the environment can be guaranteed during the operational phase</b>
Indeed,	FS 2.1 The non-radiological risks associated with a normal operating scenario can be mastered
and,	FS 2.2 The radiological risks associated with a normal operating scenario can be mastered
and,	FS 2.3 The risks resulting from accident scenarios and external events can be mastered
and,	FS 2.4 Fissile materials can be handled appropriately from a security, safeguards and criticality perspective
<b>and</b>	<b>FS 3 The costs for the construction, operation and closure of the repository can be covered</b>
Indeed,	FS 3.1 The costs for construction, operation and closure of the disposal facility for category B&C waste, including decommissioning of the site surface installations, have been evaluated
and,	FS 3.2 Waste tariffs and current funding mechanisms are adequate to cover the required costs taking into account escalation
<b>and</b>	<b>FS 4 The remaining/residual uncertainties are identified and manageable (by RD&amp;D, modification of design, etc.). They do not impact the feasibility and safety of the system.</b>



### **2.3.3. Quality assurance**

Quality assurance within the RD&D programme aims to enhance the confidence in and the quality of SFC1 (and of Safety and Feasibility Cases beyond it) by promoting quality in both the assessment basis and its application in safety and feasibility assessments. This should enable well-substantiated Safety and Feasibility Statements to be made.

There are two broad categories of quality assurance (QA) procedures and measures (ONDRAF/NIRAS, 2009c):

- specific quality procedures applied in assessment basis development and in safety and feasibility assessments;
- more general organisational measures applying to the RD&D programme as a whole.

#### **Quality procedures**

Various types of procedures are applied as part of quality assurance to ensure the quality and reliability of the assessment basis throughout its development and to ensure the quality and reliability of safety and feasibility assessments.

Quality procedures in assessment basis development and in safety and feasibility assessments relate mainly to the following:

- completeness checking using features, events and processes (FEPs) (for safety assessments) or storyboards (for feasibility assessments) (see Inset 5);
- development of geo-scientific information system (GSIS) that integrates primary scientific data (see Inset 7);
- clearance, versioning and freezing of datasets (data clearance);
- verification of the adequacy of methods and qualification, verification and validation of models and computer codes (QV&V);
- definition of the “expert judgment”;
- verification of the correctness of the application of models, computer codes and datasets;
- reviews and auditing of all elements contributing to Safety and Feasibility Cases.

#### **Organisational measures**

In addition to specific quality procedures, organisational measures such as a clear assignment of roles to individuals involved in RD&D activities and the existence of an effective knowledge management system contribute to the overall quality of the work (see Inset 6).

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## **Roadmap – Chapter 2 – Guiding approach for the development of a geological repository**

*For SFC1*, ONDRAF/NIRAS will interact with the Federal Agency for Nuclear Control or FANC. ONDRAF/NIRAS will in particular:

- take into account the regulator's expectations regarding the scope, content and level of detail of the SFC1;
- check whether its methodologies comply with the regulator's guidance;
- discuss specific points of guidance and methodology with the regulator.

ONDRAF/NIRAS will then further complete the derivation of the alternative cases and the altered scenarios. For instance, the development of the human intrusion scenario specific to geological disposal requires input from the regulator, as it is not possible to predict human intrusion activity over an extensive period.

*For SFC1*, ONDRAF/NIRAS will further develop its requirement management system (RMS), especially for feasibility aspects (and related statements). The RMS will document and describe the requirements of the disposal system and its components. In accordance with the safety strategy and the management principles, the RMS will also keep track of changes to the system or the requirements and the reasons for these changes. As the implementation of the disposal system will take several decennia and as new requirements will undoubtedly be added, the RMS is a crucial tool in guaranteeing the traceability of changes and lines of reasoning behind the different requirements.

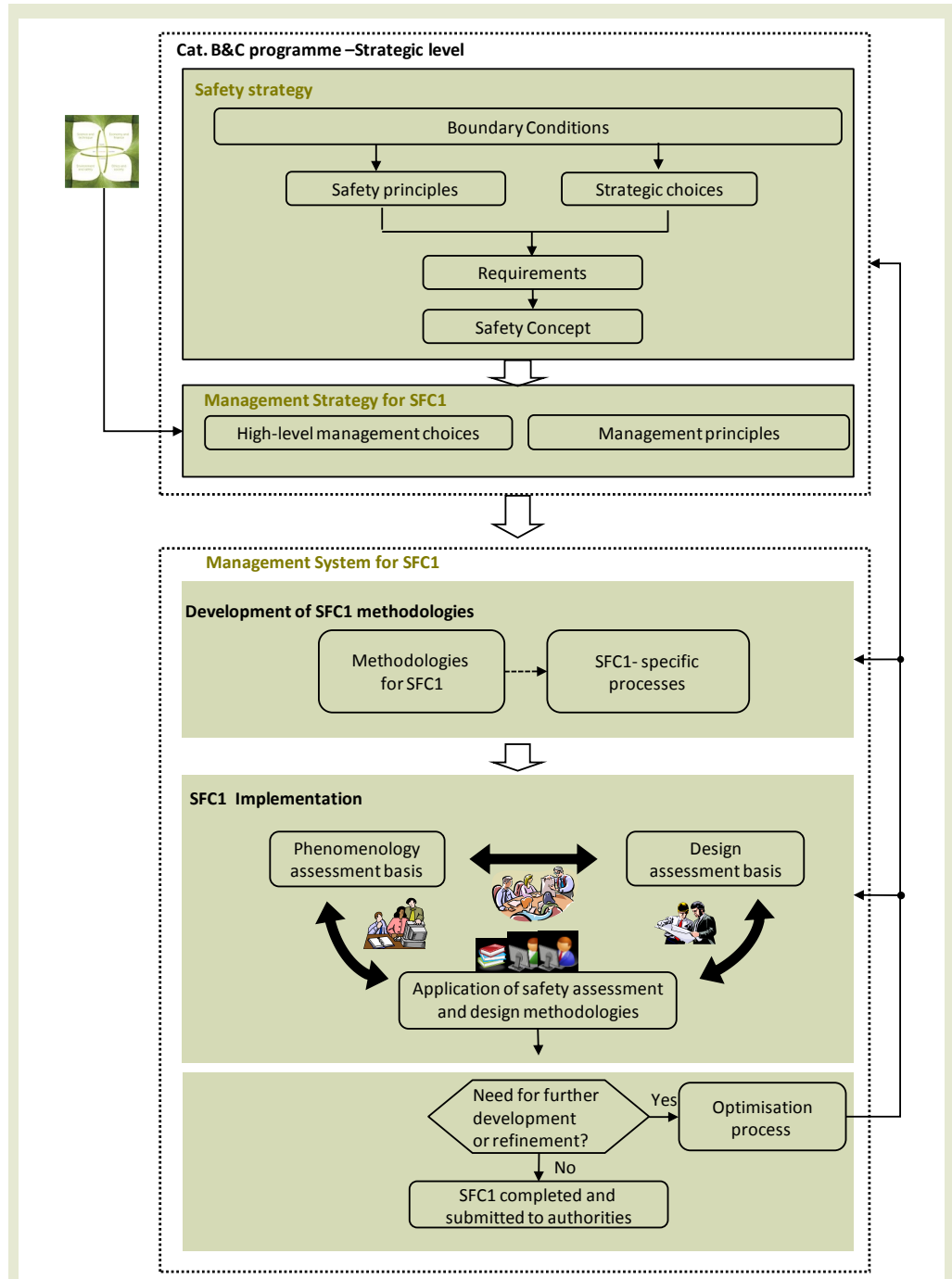
*For SFC1*, ONDRAF/NIRAS will further implement tools and procedures for supporting its methodology such as:

- the geo-scientific information system (GSIS) and the Open Text knowledge management system, to guarantee the traceability and organisation into a hierarchy of assumptions, decisions and data.
- the QA (Quality assurance) analysis of the calculation tool chains (assumptions, codes and succession of tools) and of the data clearance system.
- the documentation of the various steps in the implementation of the optimisation process in order to guarantee its traceability.

*For SFC1*, ONDRAF/NIRAS will adapt its safety concept to a disposal system in Ypresian clays, if necessary (see Chapter 10).

*For confidence building*, ONDRAF/NIRAS will continue its active involvement in the European platform IGD-TP, in the NEA (through the Integration Group for the Safety Case (IGSC), where best practices for the development of Safety Cases are collected, discussed and adopted), and in the IAEA (to follow up methodological developments and international guidance).

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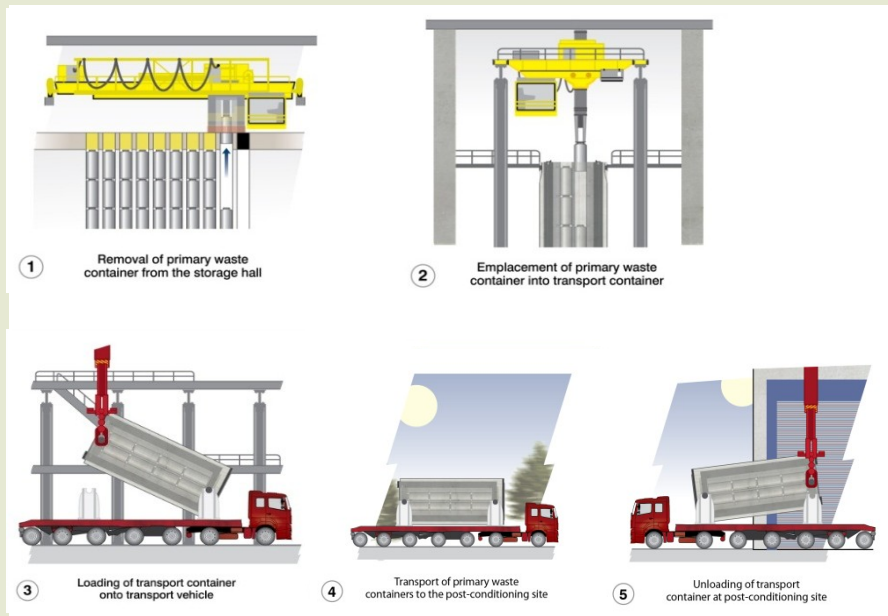
**Figure 7** – Category B&C programme – Approach for the development of SFC1. The activities to be conducted are organised in three hierarchical levels: strategy, methodology and implementation. The management strategy sets out the principles and guides the definition of a management system that will ensure that the goals defined in the safety strategy are met.

**Inset 5 – Example of QA (quality assurance) approach – Development and review of a storyboard**

In order to have confidence in the reliability of conclusions from the feasibility assessment, it is important to ensure that all aspects of the disposal design are being evaluated. In support of this requirement, a “storyboard” is being developed to check the completeness of feasibility assessment activities. The objective of the storyboard is “to give a description of all the operations (activities) related to the construction and operation of the repository” (Wacquier and Van Humbeeck, 2009).

The storyboard, which is currently a text-based tool developed in Microsoft Excel, describes the chronological chain of events in the category B&C geological disposal design, starting from the removal of primary waste packages from interim storage, through all stages to closure of the repository. It provides a global overview of all the activities covered by the feasibility programme, developed independently of the Feasibility Statements, and makes it possible to check that no steps in the disposal process have been overlooked and all significant open questions have been identified. It also helps to clarify assumptions about the disposal design, by setting out a summary of the proposed approach, and enables cross-cuttings issues, interfaces and dependencies between different components of the disposal design to be readily identified.

An initial version of the storyboard was developed in 2009, which sets out the disposal process at a high level and groups activities relating to fabrication and assembly of disposal packages; excavation and underground construction; waste emplacement, backfilling and closure. Specific components of this storyboard will be developed in greater detail and periodically updated as the RD&D programme in support of feasibility progresses, and as new decisions are made about the disposal design. A pictorial version (and/or animated version) of the storyboard may also be developed in future, for use as a communication and outreach tools. These would illustrate activities involved in the geological disposal of radioactive waste in Belgium. Some example diagrams have already been developed, as shown in figure hereafter but a full illustrative storyboard is dependent on future decisions about steps in the disposal process that are the subject of ongoing RD&D. The storyboard will need to be thoroughly reviewed, possibly by external independent experts, to support its use as a completeness-checking tool.



Examples of steps in a pictorial version of the B&C feasibility storyboard, showing the sequence of activities involved in the removal of primary waste packages from interim storage and transfer to the post-conditioning site.

### Inset 6 – Example of QA approach – Development of overarching knowledge management system

Since 2004, the RD&D department of ONDRAF/NIRAS has further developed the web-based knowledge management engine called VIGNETTE Business Collaboration Server, a tool of the company Open Text, with custom designed modules. It allows the RD&D department to work with several external partners and subcontractors in a multidisciplinary environment on the initialisation, execution, follow-up and reporting of scientific research and the development of a Safety and Feasibility Case for the geological disposal of category B&C waste. Within given access policies and while adhering to QA/QC procedures that guarantee the traceability of decisions and actions, the following is stored in the knowledge management engine: contextual information of the research being done (the rationale: requirements, decisions and previous results leading to the research to be done), minutes of meetings regarding ongoing research, scientific reports of research being done including data & methodology used, follow-up of actions and decisions, version control of documents etc.

An overview of VIGNETTE is provided in the management strategy report (ONDRAF/NIRAS, to be published). A series of training presentations set out the objectives and functionality of VIGNETTE in greater detail, and explain how to use the knowledge management system. VIGNETTE is continuously maintained and its functionality updated to ensure it is fit for purpose and fulfils user needs.

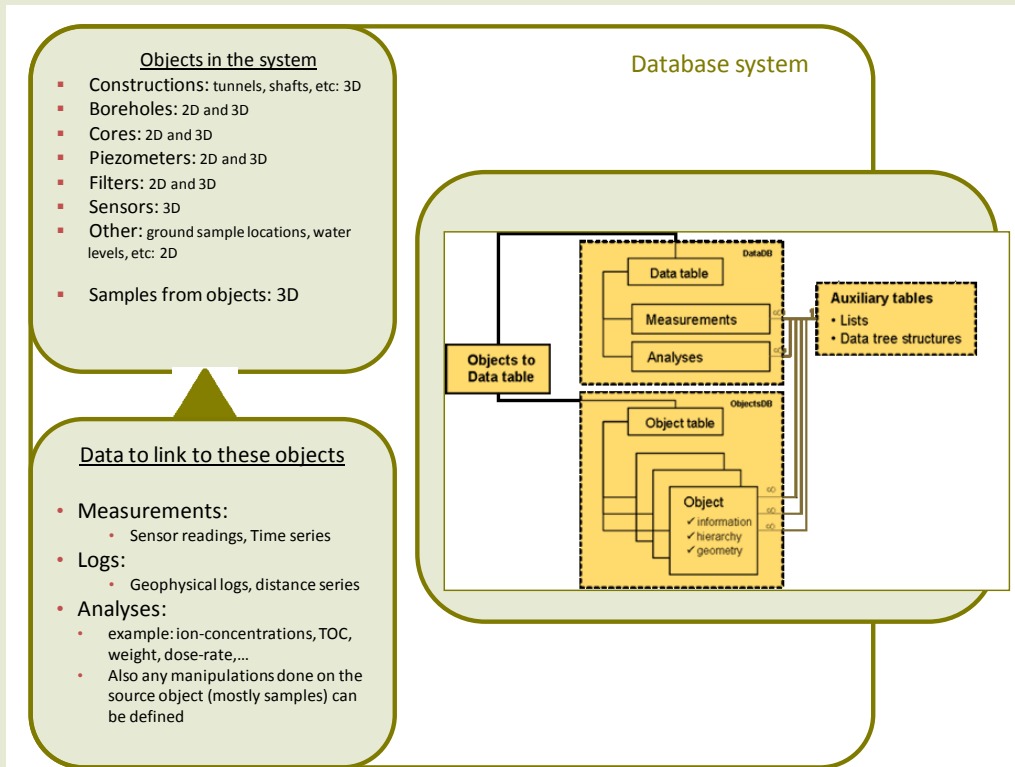
Information associated with the RD&D programme in support of safety or feasibility is organised in a dedicated area of VIGNETTE, with designated sub-sections assigned for meeting minutes. There is also an area of VIGNETTE that presents the hierarchy of the statements. This highlights the relationship of different statements to each other (figure hereafter). It also records the latest arguments supporting each statement, together with the associated open questions. The information recorded there is updated periodically as the RD&D programme progresses and new understanding is obtained. Arguments recorded in the hierarchy of statements on VIGNETTE will provide an important input to preparation for the SFC1 submission.

The screenshot displays a web-based interface for a knowledge management system. The main heading is "The proposed disposal system can be constructed, operated and progressively closed taking into account operational safety issues and with adequate funding". Below this, there is a navigation menu with options like "Show:", "Status:", and "Code Number: FS". The central part of the screen shows a hierarchical tree of statements, starting with "FS.1: The engineering practicability of the disposal system is proven" and branching down to more specific statements like "FS.1.1.1: The supercontainer can be fabricated". Each statement includes a "Last modified" date and the user "Administrator". A left sidebar contains various management actions such as "Add", "Leaf Statement", "Branch Statement", "Manage", "Link This", "Edit Properties", "Delete", "Make frozen snapshot", "Copy SFC tree to your private folder", "Export this tree to an Excel sheet", "Export Open Questions to an Excel sheet", "Export Substantiation Arguments to an Excel sheet", "Manage contents", "Switch View", "Paste Here", "Link Items", "Move Items", "Remove Items", "Inform", "Subscribe", "Subscribe Recursively", and "Tell People".

Excerpt from the knowledge management system, showing part of the hierarchy of Feasibility Statements tree.

**Inset 7 – Example of QA approach – Development of a geo-scientific information system (GSIS)**

The Geo-Scientific Information System (GSIS) integrates primary scientific data collected in frame of the programme on geological disposal of high-level/long-lived radioactive waste that is carried out by ONDRAF/NIRAS. It stores research information from various sources and of different types along with their spatial position. It provides an opportunity to combine, retrace, present and archive scientific information through a comprehensive graphical user interface.



Excerpt from the GSIS.



# 2

## **Part 2**

### **The system is known**





### 3. The system components can be characterised

One of the prerequisites for building a Safety and Feasibility Case is to acquire adequate knowledge and understanding of the disposal system and of its environment. One part of the first branch of the statements tree thus focuses on assessing that the system is sufficiently known and understood to proceed to the next stage of the programme (Table 4). This chapter reviews the knowledge gained in 30 years of RD&D on the characterisation of the conditioned wastes (Section 3.1), the other parts of the engineered barrier system (Section 3.2), the geological barrier (Section 3.3) and the environment of the disposal system (Section 3.4), focusing on the remaining uncertainties.

**Table 4** – Current structure of the Safety Statements underpinning the statement “The system components can be characterised”.

The system is known	
Indeed,	The system components can be characterised
Indeed,	The conditioned wastes can be characterised
and,	The other parts of the engineered barrier system can be characterised
and,	The geological barrier can be characterised
and,	The environment can be characterised

### 3.1. The conditioned wastes can be characterised

Knowing the wastes to be disposed of is crucial for assessing the safety. The objective of the SFC1 is to show that, for all existing and forecast category B&C waste, the building of a geological repository in a defined area of the Boom Clay or the Ypresian clays is feasible and ensures operational and long-term safety. Based on classification system already into force for SAFIR2 (Section 3.1.1) and on the technical inventory of the Belgian waste (Section 3.1.2), the RD&D for SFC1 focuses on identifying the families of waste that either require the highest system performances or are liable to impair these performances (Section 3.1.3). Sections 3.1.4 and 3.1.5 detail the remaining uncertainties and their consequences on the RD&D programme.

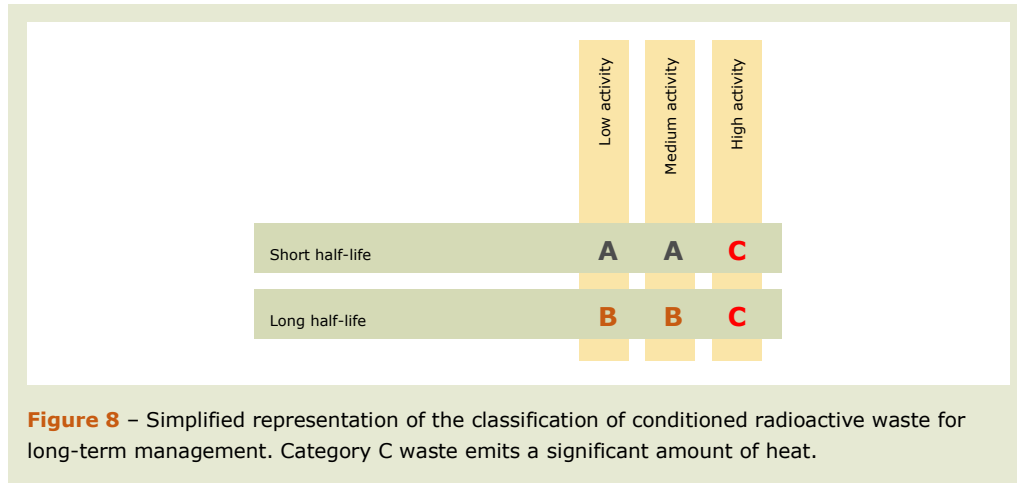
#### 3.1.1. Waste classification

For long-term management, ONDRAF/NIRAS has adopted a classification consisting of three categories in accordance with international recommendations (Figure 8) (EU, 1997). This classification is based on the activity level and half-life of the radionuclides contained in the waste at the time of conditioning, which are indicators of the radiation risk that it presents and its duration. This has been complemented by the inclusion of a thermal parameter that considers the temporary change in waste activity level due to radioactive decay.

- *Category A waste* is short-lived low-level and medium-level conditioned waste that contains limited quantities of long-lived radionuclides. It presents a risk to man and the environment over several hundreds of years. It can be considered for surface disposal.
- *Category B waste* is low-level and medium-level conditioned waste containing long-lived radionuclides in such quantities that it presents a risk over time periods ranging from several tens to several hundreds of millennia for some of the waste. Its thermal power is potentially significant at conditioning, but it emits too little heat after its storage period to be classified in category C.
- *Category C waste* is high-level conditioned waste containing large quantities of long-lived radionuclides and which, like category B waste, therefore presents a risk over time periods ranging from several tens to several hundreds of millennia for some of the waste. Its thermal power will lead to a significant rising of the temperature of its environment, well beyond the period currently considered for its storage.

Category B waste and category C waste are considered together for their long-term management because the risk that they present extends over similar timescales, from several tens to hundreds of millennia.

A solution at institutional level for the long-term management of category A waste – a surface disposal facility in the municipality of Dessel within the scope of an integrated project providing added value for the region – was decided by the Council of Ministers on 23 June 2006. This is mentioned for the record, as this RD&D Plan only considers category B&C waste.



### 3.1.2. Technical inventory of the Belgian waste

Since 1997, ONDRAF/NIRAS draws up periodically a quantitative and qualitative inventory of all existing conditioned radioactive waste and planned waste. This inventory, called “technical inventory”, is in three parts: a part relating to *quantities*, a *radiological* part and a *physicochemical* part. It is based on the knowledge of waste stored in the ONDRAF/NIRAS buildings operated by Belgoprocess and *declarations* from producers concerning their total future generation of waste from current production and decommissioning waste. This inventory is needed, in particular, to guide RD&D as best as possible, to optimise treatment and conditioning, to perform safety assessments, to design and size medium-term and long-term management facilities, and to ensure the creation of sufficient provisions to cover associated costs. Annex A2 gives an overview of the origins and characteristics of B&C waste (ONDRAF/NIRAS, 2011b).

In 2009, ONDRAF/NIRAS updated its estimate of existing volumes of conditioned waste and future waste planned within the scope of the current nuclear power programme in order to satisfy a request from the GEMIX group (Annex 7 in (GEMIX, 2009)), a group of national and international experts charged by the Royal Decree of 28 November 2008 with conducting a study intended to present Government with one or more scenarios for the ideal energy mix for Belgium (Moniteur belge, 2008). This estimate takes into account the following two elements of institutional policy:

- the provisions of the Law of 31 January 2003 to phase out nuclear energy (Moniteur belge, 2003), which bans the construction and operation of new nuclear commercial reactors and orders the closure of the seven existing nuclear commercial reactors after 40 years of operation;
- the resolution by the Chamber of 22 December 1993 (Chambre des représentants, 1993), which requires ONDRAF/NIRAS to give equal consideration to the study of the geological disposal of reprocessing waste and that of non-reprocessed irradiated fuel. However, to date, the status of irradiated fuel (resource or waste) has not been established.

According to the ONDRAF/NIRAS 2009 estimate, the volumes of B&C waste to be managed by 2070, *i.e.*, by the end of the activities relating to the dismantling of all

existing nuclear facilities or of all nuclear facilities of which the construction was planned as of 31 December 2008, are the following (ONDRAF/NIRAS, 2012):

- 11 100 or 10 430 m<sup>3</sup> of category B waste, depending on whether the current suspension of commercial irradiated fuel reprocessing is lifted or maintained. This waste originates mainly from research activities, nuclear fuel production, reprocessing of irradiated fuel and decommissioning of nuclear commercial reactors and research and fuel production facilities. It represents about 2% of the total activity of all waste.
- 600 or 4 500 m<sup>3</sup> of category C waste, depending on whether the current suspension of commercial irradiated fuel reprocessing is lifted or maintained. This waste is vitrified waste resulting from reprocessing commercial irradiated fuel and non-reprocessed irradiated fuel declared as waste. It represents approximately 97.5% of the total activity of all waste. (Reprocessed commercial fuel represents 12%tHM (ton heavy metal) of the total irradiated fuel generated by the nuclear power programme as provided by the law to phase out nuclear energy, which is 40 years of operation for the seven Belgian nuclear commercial reactors.)

A large part of this waste already exists or will inevitably be produced.

### **3.1.3. Waste characterisation: division in families**

B&C waste comes from a diverse range of origins and has various characteristics. In the frame of SAFIR2, the waste was grouped in about 100 waste streams. These were defined as groups of packages with homogeneous physical, chemical, and radiological characteristics, produced using the same process to condition the same kind of raw waste. Over the time, the number of waste streams increased to an unmanageable amount (over 1 000), imposing the development of a new classification. The waste packages are now grouped in "families". Each family gathers waste packages whose individual characteristics are sufficiently close to that of the family-average to not produce a significantly different impact of any type during any step subsequent to its production (these steps include intermediate storage, transports, post-conditioning and disposal; the SFC1 only addresses the two latter). A waste family may thus include waste produced by different producers. The waste family is the basic entity for safety and feasibility evaluations.

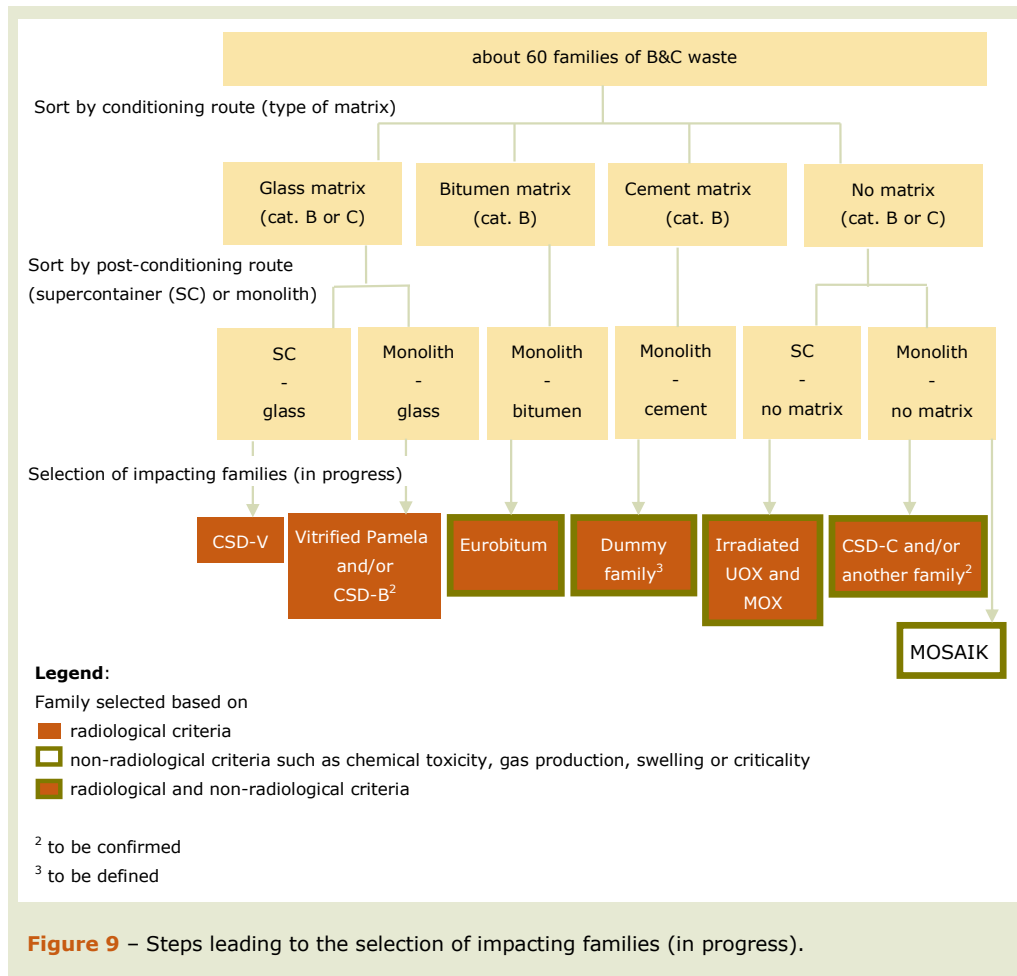
For the purpose of the evaluations, the B&C waste families are sorted in function of their conditioning and post-conditioning routes. Four conditioning routes currently exist: during the conditioning process, the waste is either mixed with a matrix<sup>7</sup> material (glass, bitumen or cement) or is compacted without addition of a matrix (matrix-free conditioning method). The post-conditioning route depends on the type of waste (B or C). The waste families are thus split into six "generic types" (Figure 9). At the present time, some families can not be sorted into these "generic types" as their conditioning and/or their post-conditioning route is still undefined.

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7 A "matrix" is a non-radioactive material used to immobilize waste (IAEA, 2003c).

For each “generic type”, ONDRAF/NIRAS (will) select at least one family that is regarded as penalising, in terms of one of more of the following criteria:

- Radiological inventory (quantity of radionuclides, radionuclides half-life, radiotoxicity);
- Chemotoxic inventory;
- Fissile inventory;
- Compatibility with geological disposal (gas production, volumetric changes, release of chemical species with detrimental effect (essentially complexing agents)).



The selection of the impacting families is under way, through systematic analysis of existing waste. The impacting families will constitute the basic input to the safety assessments. The different “generic types” are detailed hereafter.

### Waste conditioned with a glass matrix and post-conditioned in supercontainer

The generic type “glass in supercontainer” groups families of waste packages filled with high-level waste resulting from the reprocessing of (mostly) UOX irradiated fuel at the La Hague plant in France. This waste contains the minor actinides, the fission and activation products and the reprocessing losses of uranium and plutonium. The

reprocessing losses account for about 0.1% of the separated uranium and plutonium streams. The waste stream is first calcinated, then incorporated in molten borosilicate glass to form the so-called *vitrified high-level waste* (VHLW) and conditioned into stainless steel cylindrical packages, the CSD-V (standard containers for vitrified waste). Each CSD-V holds about 150 litres (about 400 kilograms) of solidified glass containing a maximum load of calcinated waste product of 18.5% by weight. One CSD-V content corresponds to the treatment of 1 to 1.7 tHM irradiated fuel. 390 CSD-V are stored in Building 136 exploited by Belgoprocess in Dessel.

The chosen impacting family contains the waste originating from the reprocessing of the commercial uranium-oxide (UOX) irradiated fuel, due to its radiological and chemical inventories. This conditioned waste is also encountered in other countries (mainly France, Germany, Japan and Switzerland).

### **Waste conditioned without matrix and post-conditioned in supercontainer**

The generic type "matrix-free in supercontainer" contains irradiated fuel from commercial nuclear reactors<sup>8</sup> that is not reprocessed. This type will only exist if irradiated fuel is declared as waste by its owner. In the current reference design, it is considered that irradiated fuel assemblies from commercial reactors are conditioned into stainless steel boxes; the interstices being filled up with an inert material before closure. This conditioning route must still be confirmed.

Two impacting waste families have been selected: uranium-oxide (UOX) irradiated fuel and mixed-oxide (MOX) irradiated fuel, due to their radiological and chemical inventories and potential risk of critical event within the disposal system.

### **Waste conditioned with a glass matrix and post-conditioned in monolith B**

The generic type "glass in monolith B" includes families of existing and forecast waste:

- Families of existing waste contain the so-called Eurochemic vitrified waste, resulting from the reprocessing of irradiated fuel performed at the Eurochemic pilot reprocessing plant).
- Families of forecast waste will contain secondary streams from reprocessing equipments at La Hague, inserted in CSD-B (standard container for secondary waste, vitrified).

The total activity in these families (Becquerel per primary waste packages at production time) is lower than in the CSD-V. The isotope vectors are similar for CSD-V and the Eurochemic vitrified waste. The CSD-B will show a rather different isotopic vector than the other glasses.

One impacting waste family has been selected: HAGALP1 (see line c3-1 in Annex A2). The decision to consider CSD-B as an impacting family will depend on its characteristics at production time.

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<sup>8</sup> The type "matrix-free in supercontainer" might possibly also include irradiated fuel from a test reactor.

### **Waste conditioned with a bitumen matrix and post-conditioned in monolith B**

The generic type “bitumen in monolith B” groups families of waste conditioned in bitumen. Most of them were conditioned in the Eurobitum facility, which performed the treatment and conditioning of radioactive waste produced by the reprocessing activities of the Eurochemic plant (Mol–Dessel, Belgium), producing about 11 500 packages of conditioned waste. Besides the effluents from Eurochemic reprocessing, other radioactive effluents (part of it are, for example, coming from Belgonucleaire fuel fabrication plant) as well as a reduced amount of solid wastes have been conditioned in the Eurobitum facility, leading to about 2 000 additional primary packages. About 50% of all category B primary waste packages (existing and forecast) are conditioned in this matrix. This matrix is not used anymore in Belgium.

The impacting family contains Eurochemic effluents conditioned in bitumen due to their potential impact on the host formation properties. The swelling of Eurochemic bituminised waste (due to the presence of hygroscopic salts) and the resulting pressures are indeed significant (Section 4.2.3.4).

### **Waste conditioned with a cement matrix and post-conditioned in monolith B**

The families in the generic type “cement in monolith B” present a large variety of origins, from fuel fabrication, operation of commercial nuclear reactors, and waste management from research, development and pilot facilities.

Unlike bituminised waste whose production is complete, a significant part of this type must still be produced. Furthermore, part of the already produced waste requires additional characterisation (Section 3.1.5).

The selection of the impacting family(ies) is under way. The chemical toxicity, criticality and content of detrimental species are checked for each family while the selection of an impacting family from a radiological viewpoint may require a specific approach due to the large variety of waste isotopic vectors.

### **Waste conditioned without matrix and post-conditioned in monolith B**

The generic type “matrix-free in monolith B” groups families from diverse origins<sup>9</sup>:

- Existing and forecast families with CSD-C primary waste packages (standard container for compacted waste). These packages contain compacted structural waste arising from reprocessing in La Hague of (mostly) UOX irradiated fuel from commercial reactors.
- Forecast family with waste from the decommissioning of commercial nuclear reactors. This family will contain large amount of metallic materials from reactor core internals.

These two families are considered as impacting families, for radiological, chemical and gas production reasons.

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<sup>9</sup> The type “matrix-free in monolith B” might possibly also include irradiated fuel from a test reactor.



### **3.1.4. Potential modifications in the technical inventory of conditioned waste**

ONDRAF/NIRAS has identified several issues, the answers to which are not a matter solely for ONDRAF/NIRAS and which are likely to impact the estimated volumes and characteristics of conditioned waste. Changes in characteristics of conditioned waste may require specific RD&D to demonstrate safety. Changes of volumes within certain limits (e.g., extension of the lifetimes of some current commercial reactors for several years) do not affect the RD&D programme as the geological repository in poorly indurated clay could be sized in a flexible way according to the waste volumes for disposal.

#### **Status of irradiated fuel and reprocessing**

ONDRAF/NIRAS does not know the form of the waste from the back-end of the nuclear fuel cycle that it will have to take charge of: will it be non-reprocessed irradiated fuel or reprocessing waste? In accordance with the resolution of the Chamber of 22 December 1993, which led to a suspension of the reprocessing of irradiated fuel from nuclear commercial reactors, confirmed by the Council of Ministers on 4 December 1998, ONDRAF/NIRAS must in fact give equal consideration to the study of the geological disposal of reprocessing waste and that of non-reprocessed irradiated fuel. It therefore considers both scenarios for the RD&D and in its technical inventory for radioactive waste. This choice may affect penalising Criteria 1 and 3 (ONDRAF/NIRAS, 2011c).

#### **Belgium's future policy in terms of electricity production**

It is possible that the current federal government with its equipment plan <sup>10</sup> will assume a 10 years extension of the operational life of the commercial reactor Tihange 1. This will lead to an increase in the estimated volumes of conditioned waste to be managed. The radiological characteristics of this waste will not pose any new difficulties in scientific and technical terms, since they would, to a large extent, be similar to those of existing waste (for example line b2-7 in Annex A2). It may affect penalising Criteria 1 and 2.

#### **Possible transfer of waste from category A to category B**

The current distinction between category A waste and category B waste is based on the provisional working assumptions of ONDRAF/NIRAS regarding the radiological limits applicable to waste for surface disposal. ONDRAF/NIRAS will propose the radiological limits applicable to waste for surface disposal based on the results of safety calculations and analyses, which take into account the characteristics of the disposal system (design, site, etc.) and the protection criteria imposed by the regulatory framework being developed. These limits will be accepted or amended by the provisions of the licence to construct and operate the repository. The content of a surface disposal facility must indeed be such that its radiological impact after the regulatory control phase does not exceed the safety and protection criteria imposed by the regulations relating to repositories. Other conditions established by the licences related, for example, to the

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<sup>10</sup> Translation of "uitrustingsplan".

physicochemical characteristics of the waste, could lead to the transfer of some waste from category A to category B. It is therefore likely that some waste currently assumed eligible for surface disposal by ONDRAF/NIRAS will have to be transferred to category B (minor transfer of waste in the opposite direction cannot be ruled out).

Any waste transferred from category A to category B could *a priori* be disposed of in a geological disposal facility. Its chemotoxic inventory and its compatibility with geological disposal will be checked in order to identify potential additional impacting families. It may affect penalising Criteria 2, 3 and 4.

### **Potential modification of the operational mode of nuclear facilities**

In the future, the operational mode of nuclear facilities might be modified in various ways, leading to change of the characteristics of the resulting waste and potential new impacting families (as defined by the screening criteria listed in Section 3.1.3):

- The discharge burnup limit of fuel assembly may be increased. The discharge burnup of nuclear fuel is usually defined as the thermal energy output during the lifetime of the fuel divided by the initial mass of heavy metal (NEA, 2006). Higher burnup will essentially lead to higher radiological impact (penalising Criterion 1).
- Changes of the composition and characteristics of the reactors materials may lead to modifications of the radiological and/or chemical content of the waste (penalising Criteria 1 and 2). It mainly concerns fuels, claddings and assembly structure materials. For instance, the introduction of niobium in zirconium alloys for fuel rod claddings leads to the presence of <sup>94</sup>Nb activation product, a long-lived radionuclide of concern for long-term safety.
- Changes of material and/or processes in waste-producing facilities may lead to changes in the waste to be handled (penalising Criteria 1 and 2). For instance, a change in production processes of medical isotopes may lead to changes in waste streams from those isotope producers.

### **Characteristics and conditioning mode of the forecast waste**

The treatment of waste and/or the conditioning package and/or the conditioning line has(have) not yet been defined for some waste families (existing or in current forecast for waste production). It is therefore not possible to assess the long-term behaviour in a geological repository for these waste families. For instance, the conditioning and post-conditioning routes for the irradiated metallic uranium fuel from a research reactor, which is highly corrodible in alkaline media, have not been defined yet. Furthermore, processing and conditioning technologies continuously evolve. This may reduce the amount of waste to be disposed of but increase the radiotoxicity of each package. This may affect penalising Criteria 1, 2, 3 and 4.

### **Addition of new waste families to the inventory**

The current technical inventory includes all existing and forecast waste, based, among others, on the declarations from the producers concerning their total future generation of waste from current production and decommissioning waste. It is possible that new (not forecast) waste streams appear in the inventory for later SFCs, due for instance to:

- The commissioning of *new nuclear installations*, to produce for instance isotopes for medical applications or of *research facilities dedicated to advanced nuclear technologies*. These facilities will generate waste that should be managed in the long term. This could require RD&D to demonstrate the safety of geological disposal (including criticality safety).
- The declaration of *new waste streams* by a producer (like irradiated fuel from research/test reactors or unexpected decommissioning waste).
- The potential declaration by the producers concerned of all or part of their *non-valued fissile materials (enriched uranium and plutonium)* as waste. It is particularly the issue of their optimal conditioning (type of matrix) to ensure the non-criticality of the system in long-term management conditions which arises; this is examined internationally. These materials would only give rise to a relatively low volume of conditioned waste compared to the total volume of category B waste, which could be placed in a geological disposal facility. Taking charge of excess materials with a view to their long-term management would however have to satisfy the requirements of the safeguards that aim to prevent their diversion and use for non-peaceful purposes. The requirements for the long-term management of such materials are currently being developed internationally.

This may affect penalising Criteria 1, 2, 3 and 4.

### **Possible modifications to the inventory of category B radium-bearing waste**

All radium-bearing waste to be managed as radioactive waste in Belgium is comprised, on the one hand, of the radium-bearing waste stored on the ONDRAF/NIRAS BP1 and BP2 sites operated by Belgoprocess in Mol and Dessel, and, on the other hand, of the radium-bearing waste contained in Umicore's licensed interim storage facilities in Olen, and waste resulting from future remediation operations in Olen. About 85 000 m<sup>3</sup> of unconditioned waste are presently stored in Umicore's licensed interim storage facilities in Olen (Umicore, 2011). Eventually, part of this waste, along with the radioactive waste that will result from the remediation operations in Olen, could, due to requirements of the regulatory framework being developed, have to be transferred to category B.

The radiological characteristics of this waste would not pose any major difficulties in scientific and technical terms. Indeed, it is similar to certain category B waste (particularly radium-bearing waste) already considered in the studies (notably line d-2 in Annex A2). The substantial increase in the volume of this waste, and therefore the risk of contamination with radon gas, would however require specific measures at the operational level.

### **3.1.5. Uncertainties inherent to the characterisation of the conditioned waste**

ONDRAF/NIRAS has identified uncertainties inherent to the characterisation of conditioned waste, due to lack of guidelines, new requirements or linked to the characterisation methodologies, as detailed hereafter.

#### **Uncertainties due to the lack of characterisation of some existing wastes**

Compared to countries with an equivalent number of commercial nuclear reactors, Belgium has much more waste to handle due to past RD&D and pilot activities (such as a reprocessing facility). These activities have generated an appreciable amount of radioactive waste, part of which has been conditioned before the establishment of a legal framework regarding waste treatment and conditioning in 1999. The characterisation of a significant part of this “historical waste” (*i.e.*, conditioned outside a legal framework) is somewhat limited. For instance, 82 Eurobitum primary waste packages containing metallic solid waste conditioned in bitumen might include some active sludge as well.

#### **Uncertainties linked to evolving requirements**

The waste acceptance criteria have evolved since the start of waste management by ONDRAF/NIRAS and may still do so in the future, to include new requirements arising from the international framework in which all geological disposal programmes operate, the Belgian legal and regulatory framework, the institutional policy or other stakeholders. This may lead to uncertainties about the existing conditioned waste, for which there is no data on the criteria added after their acceptance. For instance, it is likely that more extended requirements about chemical contaminants will be introduced in the acceptance procedure.

#### **Uncertainties inherent to characterisation processes**

The given characteristics of a waste family are mean values over a large number of primary waste packages. Several methodologies, which depend on the origin of the waste, are applied to assess these mean values. Some of them rely on generic information while others use accurate records supported by valuable experimental data. The uncertainty ranges associated with the mean values depend thus on the applied methodology.

Another uncertainty arises from the difficulty to characterise some waste. For instance, it is not easy to assess the chemical form and/or the localisation of some specific nuclides like  $^{14}\text{C}$  in irradiated fuel and consequently to predict their evolution.

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### Roadmap – Section 3.1 – Characterisation of the conditioned wastes

The inventory for SFC1 will include all existing and forecast category B&C waste. *For SFC1*, ONDRAF/NIRAS will therefore continue to update its technical inventory on a regular basis, based on the provisions from the waste producers. It will also verify that new types of anticipated waste do not raise new issues in relation to those already taken into account in the studies.

*For later SFCs*, ONDRAF/NIRAS will continue to characterise historical waste by analysing production data sheets and other available documents. This may highlight specific needs for further characterisation of some packages.

The selection of impacting families is not straightforward for the specific case of wastes conditioned in the cement matrix. It could be advisable to build up “dummy” families whose conservative characteristics encompass those of the cemented wastes.

*For later SFCs*, ONDRAF/NIRAS will continue to characterise irradiated fuels, taking into account their intrinsic evolution during the storage period needed for cooling, and considering this evolution in the studies relating to their conditioning and post-conditioning. It will pursue its selection of “impacting families”. It will for instance pay attention to the presence of components such as phthalates or cellulose in category B waste, as their degradation may affect the EBS properties (see roadmap Section 4.2.3.1) and gas production (see roadmap Section 4.2.2.5).

For specific wastes with major radiological impact, the inventory and its evolution with time are based on calculations. The associated uncertainties result from both the input data and code system performance. The evaluation of these uncertainties is a current research topic (*for SFC1*), which includes comparisons with inventories from other countries (*e.g.*, CSD-V and CSD-C are present in the inventories of Andra and Nagra). It is based on published documents (such as (Nagra, 2002b)) and on collaboration with international organisations, such as the Expert Group on Assay Data of Spent Nuclear Fuel (ADSNF) under the auspices of the NEA. The goal of this research is to guarantee that the ONDRAF/NIRAS inventory is reasonably conservative and coherent with inventories of similar waste families present in other countries.

*For later SFCs*, RD&D is also under way to determine how to handle the uncertainties inherent to the characterisation of low- and medium-level conditioned waste. This is of particular interest for instance for wastes with a large dispersion of as-measured nuclide contents. The results of this RD&D enable a decision as to which deviation from the mean value is acceptable or whether another value should be used for safety assessments.

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## 3.2. The other parts of the engineered barrier system can be characterised

The engineered barrier system (EBS) is the whole of engineered barriers of a multi-barrier system, thus excluding the natural barrier. The safety concept defines the functions that it must fulfil. Its design, that is to say the geometry of the facility and the materials used to construct it, depends on the requirements. These cover a wide range of domains, such as long-term safety, feasibility (which is taken to include operational safety and costs), characteristics of the waste to be disposed of, aspects of quality assurance or other stakeholder conditions.

The RD&D programme in this field currently focuses on developing an EBS that fulfils the requirements. Complete characterisation will be performed during the next stages of the programme. This section first outlines the reference design in force at the time of the SAFIR2 report (Section 3.2.1). ONDRAF/NIRAS took the formal assessment of the SAFIR2 report and its review as an opportunity to reconsider the disposal concept. Section 3.2.2 details thus the development of the new concept and Section 3.2.3 presents the current reference repository design.

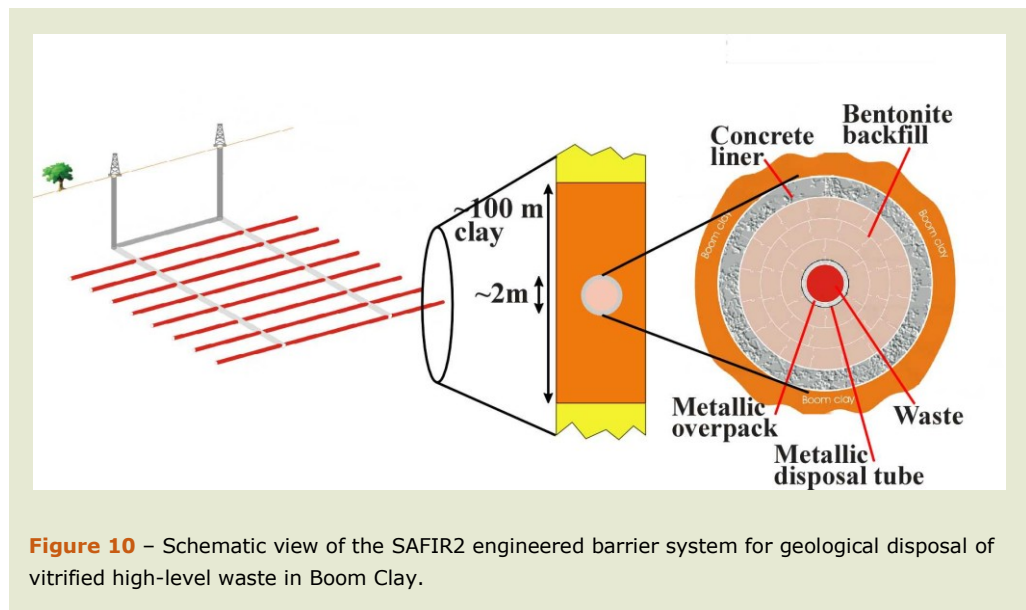
### 3.2.1. SAFIR2 reference design and its review

This section describes the reference design in use at the time of the SAFIR2 report. That design envisaged a network of rectilinear galleries in the mid-plane of the Boom Clay. At the reference site for RD&D (Mol), this mid-plane is at a depth of about 240 metres below ground level. Access to the underground was by two shafts with an effective diameter of about 6 metres and linked at their base by a Connecting gallery, 400 metres long and 2 metres in diameter, which also would serve as an escape gallery. The shafts gave access to two access galleries 3.5 metres in diameter, which lied at right angles to the Connecting gallery. The disposal galleries that would receive the radioactive waste branched out from this H-shaped vertebral column. Figure 10 illustrates the SAFIR2 reference design for vitrified high-level waste. The standard primary packages containing vitrified high-level waste were protected by an overpack made of stainless steel, whose thickness was about 30 millimetres. The role of the overpack was to contain the radionuclides and other contaminants during the thermal phase. The filled overpack was placed into a 1-centimetre thick disposal tube also made of stainless steel. The latter was assumed to be centred in a disposal gallery, lined with concrete wedge blocks needed because of the limited strength of the Boom Clay host formation. The proposed backfill was a bentonite-based material with limited swelling pressure. (Compared to other disposal programmes, it is necessary to use a bentonite with a limited swelling pressure in order to avoid damage creation in the Boom Clay, due to the low strength of the Boom Clay itself and the *in-situ* lithostatic pressure of about 4.5 MPa (Section 3.3.10) (Van Geet and Weetjens, 2012b).)

SAFIR2 assessment and its review by an international team under the auspices of the NEA highlighted that geological disposal in Boom Clay is promising and that the Boom Clay is the dominant contributor to the overall safety in the reference scenario and other plausible evolution scenarios (NEA, 2003). However, this assessment and its review also revealed possible weaknesses of the proposed solution, namely (1) the feasibility and in particular the operational safety were not very clear, if not questionable, and (2) the engineered barrier system behaviour was rather complex and, with the remaining

The **thermal phase** is the time frame during which the temperature of the host formation is expected to lie above the range of temperatures within which nominal migration properties can be relied upon (Van Geet, 2008).

uncertainties on near-field evolution, it was difficult to guarantee full containment during the thermal phase.



**Figure 10** – Schematic view of the SAFIR2 engineered barrier system for geological disposal of vitrified high-level waste in Boom Clay.

### 3.2.2. Reconsideration of the SAFIR2 reference concept

ONDRAF/NIRAS took the formal assessment of the SAFIR2 report and its review as an opportunity to reconsider the disposal concept in order to strengthen its proposed solution for the long-term management of high-level waste. ONDRAF/NIRAS brought together people from several organisations and different fields of expertise to perform a multi-criteria analysis of different concepts (ONDRAF/NIRAS, 2004). The criteria used were related to safety reserve<sup>11</sup>, host formation perturbation, intrinsic robustness, ease of demonstration<sup>12</sup>, technical operation<sup>13</sup>, flexibility and financial feasibility. The analysis resulted in the elaboration of three alternative basic concepts (called the *supercontainer*, *borehole* and *sleeve* concepts), according to a step-by-step approach and with justification of the key decisions taken during the process. The results of this analysis showed a clear preference for the supercontainer concept (ONDRAF/NIRAS, 2004) (ONDRAF/NIRAS, 2004b). On request of ONDRAF/NIRAS, the multi-criteria analysis and its outcome were submitted to an independent review, which concluded that “to the best of DBE Technology’s understanding there were no facts, conditions, or circumstances that would make unfeasible to safely constructing and operating a repository as outlined in the documents reviewed” (DBE-TEC, 2006). The supercontainer is being designed to fulfil several requirements, including radiological shielding, ease of handling and emplacement in the repository and containment of the wastes during the thermal phase (Wickham *et al.*, 2005). This concept takes into account feasibility aspects while increasing operational (through complete shielding of the disposal packages) and long-

11 The “safety reserve” is the difference between the actual period of time during which the safety function is fulfilled and the period of time which is used in safety assessments, if the latter is shorter (ONDRAF/NIRAS, 2004b).

12 “Ease of demonstration” covers natural and/or archaeological analogues, proven technology and QA/QC (Quality Assurance / Quality control) implementation.

13 “Technical operation” covers feasibility and operational safety.

term safety (through complete containment of contaminants during the thermal phase). The design developed based on this concept makes use of materials for which a broad experience and knowledge base exists. In the process, a disposal package for category B waste, called monolith B, has been developed. It fulfils several requirements, including radiological shielding and ease of handling and emplacement in the repository.

Retrievability was not taken into account in the multi-criteria analysis and it was thus not included in the development of the concept of the supercontainer and monolith B. However, a first internal screening by ONDRAF/NIRAS did not reveal major fundamental flaws for the supercontainer and monolith B reference designs with regards to retrievability. The conception of these disposal waste packages as separate entities is *a priori* a step in favour of retrievability (see Section 5.1).

### 3.2.3. Current reference design of the engineered barrier system

The current reference design of the engineered barrier system is often called the “supercontainer design”, the name of the category C waste disposal package. It comprises specific disposal waste packages developed respectively for category C waste (Section 3.2.3.1) and category B waste (Section 3.2.3.2) and an updated repository layout (Section 3.2.3.3).

#### 3.2.3.1. Supercontainer

In the supercontainer design, illustrated in Figure 11, the primary waste packages of high-level waste are surrounded by a carbon steel overpack, a buffer made of concrete containing Portland Cement and, if needed, a stainless steel envelope (Figure 11). Table 5 lists the main dimensions of the primary waste packages, the overpacks and the supercontainers. The length of the supercontainers varies from 4 metres up to 6.2 metres to accommodate the lengths of the different types of waste. The largest supercontainer is about 6.2 metres long and 2.1 metres wide, with a mass of 70 tons.

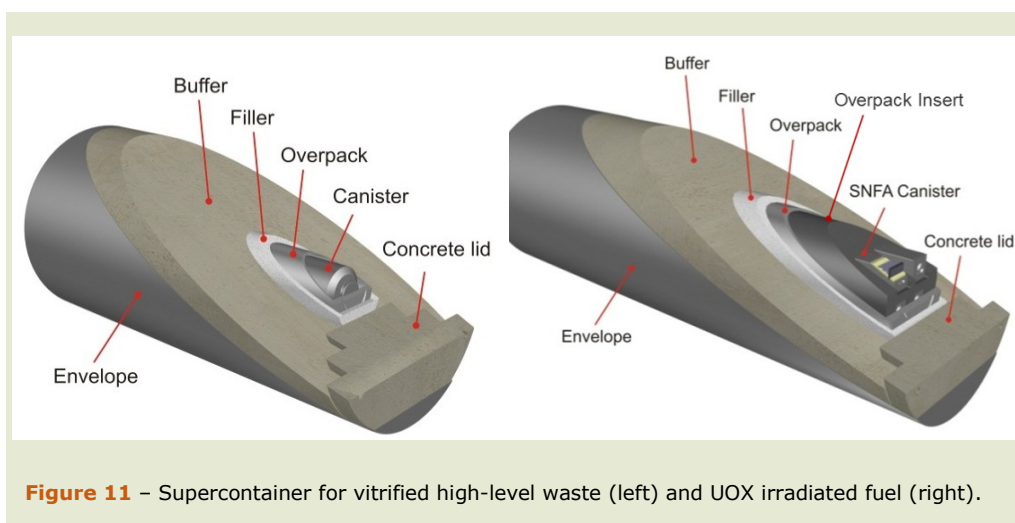


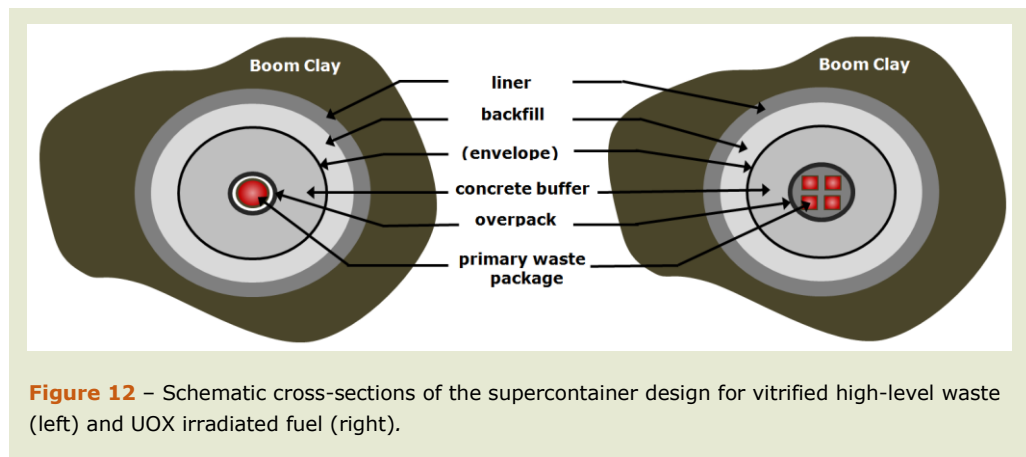
Figure 11 – Supercontainer for vitrified high-level waste (left) and UOX irradiated fuel (right).



The supercontainer fulfils several functions, contributing to the operational and long-term safety of the man and the environment:

- to provide permanent shielding for workers ( $25 \mu\text{SV}\cdot\text{h}^{-1}$  at 1 metre from the disposal waste package) (operational safety);
- to provide sufficient mechanical strength (for handling, gallery support, accidental fall, retrievability,...) (operational safety);
- to contain the radionuclides and other contaminants through at least the thermal phase. The overpack should show a low sensitivity to localised corrosion and an acceptable uniform passive corrosion rate in its environment. This implies that there would be no premature penetration of the overpack due to localised corrosion but that, over an extended period of time, there may be gradual loss of wall thickness (long-term safety).

The supercontainer is constructed at the surface before being transported underground for disposal. Section 5.1.1 details the fabrication process of the supercontainers, which is summarised hereafter. The first stage of supercontainer assembly consists of inserting the waste packages into an overpack. The overpack either contains 2 vitrified high-level waste packages in end-to-end contact, 4 boxes containing UOX irradiated fuel assemblies positioned in parallel, spaced by an 8 centimetres thick cross-shaped cast iron separator or 1 box with a MOX irradiated fuel assembly (Figure 12). Carbon steel has been chosen for the overpack because its corrosion behaviour is well known and because, under the high pH conditions expected in the supercontainer, it will undergo general corrosion, rather than the less predictable localised corrosion. Furthermore, it is easy to weld in reasonable thicknesses. It has been chosen as overpack in other disposal programmes as well (France, Switzerland). The space between containers and overpack is probably filled with an inert granular material or powder and an inert gas before the overpack is sealed by welding (Belgatom, 2006) (Wickham, 2008).



The filled overpack is then inserted in the buffer, which is closed and sealed. The intention of the buffer is to act as a radiation shield, pH controller in order to create favourable conditions with regards to passivation of carbon steel (formation of a passive layer). It establishes and maintains a favourable chemical environment around the overpack so that the overpack contains the wastes for thousands of years. The buffer is made of concrete containing Portland cement because this provides a highly alkaline chemical environment, which lasts thousands of years. In this highly alkaline chemical environment, the external surface of the overpack will be passivated and corrosion will

be inhibited (Wickham *et al.*, 2005). The formation of a passive layer on the surface of an embedded carbon steel body under the influence of a high pH environment is a well-known phenomenon and guarantees a low uniform corrosion rate (Chivot, 2004) (Pourbaix, 1974) (MacDonald, 2011b).

A stainless steel envelope a few millimetres thick may encircle the buffer. Currently, two options are open: with and without envelope. The envelope could serve as a mould for construction of the buffer, serve as a first barrier against aggressive species if present, provide mechanical strength and confinement and could facilitate retrievability.

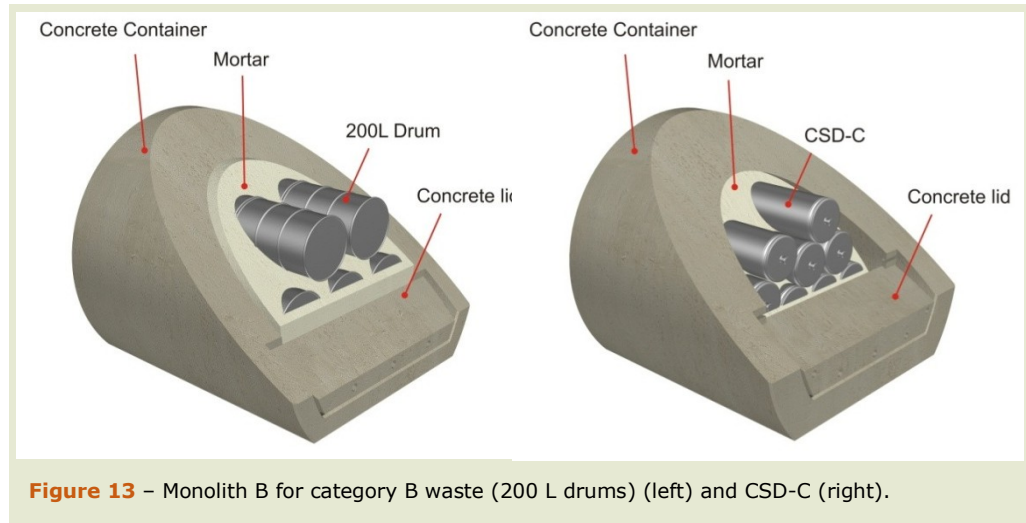
**Table 5** – Characteristics of supercontainers and of their components

<b>Types of category C waste</b>					
Vitrified high-level waste	Irradiated fuel			MOX	
	8 feet *	12 feet *	14 feet *		
<b>Number of primary waste package(s) per supercontainer</b>					
	2	4	4	4	1
<b>Primary waste package dimensions</b>					
Diameter (m)	0.4	0.25	0.25	0.25	0.25
Length (m)	1.3	3	4.2	5	4.2
<b>Overpack dimensions</b>					
Diameter (m)	0.5	1	1	1	0.4
Length (m)	2.7	3.2	4.3	5.1	4.3
<b>Supercontainer dimensions and mass</b>					
Diameter (m)	2	2.1	2.1	2.1	1.6
Length (m)	4	4.3	5.5	6.2	5.5
Mass (ton)	32	47	61.5	70	29.5

\* length of assemblies

### 3.2.3.2. Monolith B

The disposal packages for category B waste are called monoliths B. In the reference design, the primary waste packages of category B waste are immobilised in mortar in concrete caissons made with Portland cement, to form these monoliths whose conception takes advantage of the development of monoliths in the framework of the category A Programme (Figure 13). Several monolith B designs exist to accommodate the large variety of primary waste packages (Section 3.1.3). Table 6 lists the dimensions of the monolith B and of its main components. The outside diameter is always 2.8 metres, but the length of the different monolith designs ranges between 1.9 metres and 2.9 metres, and their mass ranges from 32 to 39 tons (ONDRAF/NIRAS, 2009d).



The monolith B fulfils several functions, contributing to the operational and long-term safety of the man and the environment:

- to standardise the dimensions and mass of disposal packages and limit the underground works (operational safety);
- to provide permanent shielding for workers ( $25 \mu\text{SV}\cdot\text{h}^{-1}$  at 1 metre from the disposal waste package) (operational safety);
- to provide sufficient mechanical strength (for handling, gallery support, accidental fall, retrievability,...) (operational safety);

The monolith B is constructed at the surface before being transported underground for disposal. Section 5.1.2 details the fabrication process of the monolith B, which is summarised hereafter. At the post-conditioning facility, primary waste packages are inserted in a pre-cast caisson, then mortar is poured in (eventually through the concrete lid) to fill up and close (*i.e.*, cover) the disposal package) (Wacquier and Van Humbeeck, 2009). One monolith B may contain primary waste packages from different families, to manage the variability of their characteristics (such as a higher heat output or activity than the mean package). This way of post conditioning category B waste allows standardising transportation and handling operations for disposal and disposal gallery backfilling operations. The thicknesses of the lid and the caisson walls are determined by the shielding criterion (maximum  $25 \mu\text{Sv}\cdot\text{h}^{-1}$  at 1 metre). In the current reference design, the standardised outside diameter of the monoliths B is maximised to the disposal gallery diameter (considering a minimum gap between monolith and gallery wall to allow unlimited travel of the monolith through the gallery). It follows that the number of primary waste packages inside a monolith is determined by the dimensions of these packages and by their radiological activity. If the primary packages are relatively short, a second layer of primary packages can be stacked on top of the first one. However, in order to maintain the weight and dimensions of all monoliths within a certain range, to allow standardising transportation and handling operations, no second layer is stacked if it would lead to the total length of the monolith B becoming much larger than its diameter.

**Table 6** – Characteristics of monolith B and of its components (Belgatom, 2005).

	<b>Category B waste</b>
<b>Number of primary waste packages per monolith</b>	Between 1 and 12
<b>Number of layers</b>	1 or 2
<b>Primary waste package dimensions</b>	
Diameter (m)	Between 0.3 and 1.4
Length (m)	Between 0.9 and 2.1
<b>Monolith dimensions and mass</b>	
Diameter (m)	2.8
Base width (m)	2.1
Length (m)	Between 1.9 and 2.9
Mass (ton)	Between 32 and 39

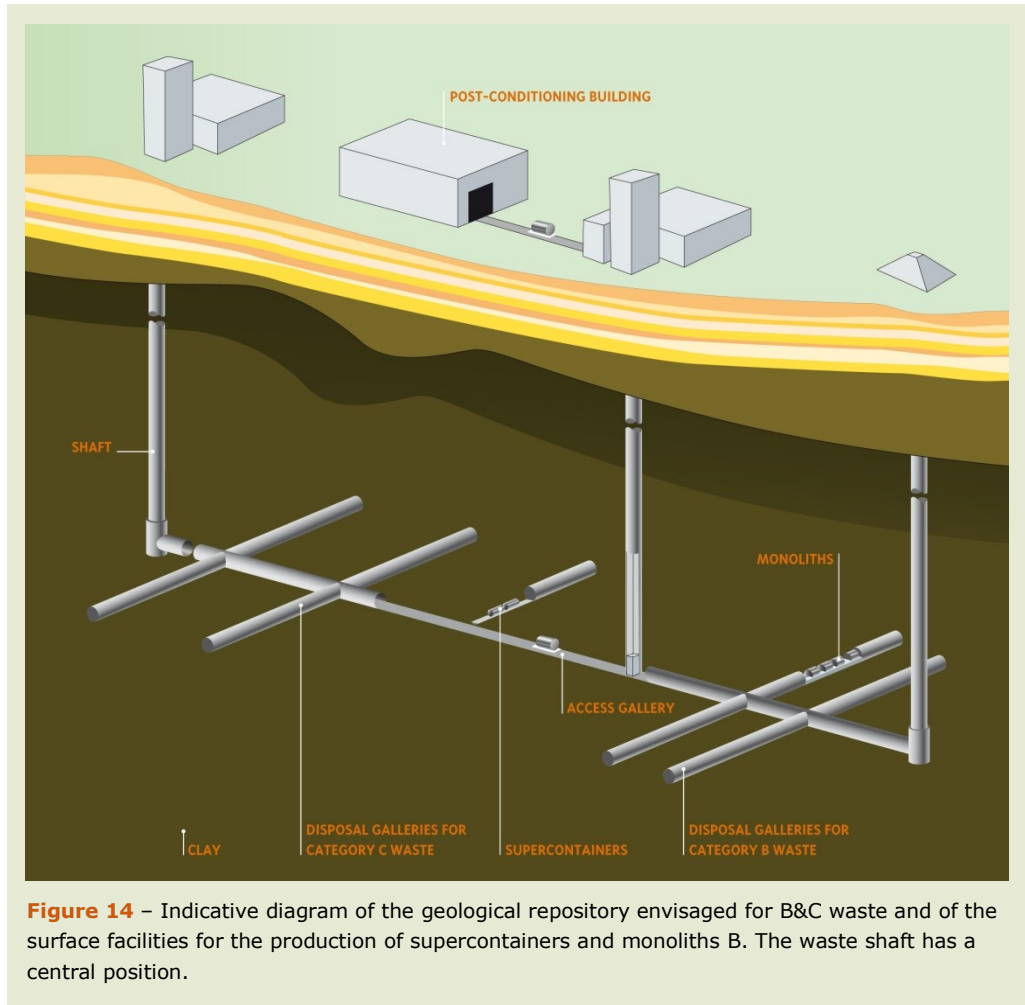
### 3.2.3.3. Repository layout

This section describes the layout of the current reference repository envisaged for B&C waste, shown in Figure 14. The repository is constructed and operated in phases. The waste would be disposed of in three groups:

- category B waste from existing nuclear liabilities would be disposed of from 2035–2040 (at the earliest);
- other category B waste would be disposed of from 2050 (at the earliest);
- category C waste, which requires a cooling period of at least 60 years in surface storage, would be disposed of from 2080 (at the earliest).

This corresponds with the ONDRAF/NIRAS view that a geological disposal facility in poorly indurated must be operational as soon as possible, but with the pace of development and implementation of the solution needing to be proportionate to its scientific and technical maturity, as well as its societal support (ONDRAF/NIRAS, 2011c).

The repository comprises two types of construction: the shafts connecting the surface with the underground and the underground facilities located in one horizontal plane at the medium level of the Boom Clay and with spatially separated sections for category B and category C waste (Wacquier and Van Humbeeck, 2009). The repository is progressively backfilled. Seals are installed at several places of the repository. The presence of seals, is consistent with the multi-barrier concept and the adoption of a cautious and conservative approach, contributes to redundancy and is thus an element of robustness, and adds to the confidence in the long-term isolation. There is currently no decision on the design of the seals (bentonite seal, concrete seal or a combination of both). Specific requirements are under development for the sealing of the different parts of the repository.



**Figure 14** – Indicative diagram of the geological repository envisaged for B&C waste and of the surface facilities for the production of supercontainers and monoliths B. The waste shaft has a central position.

The current reference design envisages the construction of three shafts to facilitate transfer of disposal waste packages, personnel and equipment from the surface to the disposal depth as well as removal of excavated spoil:

- A shaft dedicated to the category B waste disposal area. This shaft is used during construction of this area and provides access for personnel and equipment. It also provides ventilation to the category B disposal area. This shaft is filled and sealed after completion of operations in the category B section.
- A shaft dedicated to the transfer of both category B&C waste, the “waste shaft”. It has a central position. The internal diameter of the waste shaft needs to be large enough to permit the transfer of the longest supercontainer (6.25 metres in length), and must also accommodate the main hoisting system, emergency personnel hoist and potentially other infrastructure (e.g., for ventilation). This shaft is filled and sealed after completion of operations in the category C section.
- A shaft dedicated to the category C waste disposal area. This shaft is excavated after closure of the repository section dedicated to the disposal of category B waste. It is then used during construction of the category C disposal area and provides access for personnel and equipment, as well as ventilation to this area. This shaft is filled and sealed after completion of operations in the category C section.

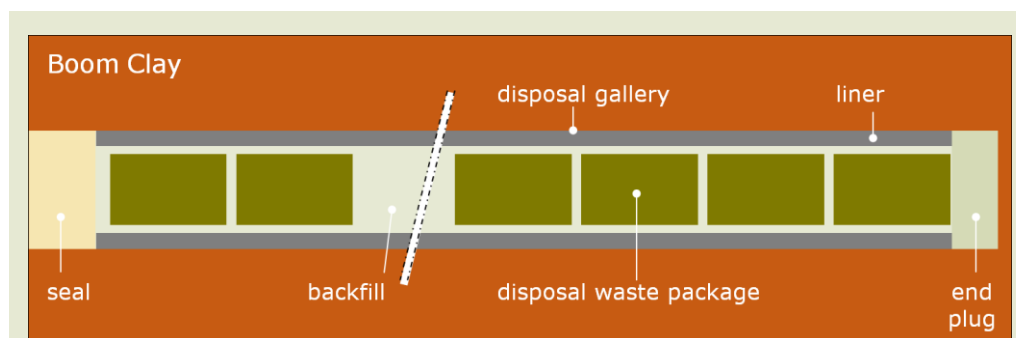
The underground facilities include the access gallery – the backbone of the repository –, the disposal galleries – where the wastes are disposed of – and the starting and mounting chambers – to assemble the tunnelling machine –. They<sup>14</sup> are lined with concrete wedge blocks. In other disposal concepts, such as those considering crystalline rock as host formation, the use of cementitious materials close to high-level waste and bentonite sealing structures is avoided. However, a concrete lining of the galleries in Boom Clay is unavoidable due to the low strength of this host rock.

The access gallery is a rectilinear circular gallery, with an internal diameter of about 6 metres and a length of about 1 kilometre. It will be constructed in two phases, starting with the building of the access gallery B for the category B section of the repository. After completion of operations in the category B section, the access gallery B will be backfilled and sealed. The access gallery C for the category C section of the repository will then be constructed. At the end of the operational period (after completion of operations in the category C section), this section will also be backfilled and sealed.

All disposal galleries are connected to the access gallery. The intersections (crossings points) between the access gallery and the disposal galleries are set at right angles in the reference design. Per crossing, two disposal galleries are facing each other (fishbone architecture with blind disposal galleries). The internal diameter of the disposal galleries is about 3 metres and their length is limited to 1 kilometre. The length of the disposal galleries depends on the waste type and its inventory. The distance between disposal galleries depends on the waste type (from 50 up to 120 metres) (Weetjens, 2009). A concrete end plug of 3 metres is foreseen at the end of the disposal galleries to avoid direct contact between the disposal waste package and the Boom Clay (Figure 15). Access and disposal galleries will be outfitted with a concrete floor, specifically designed to provide a path for the transportation. Within the disposal gallery, the floor will serve as a mechanical support to dispose the disposal waste packages. A cementitious material is used to progressively backfill remaining gaps in each disposal gallery in a stepwise manner, following emplacement of about 30 metres of waste packages. The backfill reduces the voids and, consequently, the amount of free water in the repository. Reducing all large voids in the repository is a requirement from the regulator. Furthermore, the backfill provides mechanical stability to the gallery lining and limits the risk of human intrusion. Disposal galleries will be sealed after complete backfilling, for reasons of operational and long-term safety.

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14 The choice of the lining material for the large intersections required between the access gallery and the disposal galleries is still under discussion (Section 5.2.2).



**Figure 15** – Schematic longitudinal cross-section of a disposal gallery (after (Wacquier and Van Humbeeck, 2009)).

Following the completion of underground operations, the access gallery and shafts are backfilled and sealed.

The footprint area of the reference repository is a few kilometres squares; the precise dimensions depending on whether the reprocessing moratorium is lifted or not (Table 7). The area covered by the surface installations is limited to about 75 hectares.

**Table 7** – Estimation of the footprint of a geological repository for category B and C waste with the current reference design (with closure of the seven existing nuclear commercial reactors after 40 years of operation) according to the ONDRAF/NIRAS 2009 estimate (see Section 3.1.2).

	No further reprocessing		Full reprocessing	
	Category B	Category C	Category B	Category C
<b>Quantity of waste to be disposed of (m<sup>3</sup>)</b>	10 430	4 500	11 100	600
<b>Number of disposal packages (monolith B or supercontainers)</b>	4 700	2 900	5 070	2 106
<b>Length of disposal galleries (km)</b>	14	17	16	7.5
<b>Total length of disposal galleries (km)</b>	<b>31</b>		<b>23.5</b>	
<b>Total footprint (km<sup>2</sup>)</b>	<b>3.1</b>		<b>1.8</b>	

Retrievability was not a prerequisite when the current reference design was developed. It is now included in the RD&D programme. Including retrievability affects the repository design. That will probably influence, for instance, the choice of backfilling and sealing materials and processes (Section 5.4).

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**Roadmap – Section 3.2 – Characterisation of the EBS (BC)** (Chapter 5 details the RD&D to underpin the feasibility of constructing, operating, closing, and where applicable, decommissioning, the proposed disposal design for category B&C waste.)

*For SFC1*, ONDRAF/NIRAS will further refine the design of the engineered barrier system (EBS). It will focus in particular on developing backfill and seals. It will examine the measures that could facilitate the possible retrieval of the waste after partial or complete closure of the disposal facility and highlight the technical limitations of retrievability, because it cannot occur at the expense of radiological safety, physical security and non-proliferation measures for nuclear materials (safeguards). (Enhancing retrievability could also have an impact on the cost of the disposal facility.) ONDRAF/NIRAS will then specify the requirements for the retrievability of disposed waste in collaboration with other stakeholders (by use of a participative method) (see roadmap Chapter 11). After specification of these requirements (not necessarily before SFC1), ONDRAF/NIRAS will refine its backfill design and its sealing strategy and design (see Sections 5.4.1 and 5.4.2).

*For SFC1*, ONDRAF/NIRAS will further characterise the EBS properties taking into account the evolution of its design if relevant (materials, manufacturing processes etc.).

ONDRAF/NIRAS will study the transport of solutes and fluids (water, gas) in the EBS *for later SFCs* (see roadmap Section 4.2.2.5).

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### 3.3. The geological barrier can be characterised

The characteristics of Boom Clay, the geological barrier, were already well defined at the time of SAFIR2, based on analyses from outcrops in the Antwerp area, numerous boreholes in the North Sea Basin and the Campine area (drilled by ONDRAF/NIRAS and other organisations) and from the HADES underground research facility (ONDRAF/NIRAS, 2001b). Current knowledge is adequate for the purpose of SFC1. There is nevertheless continuous research to refine the assessment basis and reduce uncertainties. This section summarises major characteristics of Boom Clay.

#### **Inset 8 – ONDRAF/NIRAS wishes to drill an additional borehole in Boom Clay**

At this stage of the research programme, data from a new borehole drilled through Boom Clay would bring valuable information. This borehole could help to:

##### **Refine the knowledge of Boom Clay, for confidence building and preparation for the siting:**

- increase the resolution of data;
- confirm the lateral continuity of Boom Clay formation;
- characterise with more precision the vertical layers, in terms of, for instance, migration parameters and thermal parameters;
- improve the correlation between migration parameters and lithology;
- apply the best available techniques for sampling, taking into account the anisotropic properties of the clay.

##### **Characterise with more precision the layers around Boom Clay in terms of:**

- hydraulic properties of the clay-silt-sand transition between Boom Clay and the Neogene aquifer and on the alternating permeable and impermeable layers of the Oligocene aquifer, for a more realistic description of the system in hydrogeological modelling;
- thermal parameters of the formations below and above the Boom Clay, for re-evaluating the uplift above a repository for heat-emitting wastes.

##### **Prepare for the siting process:**

- review the borehole geophysical tools and techniques that could be applicable to the characterisation of potential sites.

#### 3.3.1. The Boom Clay and its occurrence area

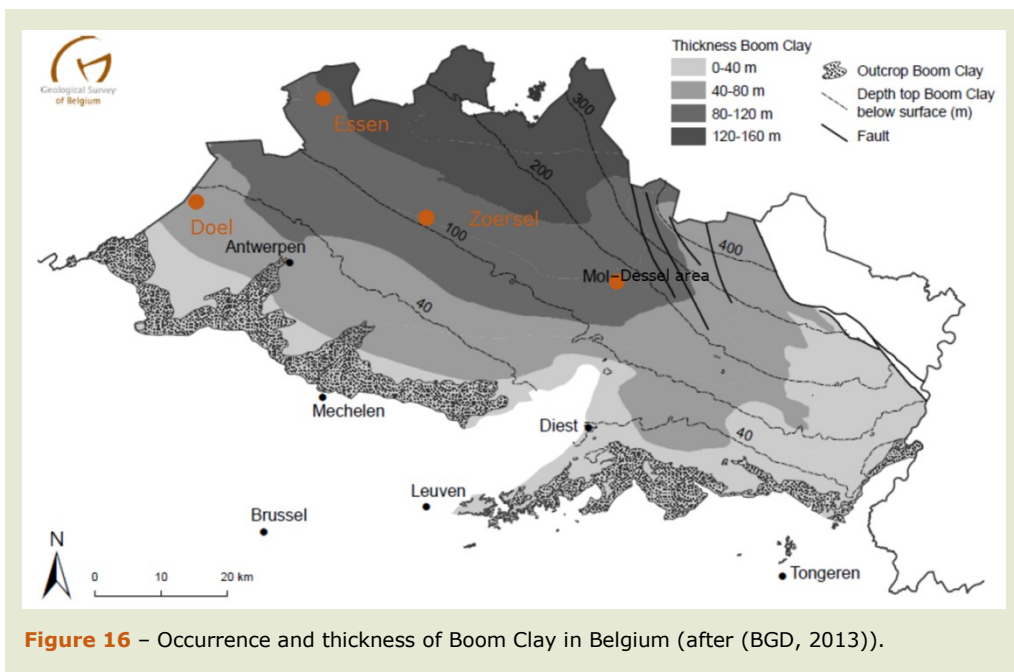
The Boom Clay, or Boom Formation, was deposited about 30 million years ago, during the Rupelian, a stage of the Paleogene Period. Boom Clay is present, under various stratigraphic names, in Belgium, the Netherlands and Germany.

In Belgium, the region in which the Boom Clay is present corresponds roughly to the Campine, the geographical region situated in the northeast of Belgium (Figure 16). Seismic investigations and reconnaissance – or prospection – boreholes enabled to quantify the dimensions of Boom Clay. The Boom Clay outcrop forms a 5 to 15 kilometres wide eastwest oriented belt, which is interrupted in the Hageland by a

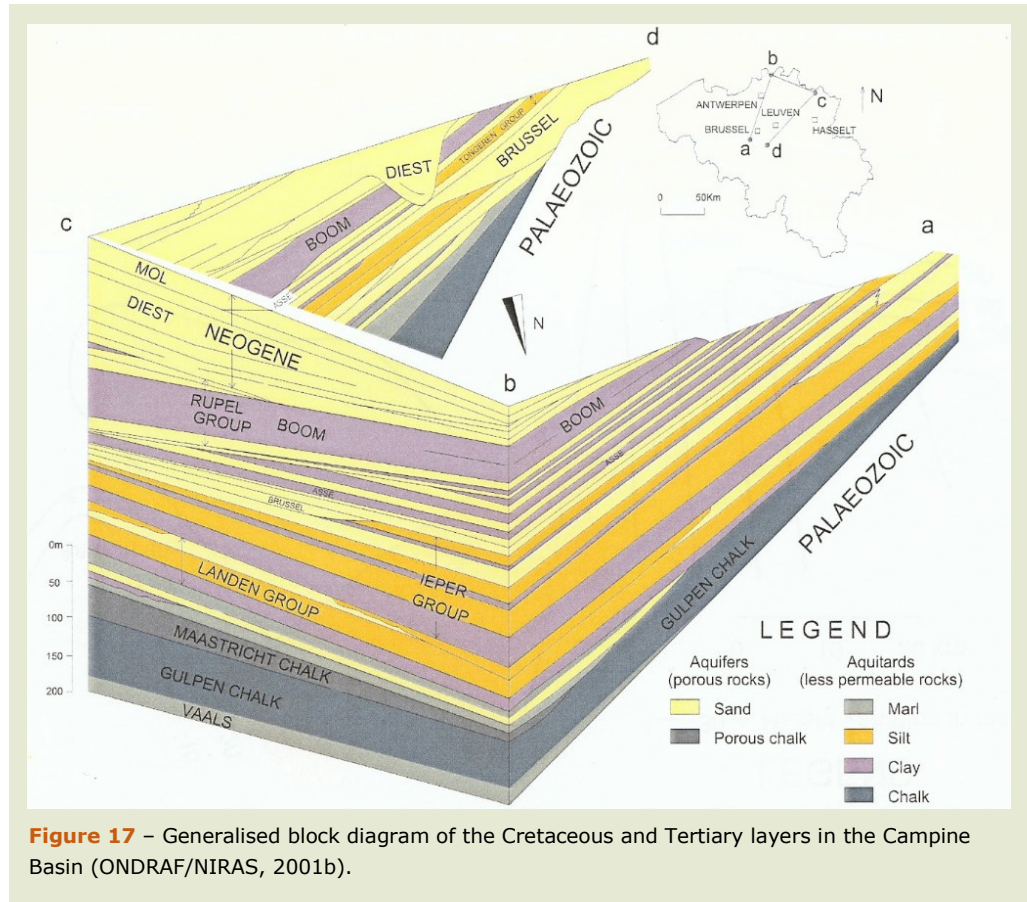
deeply eroded channel filled with Diest Sands. The western outcrop zone is bounded by the Scheldt estuary, and the Rupel and Demer rivers. The eastern outcrop zone is located in the Hageland and the Demer region in Limburg. The Boom Clay displays a 1 to 2% dip towards the north-northeast and thickens in this direction (Figure 17). In the Mol–Dessel area, the Boom Clay is present between a depth of approximately 190 and 290 metres beneath the surface, attaining a thickness of about 100 metres. In the north of the Province of Antwerp, near to the border with the Netherlands, the top of the Boom Clay is at a depth of more than 300 metres and its thickness reaches more than 150 metres.

In the Netherlands, in the Roer Valley Graben, the Boom Clay is present at a depth of more than 1 000 metres at certain places, because of fault activity (De Craen *et al.*, 2012).

Part of Boom Clay is eroded in the outcrop area and even missing in the Diest area (Figure 16). This is due to tectonic uplift during the Late Rupelian.



**Figure 16** – Occurrence and thickness of Boom Clay in Belgium (after (BGD, 2013)).



### Roadmap – Section 3.3.1 – Occurrence (BC)

The current knowledge of the occurrence of Boom Clay is adequate for the purpose of SFC1. The drilling of a new borehole will nevertheless provide valuable information in this field (see Inset 8). The first results might be included in SFC1.

*During the site selection process, ONDRAF/NIRAS will refine and confirm the depth of the base and top of the host formation at the investigated sites.*

### 3.3.2. Discontinuities

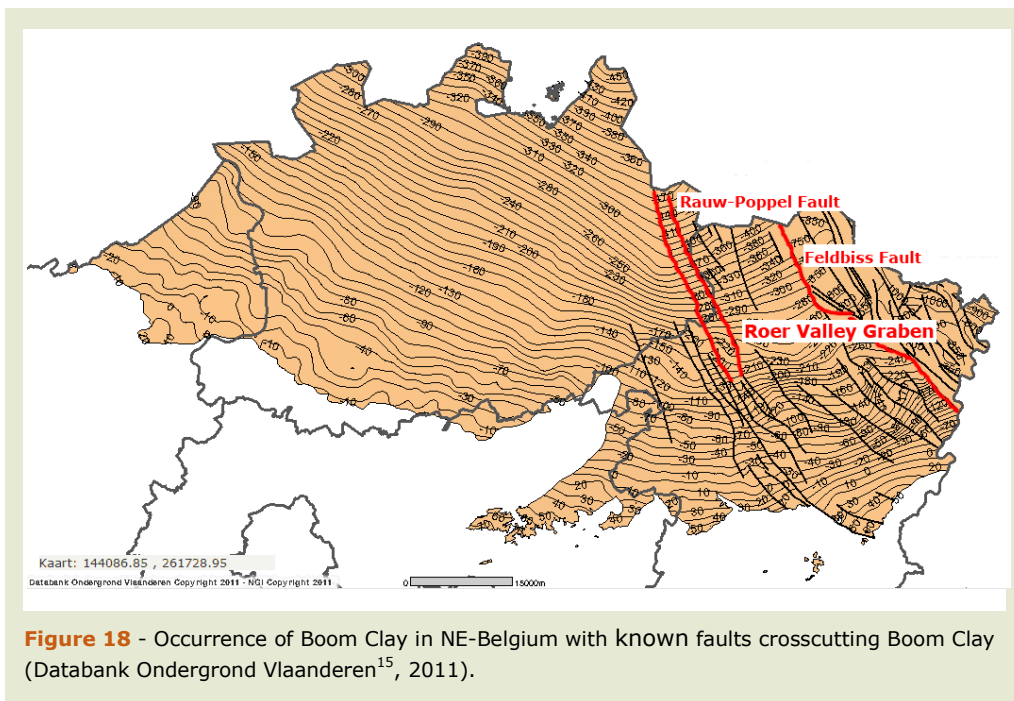
Major discontinuities were already well identified at the time of SAFIR2. The most important tectonic features recognised in the Campine are NW-SE oriented tectonic faults, present mainly in the eastern Campine. Most of these faults relate to the Palaeozoic, more than 250 millions years ago. Some of them were later re-activated and crosscut upper layers up to the Quaternary layers, and even occasionally up to the surface. The tectonic activity that led to re-activation of some faults is related to the activity of the Roer Valley Graben, which is part of a large extensional European Cenozoic Rift System, and which is still tectonically active today. Consequently, faults crosscutting Boom Clay are present in the northeast of the Campine close to the Roer

Valley Graben (Figure 18). Faults related to plate tectonics extend for several kilometres. The main faults active in the Pliocene and the Quaternary bordering the Roer Valley Graben are the Rauw-Poppel and the Feldbiss faults. The connectivity between the faults is not demonstrated (Mertens, 2005) (ONDRAF/NIRAS, 2006b).

All other discontinuities have a limited extent:

- Fractures of decimetre to decametre scale are observed in the outcrop areas of Boom Clay. Most are sub-vertical joints, considered to be shallow-depth phenomena. Only one fault has been identified in the outcrop areas of Boom Clay (in Kruibeke), with a displacement of the clay layers over a distance of about 1 metre. The fault is related to minor differential regional tectonic tilting during the Late Oligocene (Mertens *et al.*, 2003) (Dehandschutter *et al.*, 2005) (Dehandschutter *et al.*, 2005b) (De Craen *et al.*, 2012).
- Plastic deformation in the upper 20 metres of Boom Clay has been observed in the Antwerp area (Laga, 1966) (Wartel, 1980) (Schittekat *et al.*, 1983) (Henriet *et al.*, 1983) and (Verschuren, 2001). The observed features of uprising clay systematically occur at places where the Scheldt River eroded down into the top of the Boom Clay. This is likely due to valley bulging: the plastic deformation is related to river incision and associated decrease in overburden load that resulted in the vertical upward movement of the clay (Hobbs *et al.*, 2011).

In the Mol–Dessel area, more than 30 years of investigations revealed no discontinuities such as joints or faults. In the underground research facility, only excavation-induced fractures are observed. These fractures, of micrometre to metre scale, are related to stress redistributions during excavation works.



**Figure 18** - Occurrence of Boom Clay in NE-Belgium with known faults crosscutting Boom Clay (Databank Ondergrond Vlaanderen<sup>15</sup>, 2011).

15 Website of the DOV: <https://dov.vlaanderen.be/dovweb/html/engels.html> (Last visit: 28 November 2013).

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### Roadmap – Section 3.3.2 – Discontinuities (BC)

There is sufficient knowledge of discontinuities in Boom Clay for SFC1.

*For confidence building*, ONDRAF/NIRAS will further refine the understanding of some observed discontinuities, such as the sub-vertical joints in outcrop areas.

ONDRAF/NIRAS currently analyses existing geophysical data in the light of updated techniques. For instance, it reprocesses the seismic data with new numerical software, with a focus on the observation of discontinuities within Boom Clay and aquifers. This work will help the organism to select state-of-the-art investigation techniques to use during the siting process.

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### 3.3.3. Lithology

Field and laboratory investigations in outcrops and boreholes enabled to assess the lithological characteristics of the Boom Clay. The Boom Clay is a silty clay or argillaceous silt and presents a layered structure (Figure 19). Bands differ by (limited) variations in grain size (alternating clayey silt and silty clay layers), organic matter content and carbonate content. These variations are the consequence of depositional processes (sedimentary, from marine origin) and subsequent limited burial history. The bands thickness ranges between 10 centimetres and 2 metres (Vandenberghe, 1978).



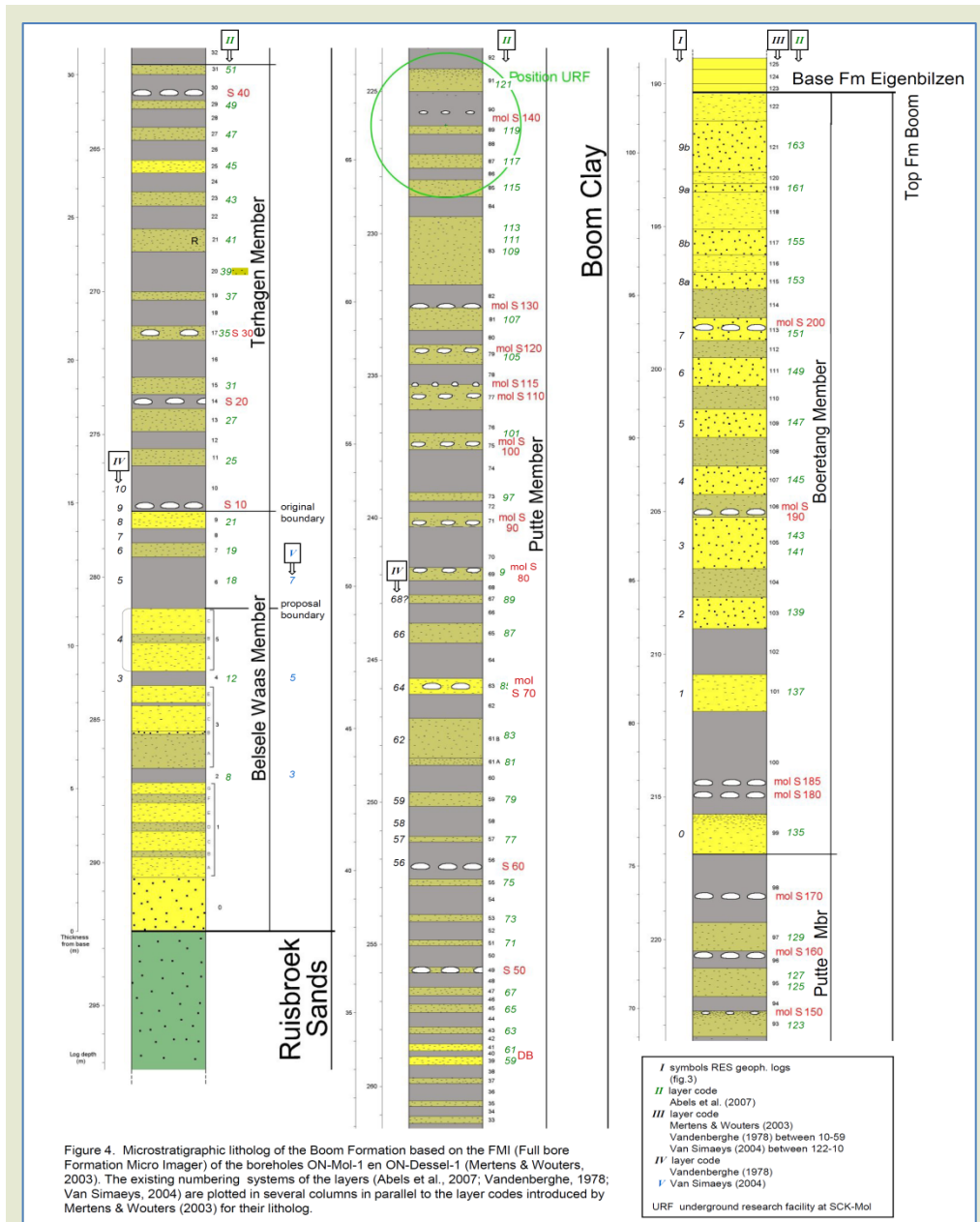
**Figure 19** – Overview of a clay quarry (Kruibeke) showing the characteristic band structure of Boom Clay.

From bottom to top, the Boom Formation is divided into four main stratigraphic units<sup>16</sup>: the Belsele-Waas Member, the Terhagen Member, the Putte Member and the Boeretang Member (formerly known as the Transition zone or 10-WIG zone, and part of the Putte Member) (Table 8). Since SAFIR2, the National Commission of Stratigraphy of Belgium has modified the limit between the Belsele-Waas and Terhagen and has introduced the Boeretang Member. The layered structure contains easy recognisable features such as the pink horizon in the Terhagen Member, the boundary between the grey clay of the Terhagen Member and the black clay of the Putte Member, the Double Band in the Putte

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16 Website of the National Commission of Stratigraphy: <http://www2.ulg.ac.be/geosed/GB/NCS.htm> (Last visit: 23 March 2012).

Member and about 20 septaria levels (carbonate concretions). Figure 20 shows the main stratigraphic units of the Boom Clay found at the Mol site.



**Figure 20** – Microstratigraphic lithology of the Boom Formation of the Mol-1 and Dessel-1 boreholes (Vandenberghe *et al.*, to be published).

The Boom Clay presents an extended lateral continuity: the same reference horizons with distinct characteristics are observed in outcrops as in boreholes over long distances, which is interesting for transferability. The mineralogy of the Boom Clay in the Essen-1 borehole (northwest of Belgium, Figure 16) is comparable to that of the Boom Clay in Mol (Honty *et al.*, 2009).

Grain size variations are generally rather small as the sizes range from clayey silt to silty clay. The existing variations reflect changes in local tectonics, eustacy (global sea level

change) and climate during deposition (Van Echelpoel, 1991) (Vandenberghe *et al.*, 1997).

**Table 8** – Hydro-stratigraphy and litho-stratigraphy in the Mol–Dessel area (Vandersteen *et al.*, 2012).

HYDRO-STRATIGRAPHY			LITHO-STRATIGRAPHY				
old SCK terminology	HCOV coding <sup>17</sup>		FORMATION		Member	Main lithology	
Miocene aquifer	(lower part of the) Campine aquifer system (0200)	Miocene aquifer (0250)	DIEST Di			sand	
			BERCHEM Bc	BOLDERBERG Bb			
			VOORT Vo				
			EIGENBILZEN Eg				
Boom aquitard	Boom aquitard (0300)	Clayey part of Eigenbilzen (0301)	BOOM Bm		Boeretang	clay	
		Putte clay (0302)			Putte BmPu	clay	
		Terhagen clay (0303)			Terhagen BmTe	clay	
		Belsele-Waas clay (0304)			Belsele Waas BmBw	clay	
Lower Rupelian aquifer	Oligocene aquifer (0400)	Kerniel sand (0410)	BILZEN Bi		Kerniel BiKe		
		Kleine-Spouwen clay (0420)			Kleine Spouwen BiKs		
		Ruisbroek-Berg Aquifer (0430)			Berg BiBe	sand	
		Tongeren Aquitard (0440)	BORGLOON Bo				
		Lower-Oligocene Aquifer system (0450)	ZELZATE Zz	St. H. HERN Sh	Ruisbroek ZzRu	Neerrepen ShNe	sand
					Watervliet ZzWa		clay
					Bassevelde ZzBa	Grimmertingen ShGr	sand
	Bartoon aquitard (0500)	Onderdijkse clay (0501)	MALDEGEM Ma		Onderdijkse MaOd	clay	
		Buisputten sand (0502)			Buisputten MaBu	sand	
		Zomergem clay (0503)			Zomergem MaZo	clay	
		Onderdaele sand (0504)			Onderdaele MaOn	sand	
Asse Clay		Ursel and/or Asse clay (0505)			Ursel MaUr	clay	
					Asse MaAs	clay	
					Wemmel MaWe	sand	
Lede-Brussels aquifer <sup>3</sup>	Ledo-Paniselian-Brusselian aquifer (0600)	Wemmel – Lede aquifer (0610)	LEDE Ld			sand	
		Brussels Sands (0620)	BRUSSELS Br			sand	
		Upper Paniselian deposits (0630)	AALTER Aa			sand + sandy clay	
		Lower Paniselian sandy deposits (0640)	GENTBRUGGE Ge		Vlierzele GeVl	sand	

17 HCOV coding: Hydrogeologische Codering van de Ondergrond van Vlaanderen.

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### Roadmap – Section 3.3.3 – Lithology (BC)

There is sufficient knowledge of the lithology of Boom Clay for the purpose of SFC1. The drilling of a new borehole will nevertheless provide valuable information in this field (see Inset 8). The first results might be included in SFC1.

*During the siting process*, ONDRAF/NIRAS will refine the characterisation of horizontal distribution of some septaria layers. It will also further characterise the vertical layers in terms of, among others, granulometry.

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### 3.3.4. Mineralogy

The present-day mineral assemblage of the Boom Clay is considered to represent more or less the mineral assemblage of the Boom Clay shortly after deposition (30 million years ago). Nevertheless, several diagenetic products are recognised, the most important being pyrite and carbonates. These are the result of early-diagenetic processes taking place in the shallow burial environment. Since then, the mineralogy of the Boom Clay remained the same (De Craen, 1998). Although Boom Clay contains up to several percent of carbonates, there is no evidence so far of significant cementation.

The same minerals are present over the whole Boom Clay formation although the proportions of the various minerals vary from one layer to another. This has been evidenced by different types of analysis: bulk rock composition, bulk rock chemistry, clay fraction composition and clay fraction chemistry. The homogeneity is expressed in the paragenesis observed both in the vertical profiles of the studied boreholes and laterally when comparing the data of various boreholes on regional scale. The main minerals are quartz and clays, in different proportions. The mineral contents reflect combination of sea-level relative variations and changeable detrital input from either source areas or different weathering rates; the areas closest to the paleo-coastlines being richer in quartz grains. Table 9 details the Boom Clay mineralogical compositions at the Mol site and on regional scale (Honty *et al.*, 2012).

The Boom Clay contains a significant amount of natural organic matter (NOM) (1 to 5% by weight), distributed between the liquid and the solid phase. Solid organic matter is defined as the NOM insoluble in aqueous solutions at all pH values. In sediments, it forms typically the largest part of all NOM, exceeding 90% or more of all organic matter. Solid organic matter is further subdivided into bitumen and kerogen. Bitumen is the part of solid organic matter that can be dissolved in usual organic solvents while kerogen is the remaining insoluble part (Bruggeman and De Craen, 2012).

The carbon/nitrogen (C/N) ratio of the natural organic matter varies between 5 and 23.8 through the Boom Clay (Vandenberghe, 1978). The measured range indicates at least two origins of organic matter input, namely a marine and a terrestrial one. The layers with larger organic content also have larger C/N ratios, suggesting a terrestrial origin. This is consistent with the observation that phytoclasts (terrestrial plant fragments) are more concentrated in these layers (Vandenberghe, 1978) (Laenen, 1997) (Van Geet *et al.*, 2003).



The natural organic matter of Boom Clay is immature (Vandenberghe, 1978). Diagenesis in Boom Clay is related to the microbial decomposition of the organic matter as pyrite and carbonate concretions were formed around an organic nucleus during early-diagenesis (< 1 million years after deposition). There are no indications that other diagenetic processes occurred during the last 30 million years (De Craen, 1998).

**Table 9** – Mineralogical composition of the Boom Clay at Mol site (Mol-1 borehole) and in the Campine basin (based on data compilation from the boreholes Mol-1, Zoersel-1, Doel-2b and the outcrop area (southern border of the Campine basin) (Honty *et al.*, 2012). The septaria levels are not taken into account.

<b>Mineralogical composition (% weight) (min-max)</b>	<b>Mol-1 borehole</b>		<b>Campine basin</b>	
Quartz	22	- 66	20	- 66
Na-plagioclase	0	- 6.3	0	- 7
K-Feldspar	0.4	- 8	0	- 8
Siderite	0	- 1.5	0	- 6
Calcite	0	- 4.6	0	- 5
Dolomite	0	- 1	0	- 1
Apatite	0	- 0.9	0	- 1
Pyrite	0.3	- 5	0	- 5
Illite/muscovite	5	- 37	4	- 37
Smectite and illite-smectite	6.8	- 37	6	- 43
Kaolinite	2	- 14	1	- 20
Chlorite	0.5	- 4	0	- 4

#### **Roadmap – Section 3.3.4 – Mineralogy (BC)**

The knowledge of Boom Clay mineralogy is sufficient for the purpose of SFC1. The drilling of a new borehole will nevertheless provide valuable information in this field (see Inset 8). The first results might be included in SFC1.

There remain uncertainties about the origin of the dissolved organic matter; matter that affects transport of some radionuclides (see roadmap Section 3.3.8). ONDRAF/NIRAS has thus launched a study to evaluate the potential genetic links between part of the kerogen and DOM. Results of this study will be integrated in SFCs *subsequent to SFC1*.

*During the siting process*, ONDRAF/NIRAS will further characterise the vertical layers in terms of mineralogy.

### 3.3.5. Density and water content

With a bulk density of about  $2\,000\text{ kg}\cdot\text{m}^{-3}$  and a grain density of about  $2\,650\text{ kg}\cdot\text{m}^{-3}$  (Mertens *et al.*, 2003) (Mertens *et al.*, 2004) (SELFAC, 2007), the typical water content of Boom water is thus about 20%. This is consistent with the water content weight range from 19 to 24% reported by De Craen *et al.* (De Craen *et al.*, 2004).

The range of Atterberg limits reported in SAFIR2 (Table 10) has been confirmed by additional data from Lima (Lima, 2011). Based on these data, the Boom Clay can be classified as stiff, plastic clay.

**Table 10** – Properties of Boom Clay at HADES URF level (ONDRAF/NIRAS, 2001).

Property	Range of values
Plastic limit	23 to 29%
Liquid limit	55 to 80%
Plastic index	32 to 50%

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### Roadmap – Section 3.3.5 – Density and water content (BC)

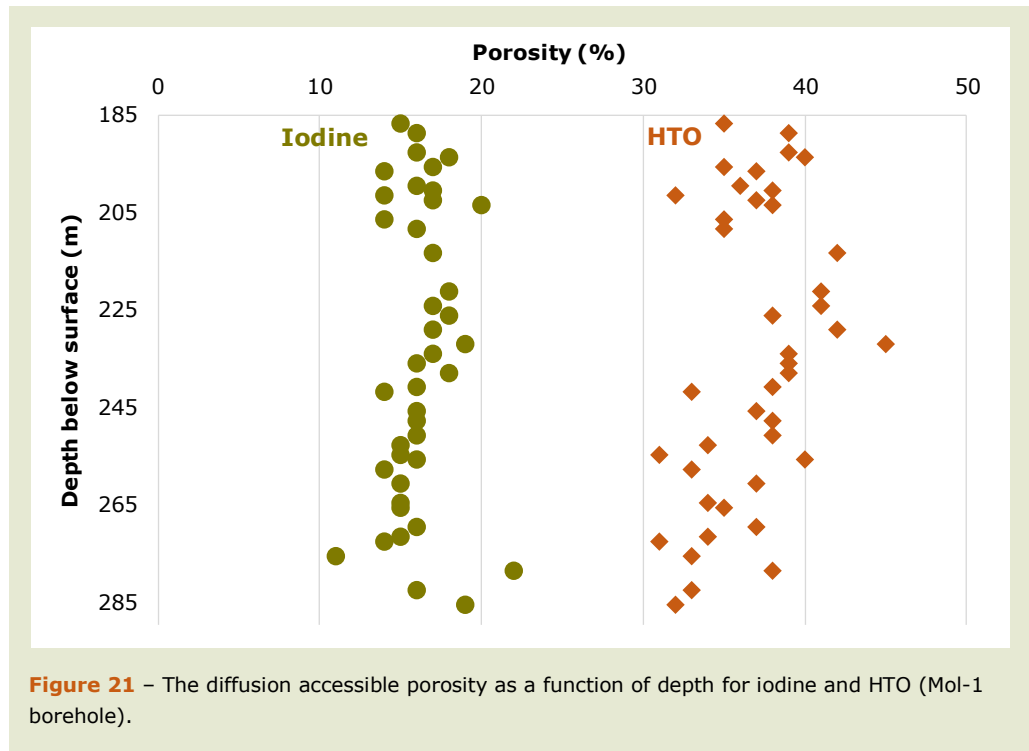
During the siting process, ONDRAF/NIRAS will further characterise the vertical and horizontal variability of density and water content.

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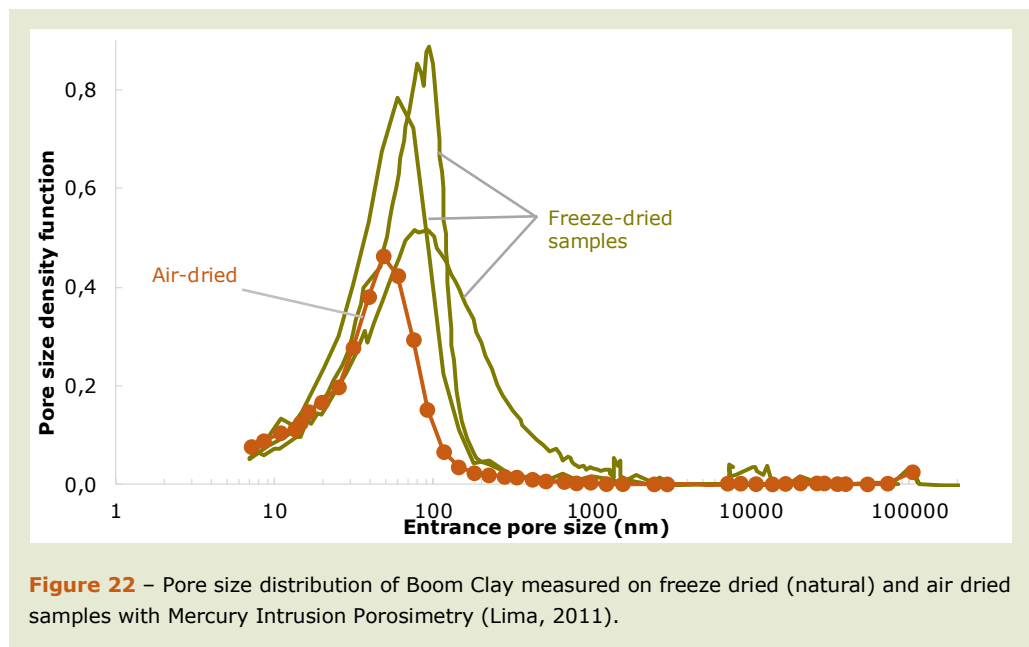
### 3.3.6. Porosity

SAFIR2 focused on assessing the total porosity of Boom Clay by study of core samples (ONDRAF/NIRAS, 2001). For water-saturated clays, the total porosity is the volume fraction of the clay occupied by water. The current RD&D aims to get more information about the diffusion accessible porosity of the bulk material, the pore size distribution, the pore structure and the connectivity between the pores. Assessing the porosity morphology in fine-grained sediments such as Boom Clay is quite complex due, among others, to the small pore sizes of this material.

The total porosity of Boom Clay derived from the water content ranges from 0.31 to 0.45. The clay bands present the highest porosities (Figure 21). The diffusion experiments with tritiated water (HTO) confirmed these values (Aertsens *et al.*, 2005). While it can easily be detected due to the radioactivity of the tritium (an hydrogen isotope), HTO behaves similarly to ordinary water in the Boom Clay and is thus an ideal, neutral, non-sorbing tracer that can access the entire diffusion accessible pore space. Results from these small-scale laboratory diffusion experiments are also in good agreement with those from the *in-situ* large-scale 25-years running diffusion tests in HADES URF (Figure 27 and Figure 28) (Section 3.3.9.2).



The pore size distribution is unimodal for the Putte and Terhagen Members, as measured by Mercury Intrusion Porosimetry (Figure 22) (Lima, 2011).



A small-scale characterisation of the pore network was performed in Aachen, combining Broad Ion Beam cross-sectioning and high-resolution Scanning Electron Microscope imaging. The combination of these techniques allows the investigation of successive 2D-sections with pores visible down to a few nanometres in size (Desbois *et al.*, 2010).

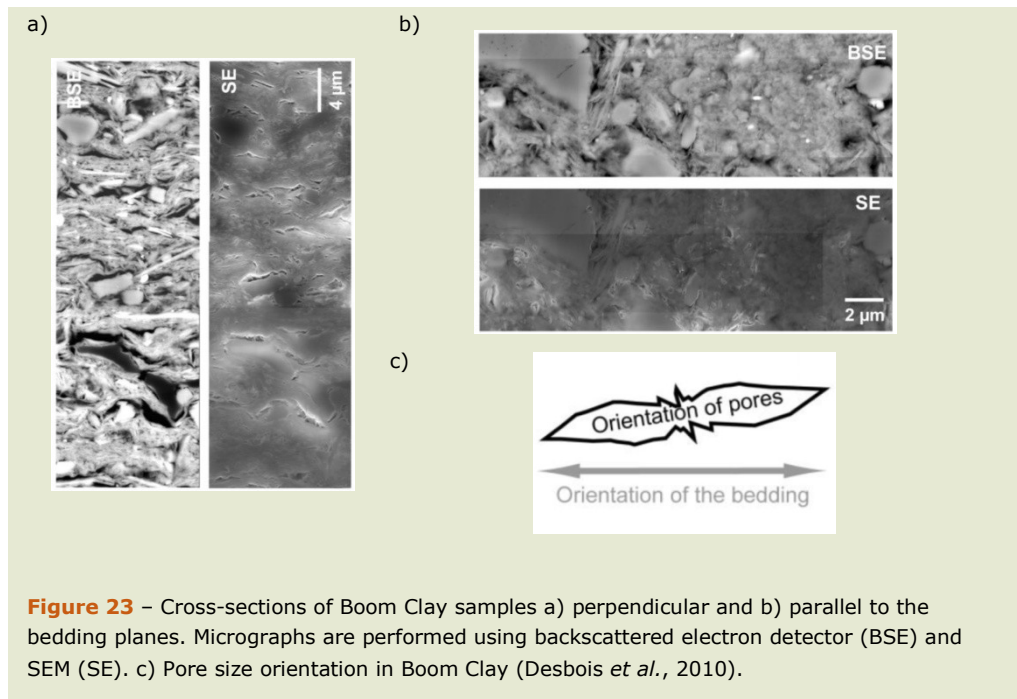
Porosities and grain sizes of three samples from the Boom Clay in Mol, from different locations (a coarse-grained sample from the Boeretang Member and two samples from the Putte Member (at different depths)), were compared, with 300 to 700 images taken from each sample at high magnification. Comparing 2D-slices parallel or perpendicular to the bedding plane evidenced that the shape of the pores is generally elongated and orientation is close to the bedding planes (which are sub-horizontal) (Figure 23) (Hemes *et al.*, 2011). The pore size distribution is similar in clay samples from different horizons.

These experiments nevertheless, present some limitations:

- The sample preparation introduces artefacts;
- The sample size is not representative;
- The resolution is limited (very small pores are not detected).

Moreover, the number of samples is too limited to draw general conclusions over the whole Boom Clay.

New experimental and analytical development is going on to improve the method.



**Figure 23** – Cross-sections of Boom Clay samples a) perpendicular and b) parallel to the bedding planes. Micrographs are performed using backscattered electron detector (BSE) and SEM (SE). c) Pore size orientation in Boom Clay (Desbois *et al.*, 2010).

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### Roadmap – Section 3.3.6 – Porosity (BC)

The knowledge of Boom Clay porosity is sufficient for the purpose of SFC1.

*For confidence building*, ONDRAF/NIRAS will pursue research on Boom Clay microstructure (e.g., characterisation in 3 dimensions of the lateral and vertical variability of pore size, distribution, structure and connectivity) as this allows linking Boom Clay properties at macroscopic scale with the microstructure.

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### 3.3.7. Hydraulic conductivity

The hydrogeological knowledge of the Campine area has been built from several studies performed by the Flemish Government, VITO<sup>18</sup>, SCK•CEN and others organisations, mainly for their interest in the natural water resources in the Campine underground (De Craen *et al.*, 2012). In the frame of geological disposal, RD&D focuses on piezometric observations from different aquifers, investigation drillings and groundwater modelling, for more than 30 years. The study zone covers a zone larger than the Campine area, up to a depth of some 600 metres, as detailed in (ONDRAF/NIRAS, 2001) (Figure 45). At the regional scale, back-analysis of the collected piezometric data supports the idea that the Boom Formation can indeed be considered as a single hydrostratigraphic unit, characterised by its very low hydraulic conductivity compared to the overlying and underlying layers (Meyus *et al.*, 2000).

A large investigation programme is running for more than 30 years to determine the range of values of the hydraulic conductivity (K). Experiments are carried out on different scales ranging from a few centimetres to decametres:

- Continuous laboratory experiments dedicated to K measurements on core samples:
  - ▶ Permeameter cell (centimetre-scale);
  - ▶ Percolation experiments performed in the framework of migration studies (centimetre-scale);
  - ▶ Experiments with the isostatic/triaxial cell in the framework of MEGAS I and MEGAS II <sup>19</sup> projects (decimetre-scale);
- *In-situ* tests in HADES URF:
  - ▶ Medium-scale (decimetre to metre scale) *in-situ* tests: piezometers used for measuring pore-water pressure around HADES URF are also used to determine the hydraulic conductivity, through either single point tests or interference tests with multi-piezometers;
  - ▶ Macro-permeameter experiment, performed in 1993 (decametre-scale): the water infiltration rate into the small vertical Experimental gallery below HADES URF was measured during 3 years (Ortiz *et al.*, 1996);
  - ▶ Time evolution of the radial hydraulic potential profiles around HADES URF (decametre-scale).
- *In-situ* tests in boreholes from the surface, using different techniques like the Modular Dynamic Tester (MDT), pressure pulse tests (dual packer) or even a continuous recording by means of magnetic resonance (CMR). As these techniques were developed for the oil industry, focussing on reservoir rocks and less on seal/cap rocks, interpretation of results is not always that straightforward.

The investigation programme provides consistent values of the hydraulic conductivity of the Boom Clay at the HADES URF level. At the time of SAFIR2, results yielded values of

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18 Vlaamse instelling voor technologisch onderzoek (Belgium).

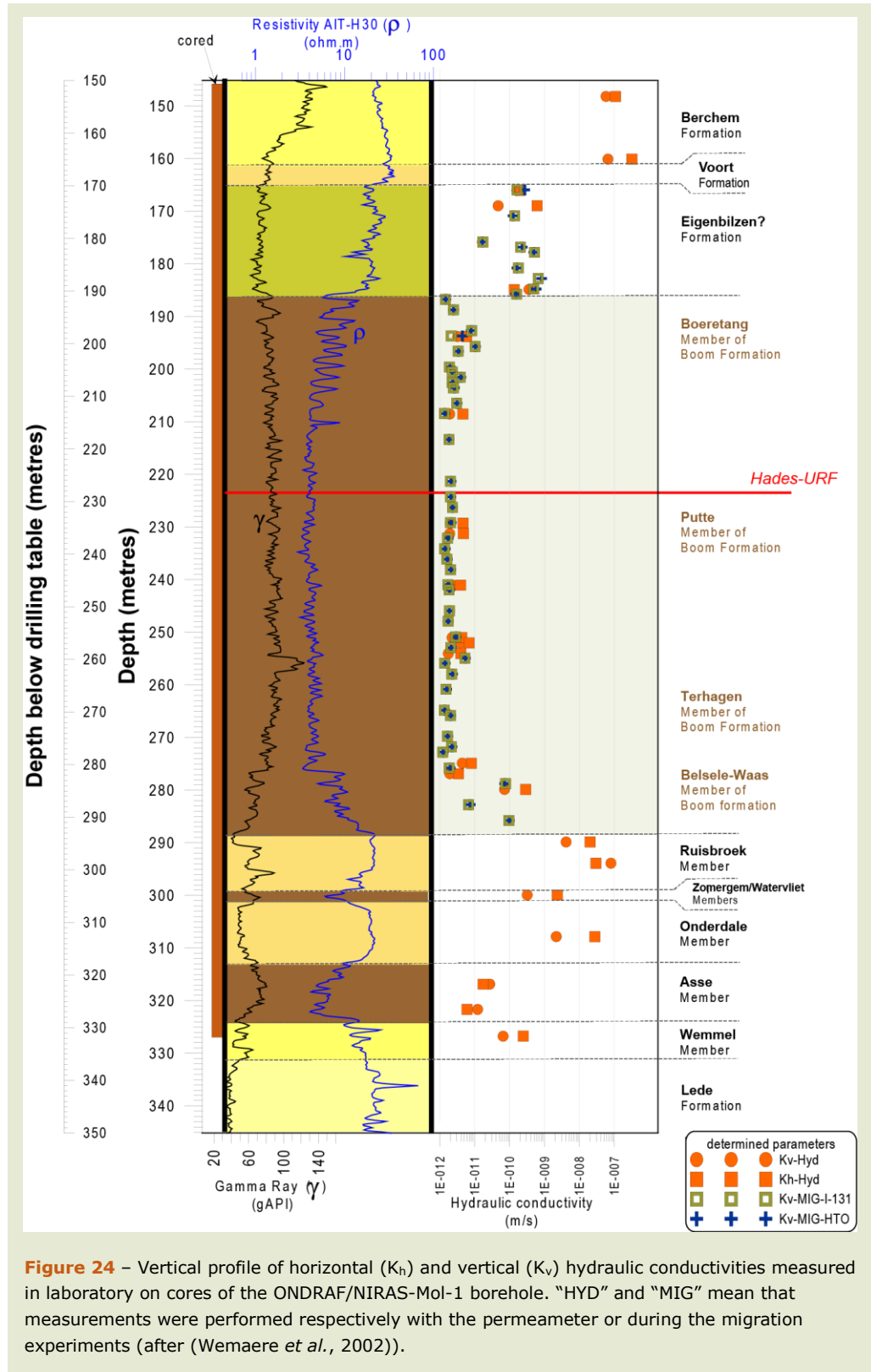
19 MEGAS I and II: Modelling and experiments on gas migration in repository host formations: *in-situ* gas injection experiments at two locations in HADES + modelling (EU projects).

hydraulic conductivity of the Boom Clay of the order of  $10^{-12} \text{ m}\cdot\text{s}^{-1}$  for the most argillaceous part of the formation and highlighted the anisotropy of this parameter. At that time, the ratio between the horizontal and vertical conductivities, as determined in the laboratory from permeameter cell measurements, was considered to be about two for the Putte and Terhagen Members and was very variable in the Belsele-Waas Member (ONDRAF/NIRAS, 2001).

Continuous RD&D led to more precise values of the hydraulic conductivities (Figure 24). It confirmed the anisotropy of this parameter. The anisotropy ratio is about 2.5 in the Putte and Terhagen Members (Yu *et al.*, 2011b). These Members form the most impervious part of the Boom Formation, except for a few thin layers (centimetre to decimetre scale) with relatively higher hydraulic conductivity as for instance the “Double Band” in the lower part of the Putte Member (factor 5).

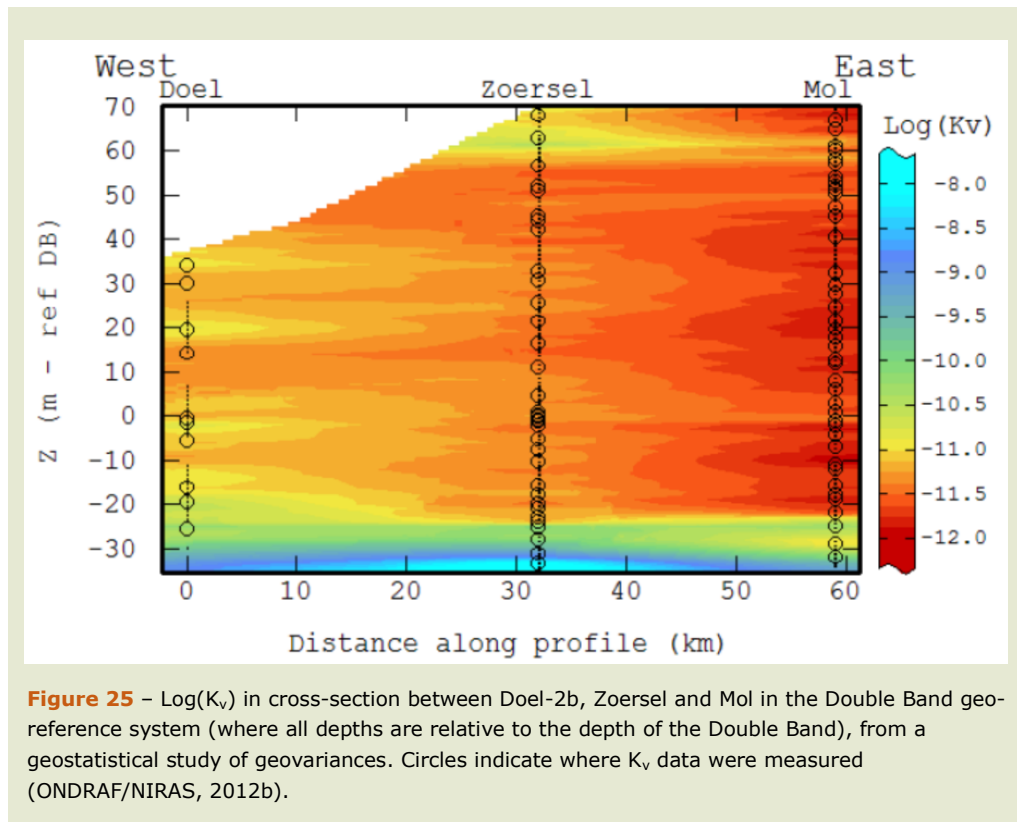
Taking into account the thickness of each sub-layer within the Putte and Terhagen Members at the reference site for RD&D for Boom Clay (Mol), the geometric mean value of the vertical hydraulic conductivity ( $K_v$ ) is  $1.7 \cdot 10^{-12} \text{ m}\cdot\text{s}^{-1}$ . The horizontal hydraulic conductivity ( $K_h$ ) is about  $4.4 \cdot 10^{-12} \text{ m}\cdot\text{s}^{-1}$ . The relatively homogenous distribution of hydraulic conductivities within the Putte and Terhagen Members implies that the vertical variability of the Boom Clay lithology (successive silty and clayey bands) has little influence on the overall hydraulic conductivities (Yu *et al.*, 2011b).

Current hydrogeological models correctly reproduce the measured hydraulic conductivities (Section 3.4.2.3).



The hydraulic conductivity of the Boom Clay, especially in the Putte and Terhagen Members, remains quasi constant at the scale of the Campine. This was stated thanks to a data acquisition campaign, composed of several exploration boreholes, set-up in the

nineties in order to characterise an area covering almost entire northeastern Belgium (about 1100 km<sup>2</sup>), closely related to the regional extent of the Boom Clay deposits (Wemaere *et al.*, 2008). Hydraulic conductivities of Boom Clay were determined from measures from permeameter cells, followed by a geostatistical study of geovariances (ONDRAF/NIRAS, 2012b). In this study, a 3D-multivariate model that included Log( $K_v$ ), Log( $K_h$ ), grain size d40 and Gamma Ray log calibrated on the Mol-1 borehole was used to estimate the hydraulic conductivities over the whole basin. Figure 25 presents a cross-section derived from the resulting 3D-cokriging. This section is globally oriented West-East (slightly dipping towards the South) and passes through three key boreholes: Doel at the West, Zoersel in the centre part and Mol at the East. Note that, because of erosion, the top of the Boom Clay formation disappears when going towards the West. The Double Band level is used as a vertical “zero” reference. The Boom Clay thickness at Mol-1 is taken as a reference and all other boreholes are rescaled to this thickness, in order to be globally consistent. The cross-section illustrates important trends of vertical hydraulic conductivities. First, vertically one can notice the expected more permeable behaviour of the Boom Clay Bottom unit (Belsele-Waas member) and, though less pronounced, of the Top one. Also, the slightly more permeable Double Band-level is visible. Laterally, a global decrease of Log( $K_v$ ) is remarkable from West to East.





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### Roadmap – Section 3.3.7 – Hydraulic conductivity (BC)

The knowledge of the hydraulic conductivity of Boom Clay is largely sufficient for the purpose of SFC1. It has been systematically analysed for decades in the reference area for RD&D, with a good correlation from measurements at different scales.

The drilling of a new borehole will nevertheless provide valuable information in this field. In particular, it will provide information on the hydraulic properties of the clay-silt-sand transition between Boom Clay and the Neogene aquifer and on the alternating permeable and impermeable layers of the Oligocene aquifer, to be used in hydrogeological modelling. The first results might be included in SFC1.

*After site selection*, ONDRAF/NIRAS will check the vertical variability of the hydraulic conductivity at the chosen site.

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### 3.3.8. Pore-water composition

Determining the pore-water composition accurately is an important step towards the understanding of the pore-water chemistry which, in turn, controls the speciation of radionuclides and hence their mobility. The composition of the pore water may also play an important role for the evolution of the disposal system. For instance, it will affect the degradation of the EBS components that will in turn locally perturb the pore water. In the nineties, the ARCHIMEDE-ARGILE<sup>20</sup> and the PHYMOL<sup>21</sup> projects already focused on the understanding of the geochemistry of the pore water in Boom Clay and of its evolution with time in the far field (due to the natural evolution) and in the near field (due to repository-induced perturbations) (ARCHIMEDE-ARGILE, 1996) (PHYMOL, 2000). Further investigations of the geochemistry of the Boom Clay are presented in a synthesis report written by De Craen *et al.*, shortly summarised hereafter (De Craen *et al.*, 2004).

The present-day Boom Clay pore water in Mol is essentially a NaHCO<sub>3</sub> solution of 15 mM. The major cations present are Na, Ca, K, Mg, Si and Fe (Table 11). A statistical analysis of the data available in 2004 for reference site for RD&D in Mol has evidenced vertical variations (perpendicular to the bedding) of this composition across the thickness of the Boom Clay (especially marked in specific layers such as the Double Band). These variations were explained at that time as resulting from cation exchange and calcite dissolution/precipitation mechanisms. There is however a much more marked lateral variability of the pore-water composition at a regional scale, with a more saline contribution towards the northwest (NaHCO<sub>3</sub> dominated water in Mol versus NaHCO<sub>3</sub>-NaCl mixed waters in Essen, closer to the North Sea) (Table 11).

Boom Clay pore water generally contains between 50 to 150 mgC·L<sup>-1</sup> of dissolved natural organic matter (DOM). These dissolved organic molecules are present as colloids, *i.e.*, evenly dispersed molecules throughout the pore water and with typical size between 1 nanometre and 1 micrometre. These organic molecules, essentially humics

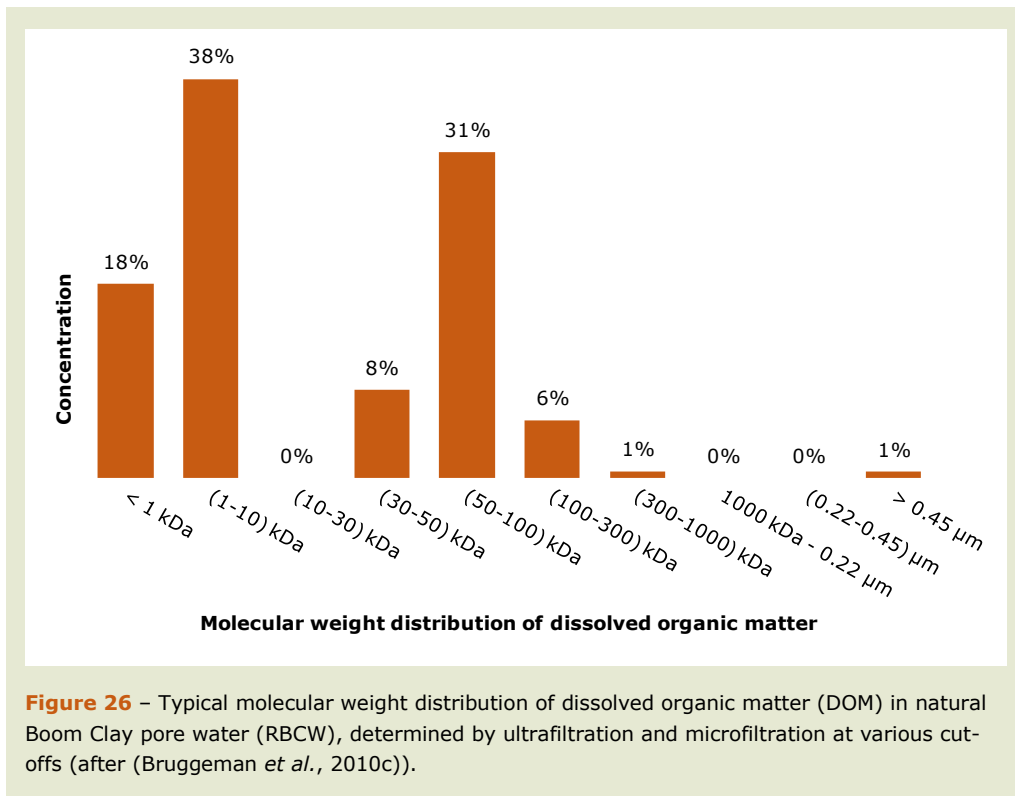
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20 ARCHIMEDE-ARGILE: Acquisition and regulation of pore-water chemistry, study of water/rock interactions and microbial activity in Boom Clay (EU project).

21 PHYMOL: Palaeohydrogeological study of the Mol site (EU project).

and fulvics, have some distinctive properties: thanks to their large specific surface areas ( $> 10 \text{ m}^2\cdot\text{g}^{-1}$ ), they are potential sorbents for environmental contaminants while being mobile through the pore network (up to a certain size, depending on the environment). Current environmental conditions in the Boom Clay at Mol are very favourable for organic colloids to be stable, the pore water having neutral to alkaline pH, relatively low ionic strength, and being Na-dominated with few multivalent cations. Moreover, ubiquitous occurrence of natural organic matter in Boom Clay favours the generation of organic colloids. Other types of colloids might exist as well but their presence is difficult to assess due to the high DOM content. These may include inorganic colloids made of clay minerals (illite, smectite, kaolinite, and chlorite), feldspars, quartz, amorphous silica and calcite, and eigencolloids as hydroxides that arise from aggregation of hydrolysed metal ions.

Sampling from filters at different depths in Mol evidenced significant variations of the DOM content with depth. The concentration probably depends on kerogen type and porosity structure (Blanchart, 2011). The dissolved organic matter presents a bimodal size distribution, as shown on Figure 26: the sampled pore water contains organic colloids of low molecular weight ( $< 10 \text{ kDa}$ ) and heavier ones (about  $30 - 300 \text{ kDa}$ ).



Boom Clay is a reducing environment with a redox potential ( $E_h$ ) lower than  $-270 \text{ mV}$  in the Mol area, where it is thought to be controlled by the equilibrium of pyrite and siderite under the local *in-situ* geochemical conditions (De Craen *et al.*, 2004).

**Table 11** – Chemical composition of squeezed Boom Clay pore water in various boreholes at a depth between S40 and S50 (for Doel, Zoersel and Mol), at depths from bottom to top of Boom Clay for Essen. Remark: the clay cores might be oxidised (De Craen *et al.*, 2004) (De Craen *et al.*, 2006).

Borehole	Doel-2b		Essen		Zoersel		Mol-1	
	Min. – Max. (mg·L <sup>-1</sup> )		Min. -Max. (mg·L <sup>-1</sup> )		Min. – Max. (mg·L <sup>-1</sup> )		Min. – Max. (mg·L <sup>-1</sup> )	
Ca	8.4 –	339	4.9 –	36	3.5 –	10.3	3.6 –	9.3
Fe	0.12 –	10.1	0.08 –	3.83	0.16 –	0.62	0.4 –	8.2
Mg	7.7 –	425	6.5 –	52	6.0 –	20.0	3.4 –	34.2
K	10.1 –	115	10 –	55	4.9 –	14.4	4.8 –	29.5
Si	5.1 –	11.5	4.2 –	10.2	5.9 –	10.5	9.1 –	33.5
Na	381 –	1 780	137 –	2 500	365 –	777	238 –	1 240
F <sup>-</sup>	0.9 –	1.4	0.62 –	1.74	1.1 –	1.9	2.2 –	3.0
Cl <sup>-</sup>	317 –	4 000	106 –	3 100	248 –	347	20.4 –	52.2
Br <sup>-</sup>	2.1 –	11.2	1.9 –	11	1.26 –	1.75	0.5 –	5.6
SO <sub>4</sub> <sup>2-</sup>	53 –	507	27 –	790	6 –	618	32 –	999
HCO <sub>3</sub> <sup>-</sup>	247 –	742	298 –	555	448 –	1 209	422 –	1 122

The pH of Boom Clay pore water is slightly alkaline (8.3), as shown by the presence of carbonates and the value of pCO<sub>2</sub>. However, artefacts related to the installation of piezometers and/or water sampling may well affect the measured Boom Clay pH (and associated pCO<sub>2</sub>) which make it difficult to conclude on the controlling mechanisms. Therefore, the pore-water composition of Boom Clay is best represented by a reference geochemical model, which is used to calculate the specific water composition under specific chemical conditions. Such a geochemical model, as described in De Craen *et al.*, reproduces fairly well the pore-water compositions measured in the underground research facility (*i.e.*, MORPHEUS<sup>22</sup> piezometer) at Mol under present-day conditions (De Craen *et al.*, 2004). This ion exchange and solubility model assumes a chemical equilibrium between the pore water and Boom Clay rock forming minerals. The current geochemical model assumes the equilibrium of calcite, siderite, pyrite, siderite, kaolinite and the cation exchange between Ca, Na, K and Mg with the pore water.

### Roadmap – Section 3.3.8 – Pore water composition (BC)

The knowledge of Boom Clay pore water composition is sufficient for the purpose of SFC1.

ONDRAF/NIRAS has launched studies whose results will be integrated in *later SFCs*. ONDRRAF/NIRAS tests the geochemical model on pore water samples from Essen, where its composition is more saline than in the Mol area, in order to assess the transferability

22 MORPHEUS: Mobile organic matter and pore water extraction in HADES URF.

of this model to locations other than Mol and determine the limits of validity of the model. ONDRAF/NIRAS also works to improve the characterisation of dissolved organic matter (DOM) and evaluate the potential genetic links between part of the kerogen and DOM. (as mentioned in roadmap of Section 3.3.4), because DOM affects transport of some radionuclides (Section 3.3.9).

*For confidence building*, ONDRAF/NIRAS will refine the geochemical model of the pore water composition in Mol, focussing on site occupancies by cations, based on, among others, additional *in-situ* measures of pH and  $E_h$ .

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### **3.3.9. Transport of solutes**

The identification of the processes affecting solutes migration through the Boom Clay is a central part of the RD&D programme since its inception. This section focuses on the migration of radionuclides as they are the major source of contaminants and are used as proxies to characterise the transport properties of other solutes in Boom Clay.

The SAFIR2 report confirmed the dominance of molecular diffusion, the importance of retention processes and stressed the possible role of organic matter in the transport of radionuclides in the Boom Clay. However, the conceptualisation of the role of organic matter (OM) in radionuclide transport was found questionable by the NEA (NEA, 2003). Since then, the conceptual model for OM–radionuclide interactions and OM–mediated radionuclide transport has been deeply refined.

The elements of the radionuclide transport model are presented sequentially hereafter, starting with the speciation and solubility of radionuclides in Boom Clay (Section 3.3.9.1), the dominant mechanism of transport (diffusion, Section 3.3.9.2) and the interactions between the solutes and the clay (Section 3.3.9.3). These are combined to describe the integrated migration model (*i.e.*, a combination of transport and retardation processes, Section 3.3.9.4). Finally, Section 3.3.9.5 presents the approach chosen to categorise all solutes of interest in geochemically coherent families.

#### **3.3.9.1. Speciation and solubility of radionuclides in Boom Clay**

The speciation of radionuclides in Boom Clay affects their migration behaviour. At the time of SAFIR2, speciation and solubility data for key radionuclides were calculated using various thermochemical databases available in the literature (Wang *et al.*, 2011). For SFC1, ONDRAF/NIRAS requested the building of a single, internally-consistent thermochemical database, to be used as reference for geochemical modelling and reactive transport calculations. The compiled database, named MOLDATA, includes thermodynamic data from different so-called “source databases” (databases from NEA, Nagra, Andra, among others). The selection procedure is mainly based on incorporating the most accurate, state-of-the-art and accepted data by the scientific community while ensuring the internal consistency of the resulting database (Salah *et al.*, 2012).

The determination of solubilities of inorganic species is based on thermodynamic calculations using MOLDATA. For a given element, such calculations yield a list of possible controlling phases and the corresponding saturation indices. A solid phase is assumed to

precipitate when its saturation index is above zero. When available, results of laboratory experiments and observations from natural analogues are used to confirm the solubilities obtained from such calculations.

The RD&D programme has included studies for assessing the impact of the organic matter on the solubility of uranium, thorium and europium. They concluded that the presence of organic matter increases the solubility of these radionuclides by several orders of magnitude (Delécaut, 2004) (Bruggeman *et al.*, 2010c).

### 3.3.9.2. Dominance of diffusion

Solute transport through saturated porous media is classically described by an advection-diffusion equation. Under the low hydraulic gradient prevailing in the region of interest and in absence of preferential flow pathways, the low hydraulic conductivity of Boom Clay strongly limits water flow (Sections 3.3.7 and 3.4.2.2). Therefore, the advective component of solute transport is generally small compared to the diffusion one, which is thus the major transport process in the host formation.

So far, experimental and modelling works confirm the dominance of diffusion. Two large-scale *in-situ* migration experiments, CP1<sup>23</sup> and TRIBICARB-3D<sup>24</sup>, are running for decades in HADES URF. In both experiments, a known quantity of a non-retarded radioactive tracer, tritiated water (HTO), has been injected in a piezometer filter located at some distance from the laboratory (Figure 27).

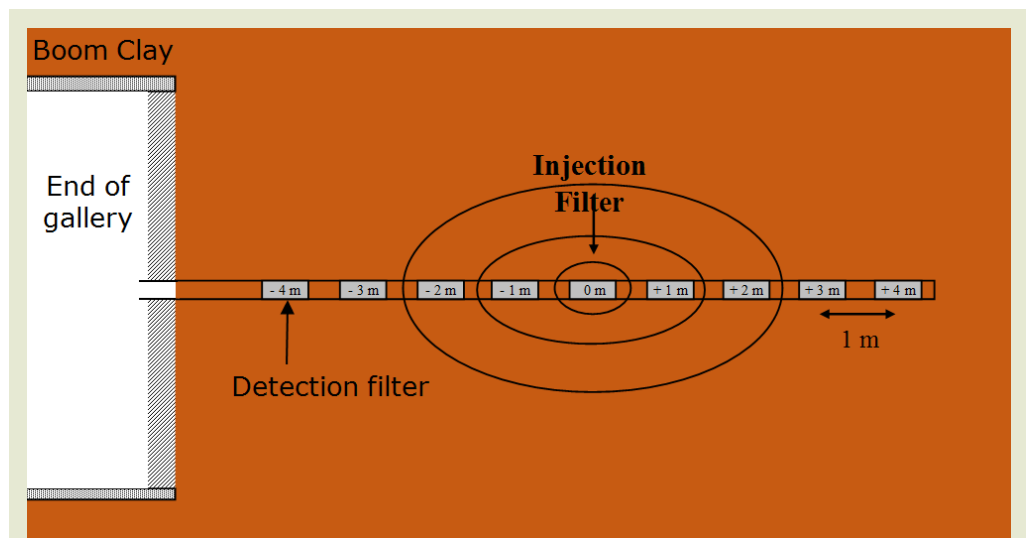


Figure 27 – CP1 experimental set-up (after (Bruggeman *et al.*, to be published)).

Tracer concentrations are monitored at adjacent filters on the same multi-piezometer or on neighbouring piezometers. Since 2007, tritium activity starts to be measured at three metres on both sides of the injection filter in the CP1 experiment. The concentrations

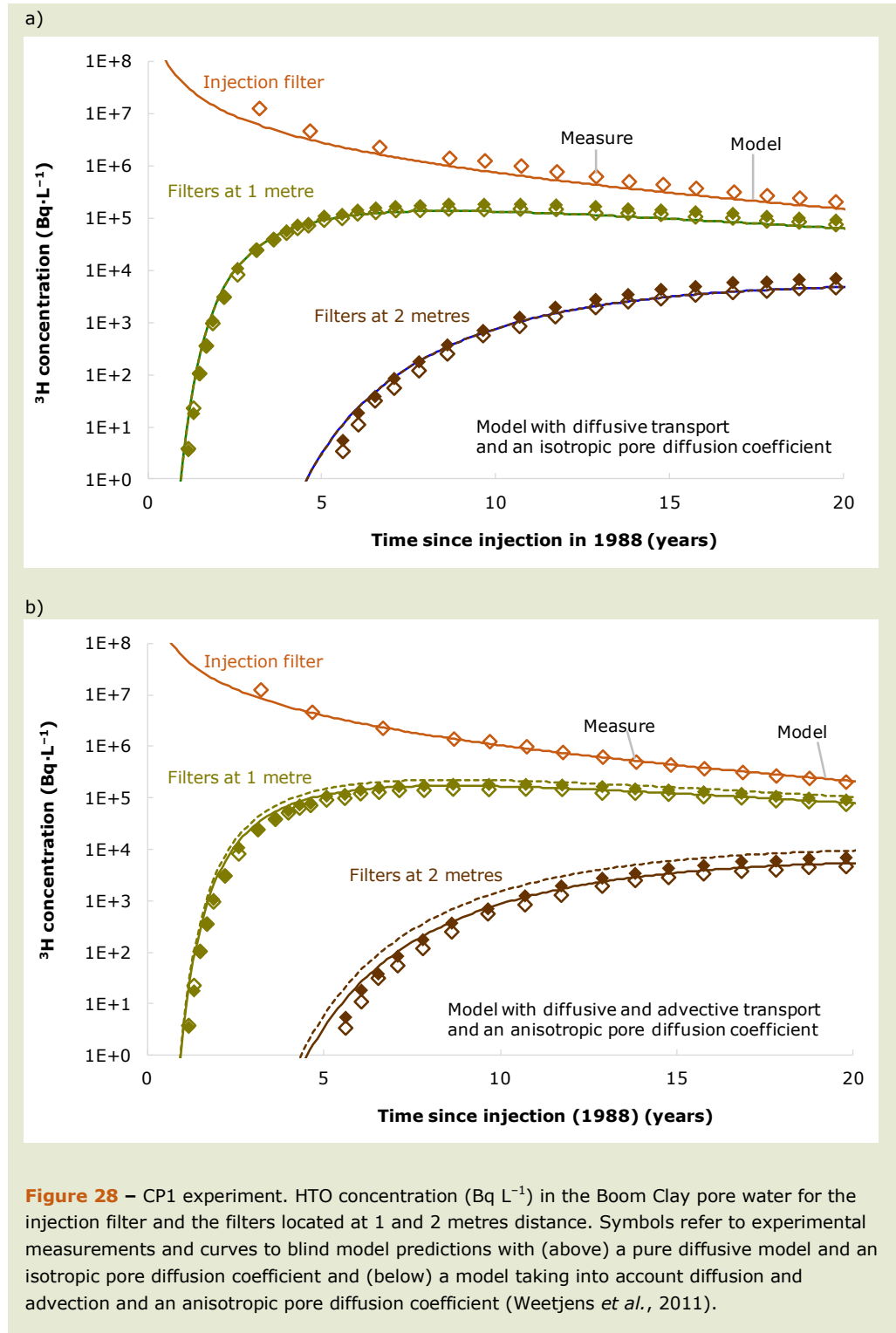
23 CP1: Concrete Plug 1 experiment, Migration *in-situ*, part of INTRAVAL project.

24 TRIBICARB-3D: TRItium and BICARBonate migration experiments, Migration *in-situ*.

measured in injection and neighbouring filters of the piezometers are compared to blind predictions of a strictly diffusive model, which uses diffusion coefficients measured in laboratory experiments (Aertsens *et al.*, 2005) (Aertsens *et al.*, 2005b). The blind model predictions are in good agreement with the *in-situ* experimental results for both experiments (Figure 28, (a)) despite a significant local hydraulic gradient due to the proximity of the underground laboratory at atmospheric pressures (in contrast, drainage towards a disposal gallery would rapidly vanish after system closure). Advection, although small, is thus not negligible in these experiments and more tracer is transported towards the gallery (filters at – 1 metre and – 2 metres from the injection filter) and less towards the formation (filters at + 1 metre and + 2 metres). Including this relatively small advective component and taking the anisotropy of the pore diffusion coefficient into account in the model further improves the agreement between experimental and modelling results (Figure 28, (b)) (Weetjens *et al.*, 2011).

Theoretically, transport through a porous medium may also occur due to Onsagerian processes (also called *off-diagonal processes*). However, the contribution of these processes to the total transport of solutes in Boom Clay seems to be limited, as indicated by the outcomes obtained so far in the programme:

- All laboratory and *in-situ* tests performed in conditions relevant for disposal in Boom Clay and involving the transport of mass, fluid or energy (solutes, water or heat) at different scales can be interpreted by using the sole advection-diffusion equation using consistent parameter values, ignoring off-diagonal processes.
- In a specific experiment designed to assess the importance of chemo-osmosis in Boom Clay, Garavito *et al.* demonstrated the limited magnitude of this off-diagonal process in Boom Clay (Garavito *et al.*, 2007).



### 3.3.9.3. Dominant interactions between radionuclides and Boom Clay

Radionuclides released from the repository may sorb onto the solid phase or react with colloids naturally present in the pore water (Section 3.3.8). Figure 29 presents the potential interactions that may occur in Boom Clay. Interactions with the solid phase retard radionuclide transport, whereas interactions with mobile compounds can enhance this transport.

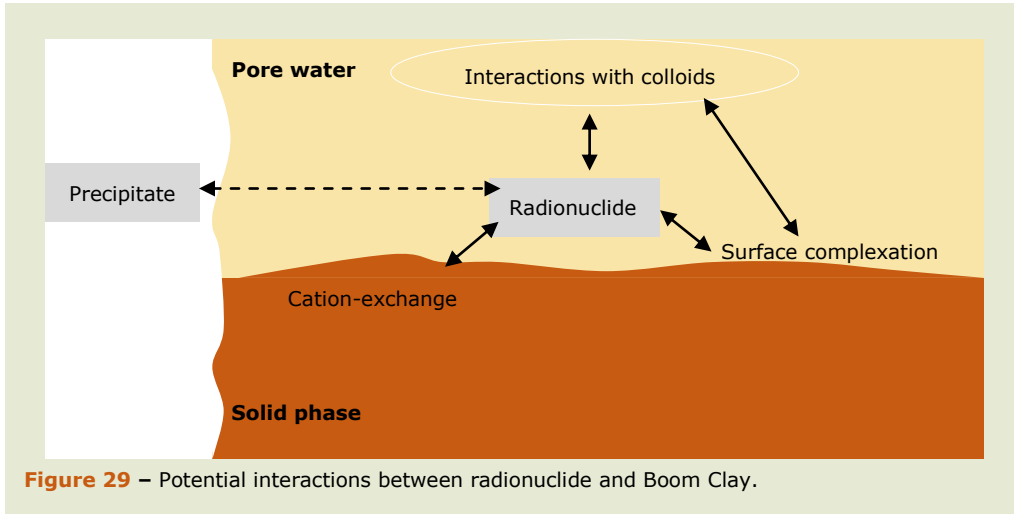
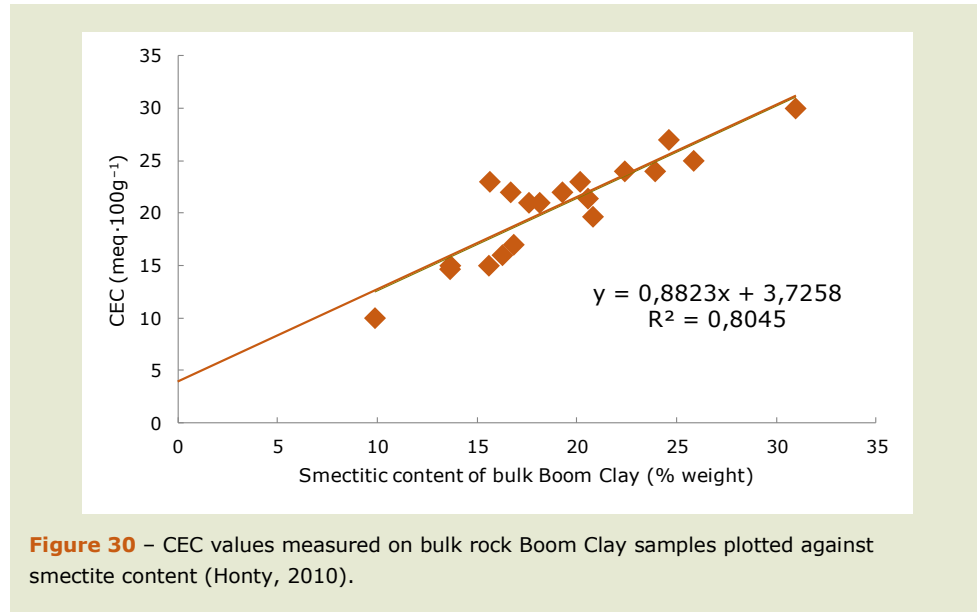


Figure 29 – Potential interactions between radionuclide and Boom Clay.

The Boom Clay solid phase has a significant cation capacity due to its net negative charge. Uptake may occur through two main sorption mechanisms: cation exchange and surface complexation.

- The cation-exchange sites represent sorption sinks for metal cations (through charge compensation mechanisms). The cation exchange capacity (CEC) is roughly proportional to the smectitic content of the Boom Clay (Section 3.3.4). The contribution of other phases (*e.g.*, organic matter) to the CEC is rather limited. In general, the maximum CEC values coincide with the silty clay layers of the Terhagen en Putte Members while the CEC is lower in the clayey silt layers of Boeretang and Belsele-Waas Members (Honty, 2010).





- Surface complexation occurs between hydrolysed metals and functional groups on the solid phase. These functional groups include the inorganic hydroxyl group associated mostly with the broken edges of clay minerals (illite and smectite) and organic functional groups (phenolic, carboxylic) associated with immobile organic matter, which is ubiquitous in Boom Clay. Both groups tend to form covalently bonded surface complexes, which assure strong sorption of hydrolysed metals under the reference pH and ionic strength conditions.

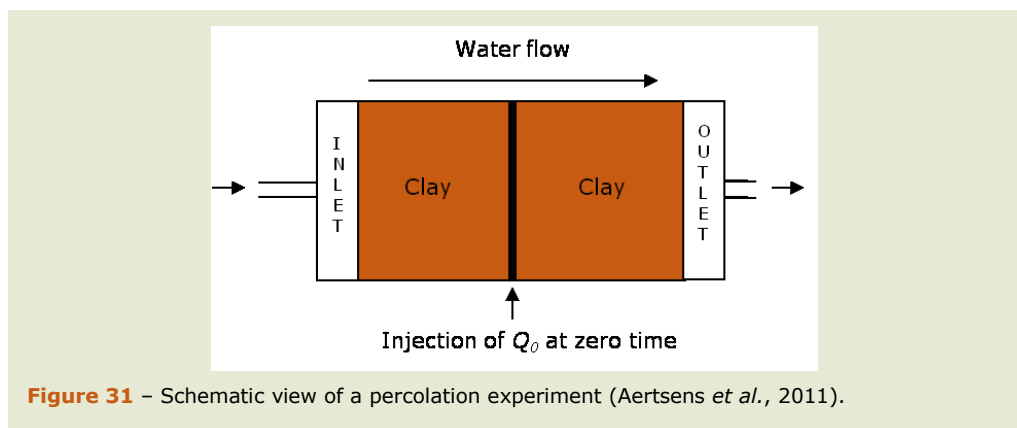
The solutes may also react with the different types of colloids present in Boom Clay pore water (Section 3.3.8). Colloids act as sorbing surfaces and are potentially mobile under *in-situ* conditions. The possible influence of the organic colloids on the migration of solutes in Boom Clay was already recognised at the time of SAFIR2 and has been confirmed since then.

Batch sorption tests are commonly used to study the interactions between solutes and Boom Clay components (NEA, 2012b). These tests might be combined to X-ray absorption spectroscopy, which provides direct structural information for adsorbed species at solid-liquid interface (De Cannière *et al.*, 2010). The batch sorption tests allow determining the solid-liquid distribution coefficient  $K_d$  ( $L \cdot kg^{-1}$ ), ratio of the sorbed fraction to the fraction in solution considering chemical equilibrium. For low solute concentrations, a linear and reversible sorption model with a constant  $K_d$  is frequently used and considered as a reasonable approximation of the sorption-desorption processes for a given set of geochemical conditions. Batch sorption tests are also performed to characterise the uptake processes under varying geochemical conditions (*i.e.*, with different pH, ionic strength, sorbate concentration or in presence of competing sorbates). In addition to tests with slurries of Boom Clay, tests with individual phases corresponding to components of Boom Clay have been performed for about 25 years. These tests allow identifying the role of these phases in radionuclide retention. The study of such well-characterised and relatively simple systems allows the development of thermodynamic sorption models. If a component additivity approach can be supported by the combinations of the results, these thermodynamic models can be refined.

Such thermodynamic sorption models can then be used to determine theoretically  $K_d$  values in varying geochemical conditions. ONDRAF/NIRAS took part in the NEA sorption project whose objective was to demonstrate the potential of thermodynamic sorption models for improving confidence in the representation of radionuclide sorption in the context of radioactive waste disposal (NEA, 2012b). Therefore, several benchmark exercises were performed and used to give recommendations on how to build such thermodynamic sorption models and to use them in the scope of radioactive waste management.

#### 3.3.9.4. Migration

Migration experiments, which combine physical transport and chemical retention, can be subdivided into two main types: pure diffusion tests and percolation tests (in which transport occurs by advection *and* diffusion). The latter is illustrated in Figure 31. In this experiment, an aliquot of tracer is spiked either directly onto the clay surface or onto a filter paper, between two clay cores in a cell. The cell is then continuously percolated with clay water. The water flowing out of the system is collected and the tracer concentration in the water is measured as a function of time. At the end of the experiment, the tracer profile in the clay core is also determined by slicing. This experiment allows the simultaneous determination of the hydraulic conductivity and of the migration parameters of the tracer in the clay core. In such experiments, the retention behaviour (assumed to be a linear and reversible sorption phenomenon) is characterised by a retardation factor, the latter being related to the dry density of the clay, the diffusion accessible porosity and the distribution coefficient of the element of concern (as determined in batch sorption tests). While most migration experiments take place in laboratory, some of them are performed *in-situ*, in HADES URF, as CP1 and TRIBICARD-3D whose results are detailed in Section 3.3.9.2 (Aertsens, 2013).



**Figure 31** – Schematic view of a percolation experiment (Aertsens *et al.*, 2011).

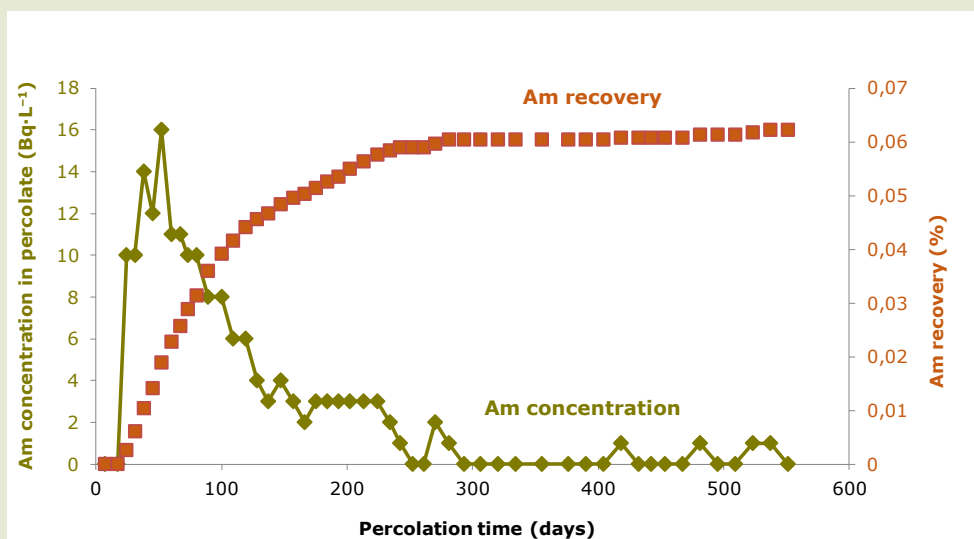
Migration experiments are conducted on many species (see Inset 9 for an example). There are detailed in topical reports dedicated to specific radionuclides: americium (Bruggeman *et al.*, 2012), caesium (Maes *et al.*, 2011), iodine (Bruggeman *et al.*, 2010), selenium (De Cannière *et al.*, 2010), strontium (Maes *et al.*, 2012) and technetium (Bruggeman *et al.*, 2010b).

**Inset 9 – Migration of americium in Boom Clay**

The migration behaviour of americium in Boom Clay has been investigated by complexing  $^{241}\text{Am}$  with  $^{14}\text{C}$ -labelled Boom Clay NOM and passing the  $^{241}\text{Am-OM}$  through Boom Clay cores. These experiments were conducted using two batches of  $^{14}\text{C}$ -labelled OM (TROM6 and TROM34) and were undertaken as part of the EC TRANCOM-CLAY<sup>25</sup> and TRANCOM-II<sup>26</sup> projects (TRANCOM-CLAY, 2000) (TRANCOM-II, 2004). The experiments found that, on contact with the Boom Clay, americium behaves as if two different species were in solution:

- there is a breakthrough of a small quantity of americium shortly after the start of the experiment, which corresponds roughly to the breakthrough of organic matter of low molecular weight.
- the bulk of americium remains in the clay core. This is maybe due to the decomplexation of the Am-OM complexes and subsequent immobilisation of Am by sorption sinks such as clay minerals and immobile organic matter (Bruggeman *et al.*, 2012).

In the experiment illustrated hereafter, the recovery of Am after more than 500 days is about 0.06%.



*Americium concentration and recovered percentage after percolation through a clay core of a solution containing Am-OM complexes.*

### 3.3.9.5. Approach to categorise the behaviour of solutes of interest in Boom Clay

An extensive programme including migration experiments such as those described in the previous section is essential for the identification of the processes governing solute migration and the determination of model parameters. There is currently a sound knowledge of these processes thanks to the 30 years of research in this field, as illustrated by Inset 10. However, performing such a RD&D programme for each solute of

25 TRANCOM-CLAY: Transport of radionuclides due to complexation with organic matter in clay formations (EU project).

26 TRANCOM-II: Migration case study: transport of radionuclides in a reducing clay sediment (EU project).

interest is not realistic for SFC1. Therefore, SCK•CEN has developed a preliminary approach to deal with the large number of relevant solutes, based on chemical analogies. The first step consists of sorting radionuclides in groups of elements with similar migration and retention behaviour under Boom Clay present-day geochemical conditions. Such a classification relies on thermodynamic considerations (similarities in inorganic speciation in Boom Clay pore water), experimental observations (similarities in sorption, solubility in presence of organics, migration behaviour) and scientific literature (general similarities in environmental conditions). For each group, a “representative solute” is selected, based on the amount of experimental and literature data available to support understanding, description and prediction of its retention/migration behaviour under Boom Clay conditions. The second step aims to develop phenomenological models that should fit all solutes of a given group. These models are geochemically consistent models that describe how these radionuclides should migrate through Boom Clay. These models are based on the combined insights gained from: 1) experimental observations of the geochemical behaviour of the different considered solutes; and 2) general scientific insights/knowledge concerning their general chemical/thermodynamic characteristics. This led to the definition of four groups: (1) tritiated water (HTO), (2) solutes subjected to anion exclusion, (3) the solutes influenced by cation-exchange and (4) the solutes whose transport could be enhanced by interaction with mobile natural organic matter (Table 12). The groups, their characteristics and associated conceptual models are developed hereafter.

#### **Group 1: Tritiated water (HTO)**

The first group contains tritiated water (HTO), a small species, which is neutral and non-sorbing radioactive form of H<sub>2</sub>O. Although not a safety-relevant nuclide, it has been studied systematically in the context of waste disposal in Boom Clay (see for instance the CP1 experiment in Section 3.3.9.2). Tritiated water is assumed not to sorb and is therefore considered as a non-retarded tracer. Due to its neutral charge, it is not subject to strong electrostatic interactions, and can access the entire diffusion accessible porosity. Therefore, HTO is ideally suited for studying the general solute transport characteristics inherent to the clay formation itself (e.g., porosity) and serves as a reference tracer for the determination of the transport parameters of a whole range of solutes (other neutral but also cationic species).

#### **Group 2: Solutes subjected to anion exclusion**

This group contains the solutes subjected to anion exclusion (or Donnan exclusion), which reduces their diffusion accessible porosity due to electrostatic repulsion. They are not retarded (or only weakly retarded) in Boom Clay.

The reference element for this group is iodine, whose dominant species in Boom Clay is the iodide anion (I<sup>-</sup>). This group contains also carbon, chlorine, molybdenum, niobium and selenium (Bruggeman *et al.*, 2010).

### **Group 3: Solutes influenced by cation-exchange**

The third group contains solutes sensitive to cation-exchange. It contains the alkali and alkaline earth metals, with caesium as the representative element. Research on caesium is summarised in Inset 10, as an example of the RD&D programme. This group also includes calcium, radium, rubidium, silver and strontium.

These radionuclides are strongly retarded due to cation-exchange processes. Surface diffusion may also influence their transport: cations adsorbing on cation-exchange sites are able to travel faster along the surface than cations in the free pore water. The exact nature of this phenomenon is not fully understood and is under investigation in the CATCLAY<sup>27</sup> project (Maes *et al.*, 2011). This group may be further subdivided in two. The first subgroup contains monovalent cations with small hydrolysed radius that are preferably bound to illite cation-exchange sites. The second subgroup contains divalent cations that may form aqueous complexes with  $\text{CO}_3^{2-}$  and preferably bind to the interlayer ion-exchange sites of smectite minerals.

These radionuclides are considered to have roughly the same diffusion accessible porosity than tritiated water, as neutral and cationic species are not repelled by the negatively charged surface of the clay (Maes *et al.*, 2011).

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27 CATCLAY: Processes of Cation Migration in Clayrocks (EU project).

**Inset 10 – Behaviour of caesium in Boom Clay**

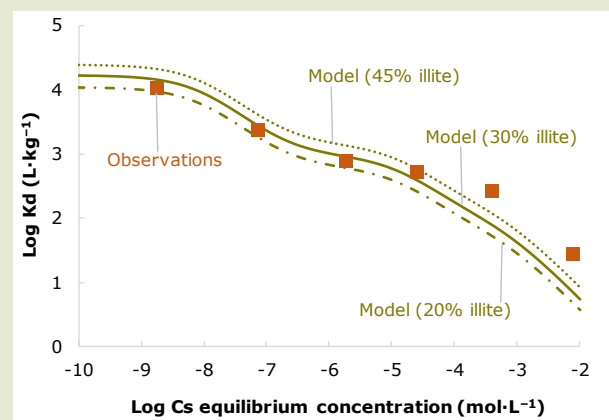
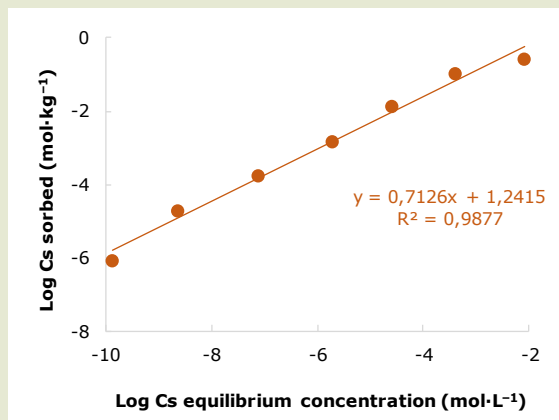
The behaviour of caesium in clay host formations is relatively well known, thanks to numerous studies worldwide. This inset summarises the most significant results acquired in the frame of the Belgian research programme.

**Caesium speciation and solubility limit**

In the Boom Clay environment, the thermodynamically stable dominant inorganic caesium species is the monovalent cation  $\text{Cs}^+$ . This cation presents no solubility limit in Boom Clay (Salah and Wang, 2012).

**Caesium sorption on Boom Clay suspensions**

Several series of batch sorption tests led to the determination of the solid-liquid distribution coefficient ( $K_d$ ) in function of caesium concentrations (figure hereafter, left). The high values of  $K_d$  confirm that caesium strongly sorbs on Boom Clay components. These experimental results are successfully modelled using the generalised three-site cation exchange model for argillaceous rocks developed by Bradbury and Baeyens for caesium uptake on argillaceous rocks (Bradbury and Baeyens, 2000). This model assumes that the sorption of caesium at low concentrations in the pH range 6–9 is dominated by the illite mineral component of the clayey rock. When varying the amount of illite in the model, the best correlation for low caesium concentrations corresponds to clay with 20% by weight of illite (figure hereafter, right).



Left: Caesium adsorption isotherm on Boom Clay suspension in natural Boom Clay water. The dots represent the experimental points (average values of duplicate experiments). The line represents a fit of the data using a Freundlich isotherm. Right: modelled caesium sorption curves onto Boom Clay based on the generalised three-site cation exchange model by (Bradbury and Baeyens, 2000) for different amounts of illite (Maes *et al.*, 2011).

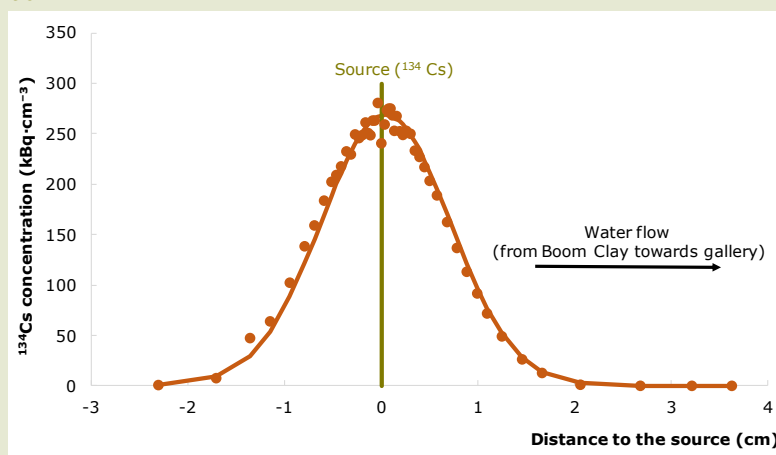
**Caesium sorption on intact Boom Clay core**

SCK•CEN performed a sorption test with caesium on an intact Boom Clay sample in order to investigate the transferability of results from dispersed solutions onto bulk material, where compaction could limit the number of sites accessible for sorption. The measured distribution coefficient matches those observed on dispersed clay systems at low caesium concentrations.

**Laboratory and *in-situ* percolation experiments with caesium**

The research programme included percolation experiments with caesium, performed in laboratory and *in-situ*, which respectively lasted nearly 14 years and 7 years (De Cannière *et al.*, 1996) (Maes *et al.*, 2011). The figure hereafter presents the migration profile of caesium in the clay core along the vertical axis for the *in-situ* experiment (dots). This experiment took advantage of permanent direct supply of fresh interstitial clay water from the formation and of long-term stability of physico-chemical parameters (P, T,  $E_h$ , pH,  $p\text{CO}_2$ , OM concentration, etc.).

Diffusion is clearly the dominant mechanism. Advection, due to gallery drainage and indicated by the slight shift in the position of the maximum of the curve, only plays a negligible role in the transport processes. The migration profile was modelled by solving the advection-dispersion equation. This profile presents a Gaussian shape (typical dispersion profile) (figure hereafter) when the aberrant points at the source position (probably due to an artefact) are discarded. The width of the Gaussian curve gives the value of the apparent diffusion coefficient ( $D_{app}$ ) while the  $\eta R$  product (diffusion accessible porosity times retardation factor) depends on the peak displacement. The values of  $D_{app}$  are robust and consistent with other results. These experimental results also confirm the good retention properties of Boom Clay for caesium. The values obtained for  $\eta R$  are less robust (% error on the fit larger than 100%) because the displacement of the profile is very small due to the high retention.



Experimental and modelled caesium diffusion profile in Boom Clay after 7 years in-situ percolation (De Cannière *et al.*, 1996).

### Caesium in-diffusion experiment

In the frame of the EU FUNMIG<sup>28</sup> project, SCK•CEN performed an in-diffusion experiment on an intact clay core, which was in contact with two reservoirs of Boom Clay pore water; one of them also containing a known <sup>137</sup>Cs concentration (Altmann *et al.*, 2012). This caesium diffused into the clay. The decrease in caesium concentration due to diffusion into the clay was monitored. At the end of the experiment, which lasted 200 days, the clay core was cut in thin slices for determination of the caesium activity profile by gamma analysis. Results indicate a good agreement between the  $D_{app}$  value obtained from the caesium profile in the clay and the values from previous experiments but the value of  $\eta R$ , deduced from modelling of experimental results, was not reliable.

### Conclusions on the caesium diffusion coefficient data in Boom Clay Coupling of models

The experimental and modelling results evidenced that caesium is strongly retarded in clay formations and that the caesium uptake mechanism on Boom Clay is due to ion-exchange mechanisms with cations already present on the clay mineral surfaces. The RD&D programme led to reliable sorption data from batch sorption tests and robust  $D_{app}$  data from migration experiments. Uncertainties remain however about the phenomenological description of the caesium transport in clays: coupling sorption and diffusion parameter values leads to inconsistencies – the pore diffusion coefficient values ( $D_{pore}$ ) derived from the measured  $D_{app}$  and  $R(K_d)$  values exceeding the  $D_{pore}$  value of HTO –. Other research groups also report this phenomenon, often referred to as “surface diffusion” (Van Loon *et al.*, 2004) (Van Loon *et al.*, 2005) (Melkior *et al.*, 2005) (Melkior *et al.*, 2007) (Glaus *et al.*, 2007). There is research under way to understand this phenomenon, among others in the frame of the CATCLAY<sup>29</sup> project.

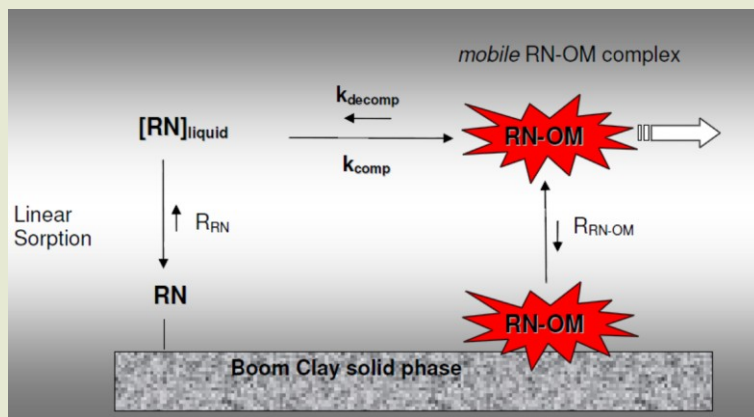
28 FUNMIG: Fundamental Processes of Radionuclide Migration (EU project).

29 CATCLAY: Processes of Cation Migration in Clayrocks (EU project).

**Group 4: Solutes interacting with natural organic matter**

Group 4 contains radionuclides that strongly associate with natural organic matter. The representative element of this group is technetium. The other elements of this group are actinium, americium, curium, neptunium, palladium, plutonium, protactinium, samarium, thorium, tin, uranium and zirconium (Bruggeman *et al.*, 2010b).

The results of sequential percolation experiments with curium, plutonium, neptunium, technetium and protactinium in Boom Clay, initiated more than a decade ago, have been interpreted thanks to the development of a model taking into account the interaction of these radionuclides with natural organic matter. In this model, radionuclides in solution are either present in combination with a natural organic matter colloid (“RN-OM complex”) or as a “free inorganic” radionuclide species in solution ( $[RN]_{liquid}$ ) (“free species”) (Figure 32). The transfer between the free species and the RN-OM complexes is described a distribution coefficient, ratio of a complexation constant ( $k_{comp}$ ) and a decomplexation constant ( $k_{decomp}$ ). Both species can interact with the solid phase. It is assumed that this interaction in case of the free species is mainly due to sorption processes and can be described by a retardation factor ( $R_{RN}$ ) that can be linked to batch sorption data. For the RN-OM complexes, the retardation factor ( $R_{RN-OM}$ ) is a lumped factor that includes both sorption and colloid filtration processes. Overall, dissolved organic matter is thought to be only poorly retarded within Boom Clay and the value of  $R_{RN-OM}$  is therefore expected to be low.



**Figure 32** – Schematic representation of the interactions between some radionuclides, organic matter and Boom Clay (Bruggeman *et al.*, 2012).



**Table 12** – Grouping of radionuclides (The representative element for each group is underlined).

Group	Element
<b>Group 1 – Reference non-retarded tracer</b>	
	<u>Tritiated water (HTO)</u>
<b>Group 2 – Solutes subjected to anion exclusion</b>	
	Carbon (C), Chlorine (Cl), <u>Iodine (I)</u> , Molybdenum (Mo), Niobium (Nb), Selenium (Se)
<b>Group 3 – Solutes influenced by cation-exchange</b>	
	<u>Caesium (Cs)</u> , Calcium (Ca), Radium (Ra), Rubidium (Rb), Silver (Ag), Strontium (Sr)
<b>Group 4 – Solutes interacting with natural organic matter</b>	
	Actinium (Ac), Americium (Am), Curium (Cm), Neptunium (Np), Palladium (Pd), Protactinium (Pa), Plutonium (Pu), Samarium (Sm), <u>Technetium (Tc)</u> , Tin (Sn), Thorium (Th), Uranium (U), Zirconium (Zr)

### Roadmap – Section 3.3.9 – Solutes transport (BC)

*For later SFCs*, ONDRAF/NIRAS will perform a literature review on the impact of saline water on transport and retention processes in clays (analysing, among others, data from Opalinus clay). It will launch experiments to evaluate the impact of different geochemical conditions on the sorting of radionuclides in groups of elements with similar migration and retention behaviour under Boom Clay present-day geochemical conditions, and will adapt the grouping accordingly, if necessary.

ONDRAF/NIRAS investigates the surface diffusion phenomena, among others in the frame of the CATCLAY project. It plans to refine knowledge of the mobility of dissolved organic matter (DOM) (see roadmap Section 3.3.8). Results will be included in later SFCs.

*For confidence building*, ONDRAF/NIRAS will start migration experiments on a few radionuclides not yet studied to confirm their expected migration behaviour and their sorting in groups of elements with similar migration and retention behaviour. It follows up the evolution of thermochemical databases at an international level. It will update MOLDATA, if necessary. It will assess the impact of colloids (in particular of organic colloids) on the solubility of some elements not yet studied.

*For confidence building*, ONDRAF/NIRAS wants to refine the understanding of the retention phenomena of radionuclides and chemical contaminants by Boom Clay. It will integrate the available knowledge of interactions between radionuclides and the various components of Boom Clay and perform additional batch experiments. The experiments, first with pure phases and then with Boom Clay, enable investigation into whether the component additivity approach can be used in thermodynamic models, the final aim being to develop a thermodynamic sorption model for Boom Clay. ONDRAF/NIRAS also pursues the long-term migration experiments (e.g., CP1 and TRIBICARB-3D).

The new boring will lead to improve the vertical resolution of migration parameters. ONDRAF/NIRAS will start studies to improve the correlation between migration parameters and lithology. Results will be included in later SFCs.

### 3.3.10. *In-situ* stress state and hydro-mechanical behaviour

Characterising the *in-situ* stress state at the planned location and the hydro-mechanical behaviour of the host rock is of prime importance for the construction of a repository but also for the description of its long-term evolution. At this stage of the Belgian programme, Boom Clay and Ypresian clays are considered as potential hosts but no site selection process has been started yet. The presence of the HADES underground research facility at the reference site for RD&D in Mol has been an opportunity for intensive investigation of the hydro-mechanical behaviour of Boom Clay, starting with the construction of the laboratory itself and continuing through targeted experiments installed in or around HADES URF. Cored drillings from HADES URF also provided numerous good quality samples for laboratory testing. Different actors<sup>30</sup> have collected many data during the 30 years of research; each of them investigating the behaviour of Boom Clay in specific and often different conditions. Integration of these data is a continuous, challenging process.

#### 3.3.10.1. *In-situ* stress state

The *in-situ* stress state near the HADES underground research facility is briefly presented here only to contextualize the RD&D results on the hydro-mechanical behaviour of Boom Clay.

At the depth<sup>31</sup> of the HADES underground research facility, the lithostatic pressure, or total vertical stress  $\sigma_v$ , imposed by the weight of the overlying material is about 4.5 MPa. The undisturbed pore pressure  $u$  at the depth of HADES URF (but measured at a sufficient distance from the galleries) is about 2.2 MPa and corresponds well to a hydrostatic distribution up to the water table which is close to the surface. The effective vertical stress is thus  $\sigma'_v = \sigma_v - u \cong 2.3$  MPa. In SAFIR2, a ratio between the vertical and horizontal total stresses  $\sigma_H/\sigma_v = 0.9$  is reported. In terms of effective stresses, this corresponds to a coefficient of earth pressure at rest  $K_0 = \sigma'_H/\sigma'_v \cong 0.8$  and a horizontal effective stress  $\sigma'_H$  of about 1.9 MPa.

In 2009, self-boring pressuremeter tests (SBP) and hydro-fracturing tests were conducted at different distances (up to 40 metres) from the underground laboratory in three boreholes along different directions (horizontal, vertical downwards and inclined at 45°) to map the 3D-stress state and also to delineate the damaged zone around the Connecting gallery (Cambridge, 2009) (Cornet, 2009). The results of these tests confirm that the *in-situ* stress state in the far field of HADES URF is transverse isotropic, with the major stress component being vertical. The interpretation of the tests yields values for the coefficient of earth pressure at rest in the range 0.7–0.8. It should be noted, however, that the interpretation of SBP tests and hydro-fracturing tests in a medium that may also present anisotropic material properties is delicate so these values of  $K_0$  and  $\sigma'_H$  will undergo revisions as additional tests results become available.

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30 SCK•CEN, EURIDICE, numerous university laboratories, modelling teams etc.

31 The axis of the main gallery in HADES is about 223 meters below the ground surface.

### 3.3.10.2. Basic geotechnical properties

Basic geotechnical properties of the Boom Clay have been reported in SAFIR2. An updated set of geotechnical properties is provided in Table 13. The ranges of values for these properties have been compiled from the results of numerous laboratory tests (mostly triaxial tests) and the back-analysis of *in-situ* measurements around excavation works (starting with the Test Drift excavation in HADES URF in 1987, later complemented with the MINE-BY-TEST<sup>32</sup> during the excavation of the Connecting gallery in 2001–2002). These properties are those that can typically be used for the design of the excavation technique and the dimensioning of the lining of disposal galleries. Using these parameters values, convergences and pressures exerted on the lining computed using a basic elasto-plastic constitutive model with a Mohr–Coulomb yield criteria are in good agreement with the measured values obtained during and after excavation of the Connecting gallery and the PRACLAY gallery (Li *et al.*, 2010) (see Annex A3).

**Table 13** – Basic geotechnical properties of Boom Clay at HADES URF level (adapted from (ONDRAF/NIRAS, 2001) and including data from (Horseman *et al.*, 1987), (Rousset, 1988), (Mair *et al.*, 1992), (Coll, 2005) and (SELFAC, 2007).

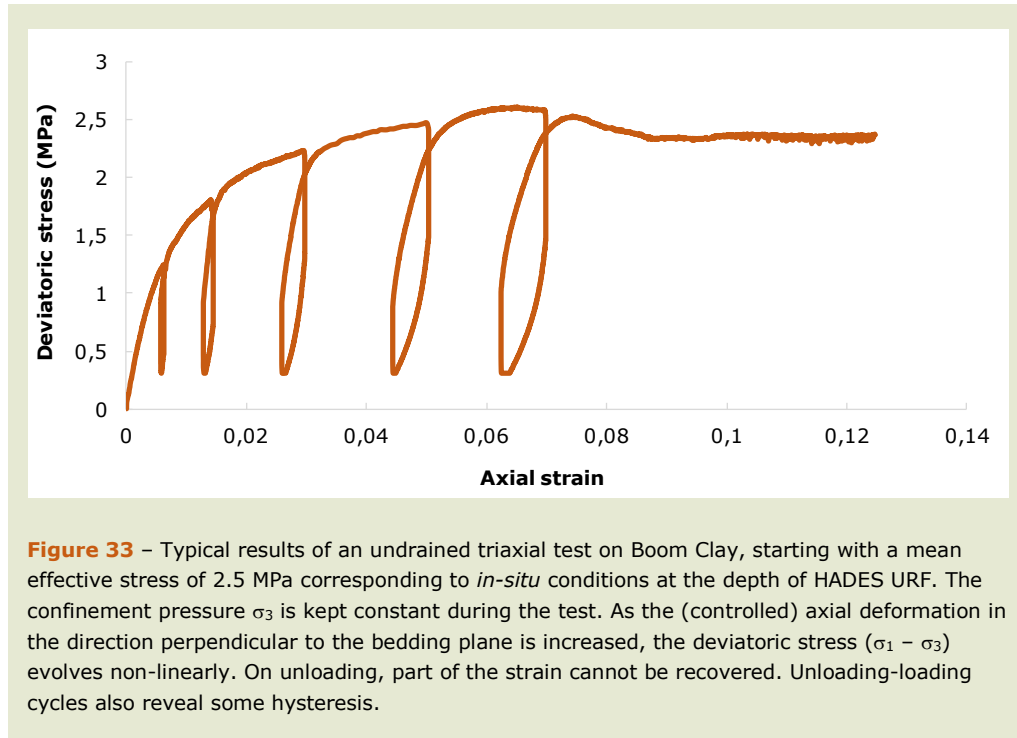
Property	Range (min. – max.)		
Drained Young's modulus ( $E'$ )	200	–	400 MPa
Drained Poisson's ratio ( $\nu'$ )	0.125	–	0.15
Angle of friction ( $\phi'$ )	13	–	25°
Cohesion ( $c'$ )	0.015	–	1 MPa
Undrained shear modulus ( $G_u$ )	100	–	450 MPa
Undrained Poisson's ratio ( $\nu_u$ )	0.40	–	0.45
Undrained shear strength ( $c_u$ )	1	–	2 MPa

The ranges in Table 13 reflect the variability of samples and the diversity of tests performed and laboratories involved and of the fact that the mechanical anisotropy of Boom Clay has not been systematically taken into account when interpreting test results. In addition, the non-linearity of the mechanical behaviour of Boom Clay makes that the determination of elastic parameters, for instance, is affected by the range of deformations applied (Mair *et al.*, 1992) (Figure 33). It is also important to note that the values in Table 13 are representative of Boom Clay near the underground research facility at Mol. The transferability of these properties to other locations in Boom Clay and to greater depths in particular is an ongoing research topic.

32 MINE-BY-TEST: long-term monitoring programme around an underground structure in the Boom Clay.

### 3.3.10.3. Stiffness of Boom Clay

The stress-strain behaviour of Boom Clay is very non-linear, as illustrated by Figure 33 showing the typical results of a triaxial test on this material.



**Figure 33** – Typical results of an undrained triaxial test on Boom Clay, starting with a mean effective stress of 2.5 MPa corresponding to *in-situ* conditions at the depth of HADES URF. The confinement pressure  $\sigma_3$  is kept constant during the test. As the (controlled) axial deformation in the direction perpendicular to the bedding plane is increased, the deviatoric stress ( $\sigma_1 - \sigma_3$ ) evolves non-linearly. On unloading, part of the strain cannot be recovered. Unloading-loading cycles also reveal some hysteresis.

Such non-linear stress-strain behaviour is generally expected for relatively soft materials like Boom Clay (Atkinson, 2000). Already in 1992, Mair *et al.* performed a detailed study of the relationship between stiffness and strain magnitude (Mair *et al.*, 1992). Laboratory tests performed early on in the programme (Baldi *et al.*, 1991) evidenced that the stiffness of Boom Clay is moreover anisotropic. Recent back-analyses of the observed pore-water pressure variations in the far field of the Connecting and PRACLAY galleries during excavations and around the small-scale *in-situ* heater test ATLAS<sup>33</sup> support these early observations (Yu *et al.*, 2011) (Chen *et al.*, 2011). These analyses reveal that perturbations in the far field – where deformations are small – can be much better represented by models when using different Young's moduli along the vertical and horizontal directions, with values generally larger than those summarised in Table 13.

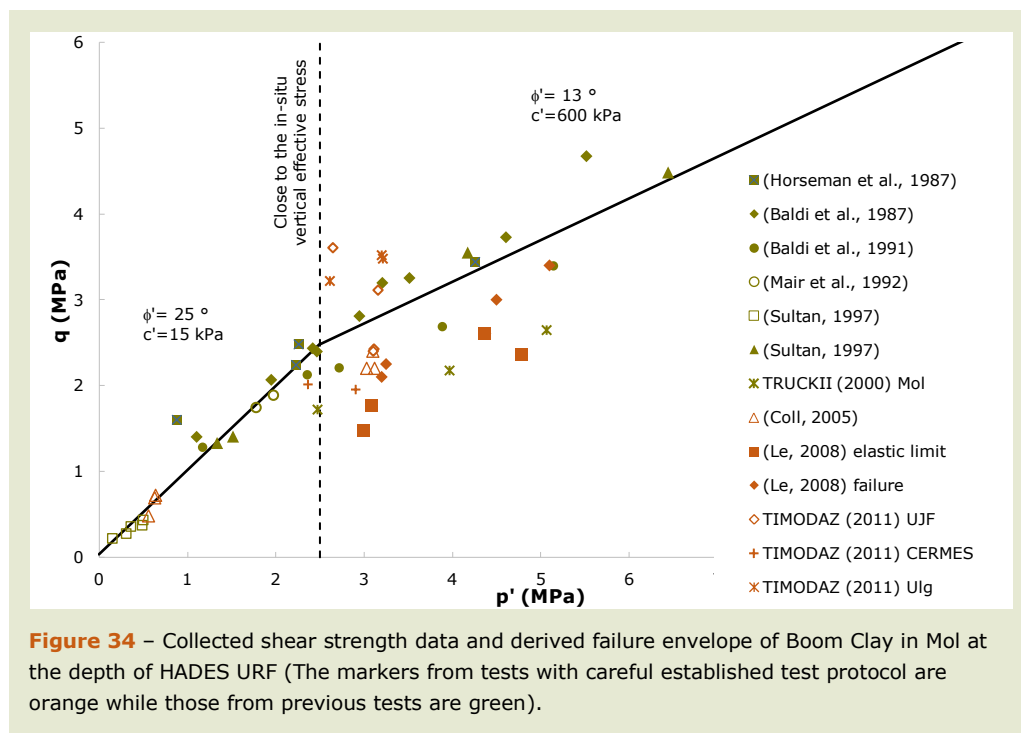
Additional tests executed in the wake of these back-analyses confirmed this transversely anisotropic behaviour (Yu H.D. *et al.*, 2013) (Lima, 2011), which can reasonably be traced back to the microstructure of the Boom Clay resulting from its deposition (Section 3.3.6) (Hemes *et al.*, 2011). For small deformations, Boom Clay is about twice as stiff when loaded in the direction of the bedding planes, *i.e.*, sub-horizontally, than when loaded in the perpendicular direction.

33 ATLAS I and II: Admissible thermal loading for argillaceous storage, part of the INTERCLAY project (EU project).

### 3.3.10.4. Shear strength of Boom Clay

At the time of SAFIR2, values of the parameters controlling shear strength were mostly determined from undrained testing of Boom Clay. These tests were sufficient for sizing the excavation works, as excavation can be considered to happen in undrained conditions<sup>34</sup>. A simple Mohr–Coulomb failure envelope with an angle of friction  $\phi' = 18^\circ$  and a cohesion  $c' = 300$  kPa was found suitable for the design of the excavation works and the dimensioning of the support and linings of the different gallery sections of HADES URF.

For improved modelling of repository-induced hydro-mechanical perturbations, EURIDICE has re-examined results from tests from which the shear strength can be derived (Horseman *et al.*, 1987) (Sultan, 1997) (Van Impe, 1993) (Baldi *et al.*, 1991) (Coll, 2005). New tests have since been executed with a carefully established test protocol (Le, 2008) (Delage *et al.*, 2007) (Yu H.D., 2010) (Yu H.D. *et al.*, 2012) (Deng *et al.*, 2012b). The selected tests were performed on carefully sampled Boom Clay cores<sup>35</sup> either from excavation works or core drillings from HADES URF. The results of all these tests are summarised in Figure 34 in the  $p' - q$  plane ( $p'$ : effective mean stress,  $q$ : deviatoric stress).



In the data presented in Figure 34, two groups of results can be distinguished: one for the low  $p'$  range ( $< 2.5$  MPa) and another for the high  $p'$  range ( $> 2.5$  MPa). A set of parameters describing the shear strength of Boom Clay at the HADES URF level is proposed in Table 14. Such an approach is consistent with observations of non-linear failure envelopes for comparable clays such as the London Clay (Petley, 1999) but needs

34 The clay has no time to dissipate the water pressure as the clay is highly impermeable and the rate of excavation is fast compared to the rate of hydraulic response of the clay.

35 The inevitable perturbations due to excavation are explained in detail in (Blümling *et al.*, 2007).

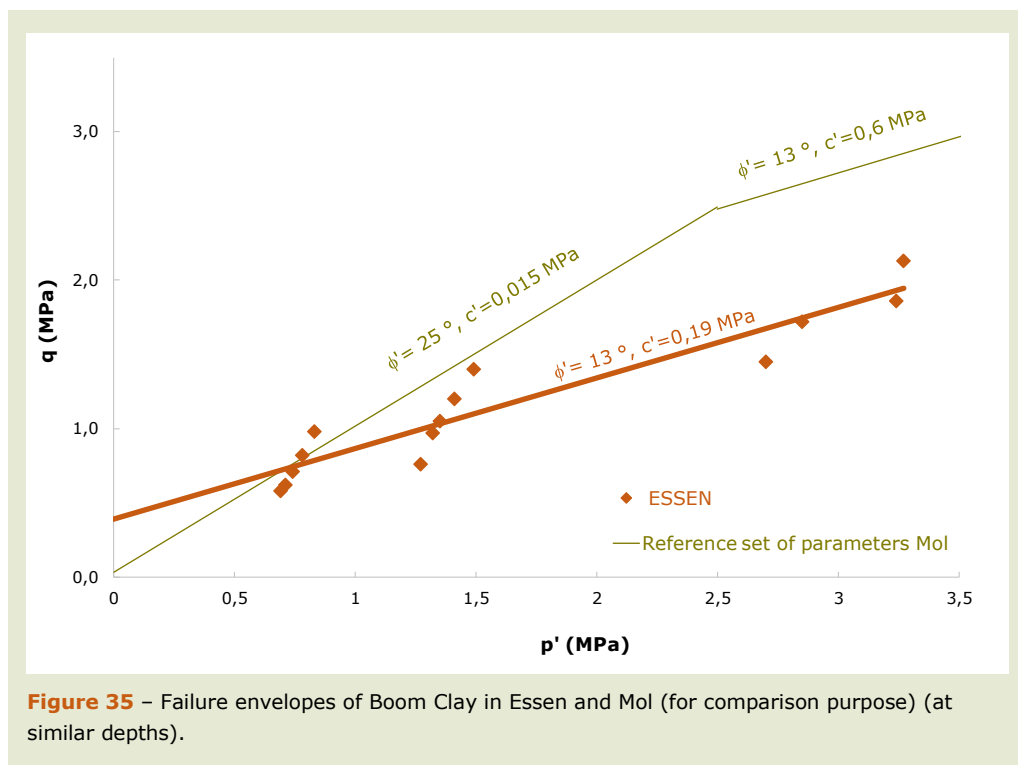
to be confirmed by more laboratory tests with the new established test protocol. Considering that many key properties of Boom Clay display some level of anisotropy, strength characteristics are currently being re-examined for different orientations of the major and minor principal stresses with respect to the bedding planes.

**Table 14** – Mechanical parameters from triaxial and consolidation tests at HADES URF level.

Mechanical property		Value
Angle of friction ( $\phi'$ )	$p' < 2.5$ MPa	25°
	$p' > 2.5$ MPa	13°
Cohesion ( $c'$ )	$p' < 2.5$ MPa	15 kPa
	$p' > 2.5$ MPa	600 kPa
Dilatancy angle		0 – 10°

Many geomechanical tests have been performed on Boom Clay sampled near the HADES URF; comparatively, few data are available for other locations.

Figure 35 presents shear strength data obtained from Boom Clay samples taken in Essen, at a depth comparable to the one of the HADES URF. A linear failure envelope can be derived with an angle of friction  $\phi' = 13^\circ$  and a cohesion  $c' = 190$  kPa (Deng *et al.*, 2012). The confidence in these results is good as these were obtained with the newly established test protocol.



Regarding the transferability of shear strength, it is currently unclear whether the differences between Essen and Mol can be explained by different burial histories, pore waters (Essen pore water is more saline than the Mol one) and/or mineral compositions.

### 3.3.10.5. Change of volume and pre-consolidation

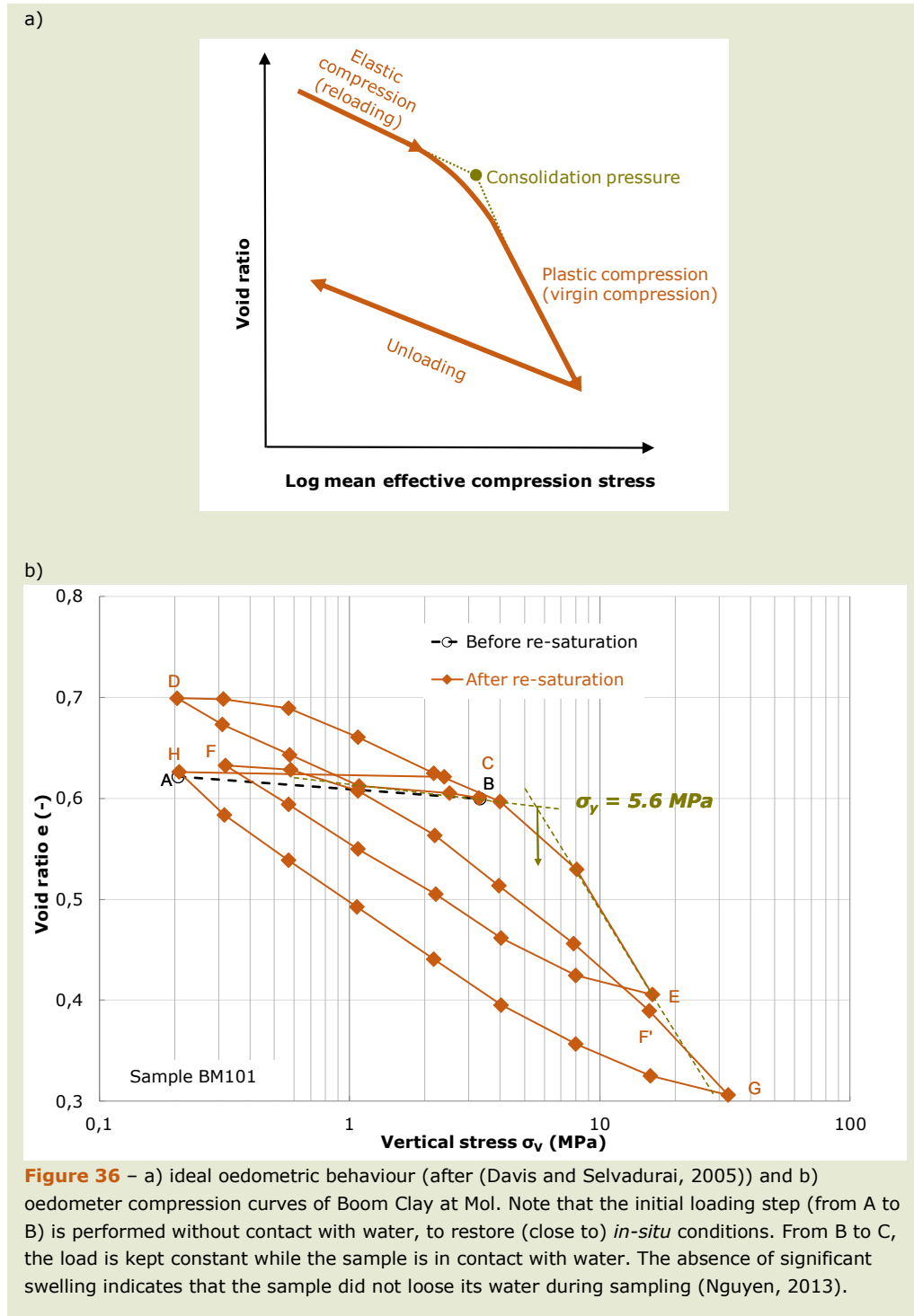
Because of the very low permeability of Boom Clay, the excavation of galleries takes place in nearly undrained conditions and involves principally the shear behaviour of Boom Clay; the low compressibility of the pore water and clay minerals limiting the volume changes. Volumetric behaviour may however play a significant role in the later evolution of the system, for instance as a consequence of the thermal load imposed to the clay by heat-emitting wastes.

The volume change behaviour of materials such as Boom Clay is generally investigated with drained oedometer tests and triaxial tests. In the latter case, only variations of the confinement pressure are applied, with no extra axial loading so that compression stresses are isotropic. Oedometric tests and isotropic triaxial test results have been reported in the following references (among others): (Baldi *et al.*, 1987), (Baldi *et al.*, 1991), (Horseman *et al.*, 1987), (Sultan, 1997), (Coll, 2005) and (Le, 2008). Plotting the evolution of the void ratio<sup>36</sup>  $e$  against the logarithm of the mean effective compression stress in these tests allows in principle to distinguish between a pseudo-elastic compression for small loads and plastic deformations beyond a threshold compression stress called the pre-consolidation pressure. In Figure 36, typical test results for Boom Clay are compared to ideal oedometric behaviour.

According to these tests, the transition between *elastic reloading* and *virgin compression* of Boom Clay is not sharp. Moreover, the *unloading* path is not linear either. This is also observed for other clays such as Ypresian clays and London Clay and is associated with their swelling behaviour (Section 3.3.10.7). Values of the *pre-consolidation pressure* in the range 5 – 6 MPa are obtained from these tests on Boom Clay. The over-consolidation ratio (OCR) of Boom Clay at Mol and at the depth of HADES URF, defined as the ratio between the pre-consolidation pressure and the *in-situ* effective vertical stress is thus in the range 2.1 – 2.6 MPa. Although interpretations of these oedometer tests should be done with care, it is noted that this over-consolidation ratio (OCR) cannot be explained by the burial history of Boom Clay (Section 3.3.3).

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36 The void ratio  $e$  is a measure of the compression state of the clay skeleton and is defined as  $\eta/(1-\eta)$  where  $\eta$  is the porosity of the clay.

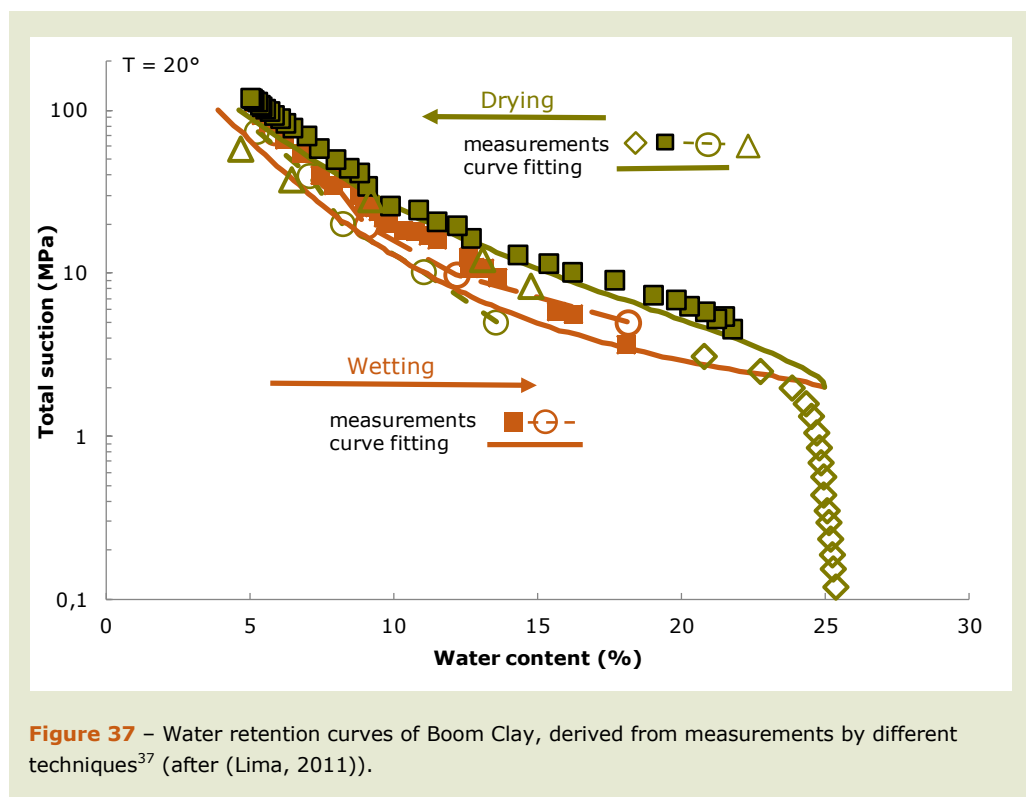


### 3.3.10.6. Unsaturated hydro-mechanical properties

The potential role of suction (negative pore-water pressures) arising from, for instance decompression of Boom Clay in nearly undrained condition, was recognised early on in the Belgian programme. While freezing of Boom Clay was used to facilitate the excavations of the first shaft and gallery section of HADES URF (1980–1983), in 1984, the small diameter Experimental shaft and gallery were excavated at one end of the



underground facility in unfrozen clay, evidencing the role of suction in stabilising the excavation front (Section 5.2) (Annex A3). Indeed, suction increases the effective mean stress  $p'$  and thus also the shear strength. Suction is closely related to the water content or saturation state of Boom Clay and can also be seen as the potential of the clay to retain its water when put in contact with an unsaturated environment, such as a ventilated gallery. By the time of SAFIR2, water retention properties had been determined for Boom Clay but only on remoulded samples, *i.e.*, starting from compacted clay powder (Volckaert *et al.*, 1995) (Romero, 1999). Since then, water retention properties of Boom Clay, covering a wide suction range and using different complementary techniques for both drying and wetting paths, have been investigated intensively at the Polytechnic University of Catalunya, Spain (Lima *et al.*, 2011), illustrated in Figure 37 and at the Ecole Nationale des Ponts et Chaussées (ENPC) in France (Le, 2008).



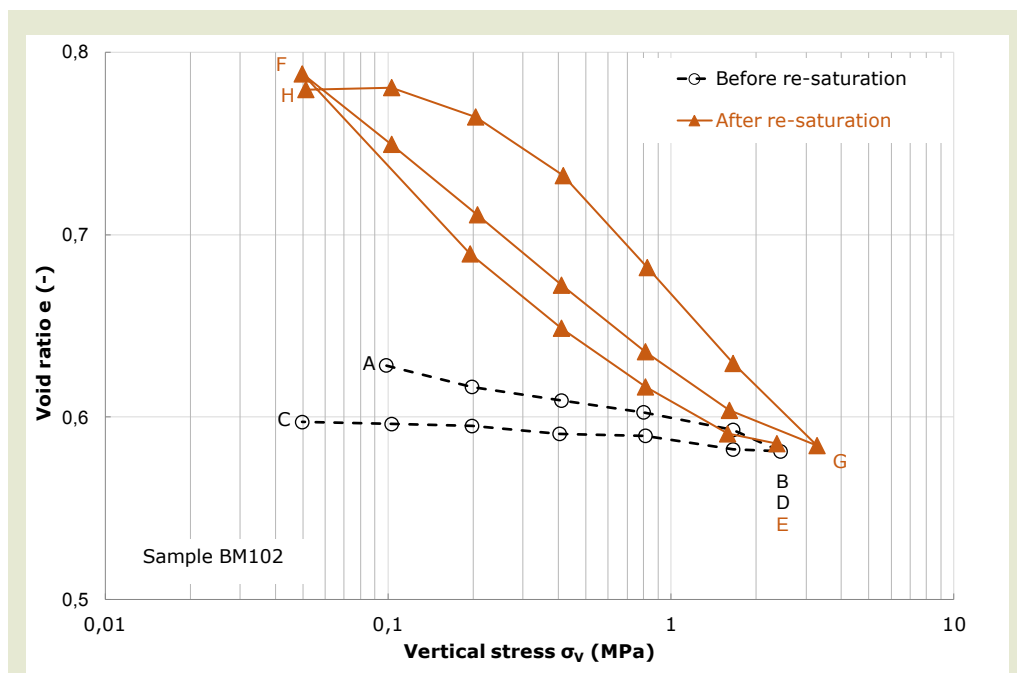
The results obtained by the two laboratories are generally consistent. The air entry value (AEV), in other words the suction above which actual desaturation begins and the water content starts to decrease, which can be deduced from the chilled-mirror dew-point psychrometer data in Figure 37, is about 4 MPa. A somewhat higher value of about 5 MPa was obtained by ENPC using a similar technique, while a value of 3 MPa was obtained by filter paper by EPFL (Salager *et al.*, 2011). These values can be considered as reasonably similar, considering the differences in test protocols or measurement techniques and the experimental difficulties involved in the determination of this parameter.

<sup>37</sup> Additional data, not shown on Figure 37, were used for curve fitting.

The hydro-mechanical behaviour of Boom Clay under unsaturated condition, and in particular the effect of suction on shear strength, was investigated by Lima (Lima, 2011). However, the data collected by Lima have not fully been exploited yet and it is unclear whether these can be fitted by a classical model such as the Barcelona Basic Model (BBM) (Alonso *et al.*, 1990).

### 3.3.10.7. Swelling capacity and creep

Because it contains swelling minerals that react readily with water, Boom Clay as a whole also exhibits a capacity to swell. This capacity was investigated by Horseman *et al.*, who reported a maximum value for the swelling pressures of about 1 MPa (Horseman *et al.*, 1987). While this is a much lower swelling pressure than that of a pure bentonite<sup>38</sup> of comparable density, Boom Clay can be considered as moderately swelling (Bernier *et al.*, 1997). The swelling behaviour is particularly noticeable during unloading phases in some laboratory tests in drained conditions (Coll, 2005) (Le, 2008) (TIMODAZ, 2011) (Deng *et al.*, 2012b). It complicates the interpretation of such tests, as it is not always easy to separate the elastic unloading response from the swelling. Figure 38 illustrates the swelling of a Boom Clay sample in oedometric conditions.

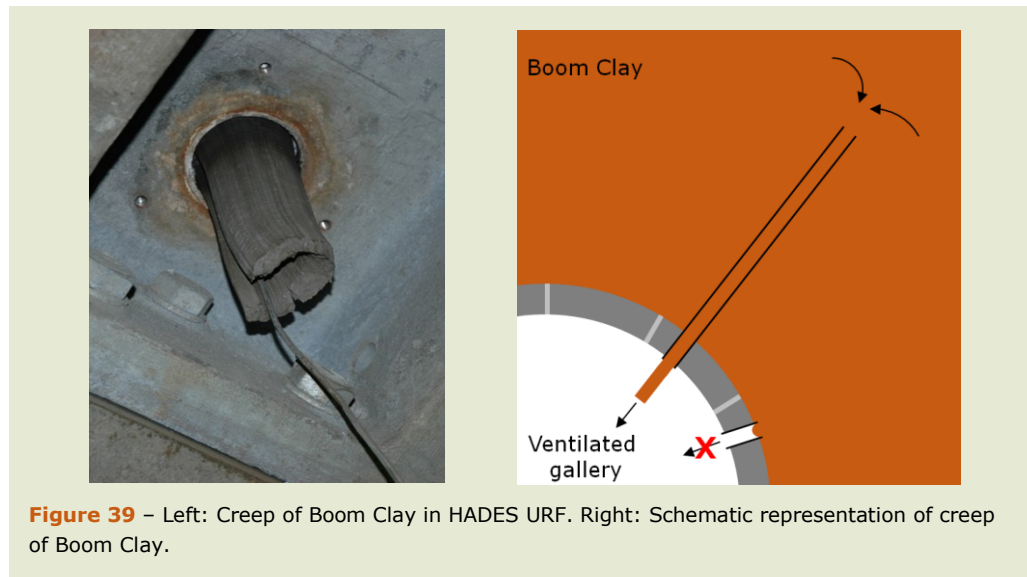


**Figure 38** – Swelling in oedometric conditions. Note that the initial loading step (from A to B) is performed without contact with water, to restore (close to) *in-situ* conditions. From D to E, the load is kept constant while the sample is in contact with water. The absence of significant swelling indicates that the sample did not loose its water during sampling (Nguyen, 2013).

Boom Clay is poorly indurated. Owing to its high water content and apparent absence of significant cementation, it can exhibit creep, *i.e.*, time-dependent deformations under quasi-constant effective stresses, or “viscous” behaviour. This is illustrated in a rather spectacular way in Figure 39 left which shows the ingress of Boom Clay into HADES URF

38 The swelling pressure of a bentonite MX80 at dry density of about  $1650 \text{ kg}\cdot\text{m}^{-3}$  is around 10 MPa.

by slow extrusion through an open borehole casing. In absence of casing, the suction due to ventilation (and possible slight desaturation in clay) prevents creep (Figure 39 right).



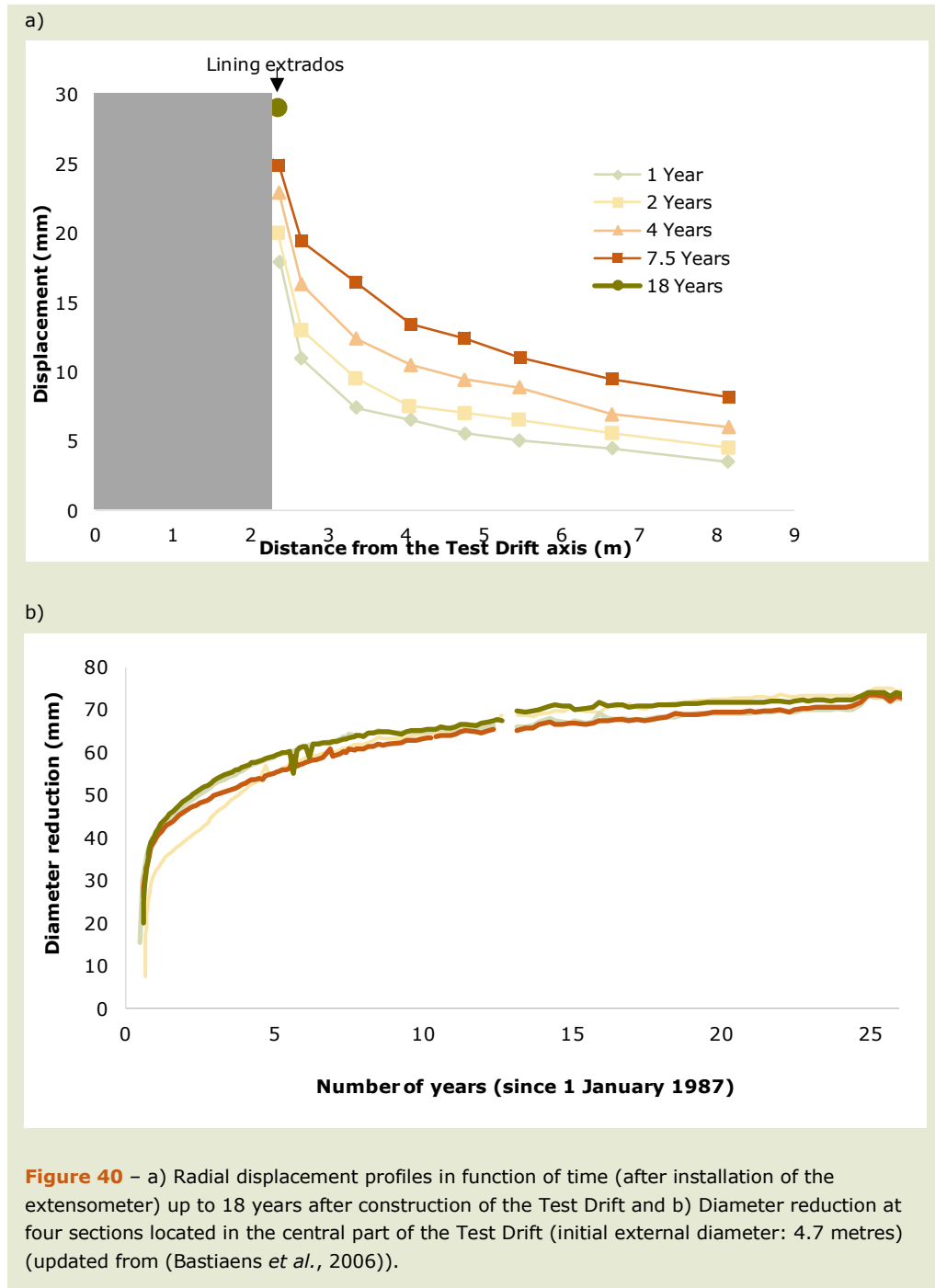
Less spectacular but equally relevant, the long-term convergence of Boom Clay towards the HADES URF galleries is another manifestation of the time-dependent behaviour of Boom Clay, illustrated in Figure 40. In Figure 40 a) the convergence of Boom Clay toward the Test Drift (built in 1987) is shown in function of time. During the first years after construction, the convergence is mainly due to consolidation, *i.e.*, drainage towards the gallery resulting in a reduction of pore pressures and consequently in an increase of effective stresses and deformations. After several years, however, pore-water pressures evolve much less rapidly and the convergence is then dominated by creep.

Figure 40 b) shows the shrinking of the diameter of four sections from the central part of the Test Drift because of this increasing load. The decrease of the lining diameter is fastest during the first year after construction. It slows down afterwards but still goes on. In 2005 (some 18 years after construction), the rate was about 0.5 millimetre per year. Since the measurements started, the diameter was reduced by some 60 millimetres. The same type of measurements was performed during 13 years on the lining of the Experimental gallery, during this period a diameter reduction of about 15 millimetres was measured. The evolution of the convergence was similar.

In the Test Drift, the host rock is supported by sliding ribs. This allows a significant convergence (controlled by the friction between the sliding ribs) and limits the stresses on the support. For other types of support, such as the concrete segments used in the Connecting gallery, consolidation and creep of Boom Clay result in loads on the lining that increases with time. The dimensioning of the lining must consider this load increase if retrievability of the waste is required.

Thorough investigation of this elasto-visco-plastic behaviour of Boom Clay started after SAFIR2. Several laboratory test series have been started to characterise this time-dependent behaviour (Le, 2008) (Cui *et al.* 2009) (Cui *et al.*, 2012). Cui *et al.* performed tests at different temperatures and have shown that creep increases with temperature. Some of the oedometer and triaxial tests on Boom Clay performed by IRSM lasted

almost two years. Creep rates of about  $10^{-5} \cdot h^{-1}$  were observed. For the *in-situ* average effective stress, the deviatoric stress threshold of the creep is about 1 MPa. Development of models based on those laboratory test results is under way (Jia, 2009) Together with swelling, creep is a very important process for self-sealing (Section 4.1.2.1).



### 3.3.10.8. Constitutive models

Constitutive models describe the mechanical behaviour of the solid phase of a porous media, linking volumetric and shear strain increments to effective stress increments. Several constitutive models of Boom Clay have been used so far for different purposes and are discussed in, among others, (Yu H.D., 2010) (Dizier, 2011) (Yu *et al.* 2012). Classical elastoplastic models based on Mohr–Coulomb or Drucker–Prager failure criteria and modified Cam–Clay models have been used to simulate the excavation of the galleries and to fit laboratory test results. As mentioned above the pre-consolidation pressure of Boom Clay<sup>39</sup> – which is one of the parameters of the Cam Clay models – is about 5 – 6 MPa corresponding to an over-consolidation ratio (OCR) of 2. However, fitting the same model to tests on Boom Clay samples from Essen gives an OCR of 1, suggesting that the high value of OCR in Mol could have been chemically induced.

Extensions of elastoplastic models of Boom Clay to unsaturated state, *i.e.*, considering an extension of the elastic domain with suction, were mainly used to model the BACCHUS<sup>40 41</sup> and RESEAL<sup>42 43</sup> tests. However, in both tests, Boom Clay was hardly desaturated beyond a few centimetres from the experimental setup and the role of interfaces between materials was suspected to play a predominant role.

Elastoplastic models have been extended to cope with variable temperature conditions. Introducing thermo-plasticity in these models, *i.e.*, a reduction of the elastic domain with increasing temperature led to a reasonably successful reproduction of the thermo-dilatant or thermo-contractant behaviour of clay samples (depending on their initial pre-consolidation) that can be observed in thermal consolidation experiments.

As those models have usually been developed to fit the behaviour of Boom Clay under specific conditions and in particular along certain types of stress-strain paths, building a unified, general-purpose constitutive model of Boom Clay remains elusive. Recently, saturated elasto-visco-plastic-damage models including anisotropy of elastic behaviour and of permeability and introducing an empirical representation of self-sealing have been developed (Jia, 2009) (Yu H.D., 2010), (Yu H.D. *et al.*, 2013). These models are tested through simulation of decades-long *in-situ* measurements around HADES URF (pore pressure, permeability evolution, pressure on the lining, convergence of Test Drift). Because parameter values are obtained from laboratory test results but also by back-analysis of *in-situ* measurements, it is difficult at this stage to assess their predictive capability.

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39 at Mol and at the depth of HADES URF.

40 BACCHUS: Backfilling control experiment for high-level wastes in underground storage (EU project).

41 BACCHUS II: Demonstration of the *in-situ* application of an industrial clay-based backfill material (EU project).

42 RESEAL I: Large-scale *in-situ* demonstration test for repository sealing in an argillaceous host formation – Feasibility: borehole sealing and shaft sealing (EU project).

43 RESEAL II: A large-scale *in-situ* demonstration test for repository sealing in an argillaceous host formation – Phase II (EU project).

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### Roadmap – Section 3.3.10 – *In-situ* stress state and hydro-mechanical behaviour (BC)

The *in-situ* stress state and hydro-mechanical behaviour of Boom Clay are sufficiently known for SFC1.

ONDRAF/NIRAS nevertheless continues to characterise the stress state and the hydro-mechanical properties. The results of these characterisations will be integrated in subsequent SFCs. In particular, ONDRAF/NIRAS will continue to assess the combined effects of the different types of anisotropy (*in-situ* stresses, Boom Clay stiffness and strength) as this may build confidence in the long-term evolution of the system and support optimisation of construction techniques. ONDRAF/NIRAS will also pursue the integration of the large amount of data collected over more than 30 years of research in support of the development of constitutive models.

The transferability of geotechnical properties to other locations in Boom Clay and to greater depths in particular is an ongoing research topic *in preparation for the siting process*.

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#### 3.3.11. Thermal properties

A characterisation of the thermal properties of the host and surrounding formations is required to determine the evolution of the temperature field in the clay around disposal galleries for heat-emitting waste and, in turn, to assess the perturbations to the system resulting from the temperature changes.

Limiting the near field and far field temperature increases to acceptable values is one of the major constraints on the design of a repository for heat-emitting waste (NEA, 2005). Near-field temperature criteria result from EBS and host formation performance – or demonstrability of performance – considerations. In the far field, the maximum temperature criterion is usually derived from environmental guidelines (Chapter 3). As thermal criteria are usually set in terms of absolute temperature, the allowable temperature increase also depends on the *in-situ* temperature at the depth of the repository. The present-day temperature at the HADES URF level (223 metres below ground level) is about 16°C.

Based on a laboratory testing programme and back-analysis of the results of *in-situ* experiments such as BACCHUS<sup>44 45</sup>, CERBERUS<sup>46</sup> and CACTUS<sup>47</sup>, Van Cauteren reported a thermal conductivity of 1.6 to 1.7 W·m<sup>-1</sup>·K<sup>-1</sup> and a heat capacity of 2.84×10<sup>6</sup> J·m<sup>-3</sup> K<sup>-1</sup> for the saturated Boom Clay (Van Cauteren, 1994) (CACTUS, 1994). SAFIR2 reported a

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44 BACCHUS I: Backfilling control experiment for high-level wastes in underground storage (EU project).

45 BACCHUS II: Demonstration of the *in-situ* application of an industrial clay-based backfill material (EU project).

46 CERBERUS: Control Experiment with Radiation of the BELgian Repository for Underground Storage) (EU project).

47 CACTUS: Characterization of clay under thermal loading for underground storage (EU project).

value of  $1.7 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  for the thermal conductivity, based on the previous results and those of the ATLAS I and II <sup>48</sup> *in-situ* heater experiments.

Since SAFIR2, the refined interpretation of the results of ATLAS I and II experiments and of additional results obtained from ATLAS III <sup>49</sup> led to more accurate values of the thermal conductivity.

ATLAS III also highlighted the anisotropy of the thermal conductivity of Boom Clay, which is higher in the horizontal direction ( $1.65 - 1.7 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ) than in the vertical one ( $1.31 - 1.35 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ) (Chen *et al.*, 2011). As the geothermal gradient is about constant over the formation thickness (Figure 44), the variability of the vertical thermal conductivity with depth is assumed to be rather limited at a given location.

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### Roadmap – Section 3.3.11 – Thermal properties (BC)

*The new drilling* will allow ONDRAF/NIRAS to characterise further the vertical variability of thermal parameters in Boom Clay, because these parameters may affect the design of the repository (thermal load per meter of gallery and distance between galleries). The first results might be included in SFC1.

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### 3.3.12. Microbes

At the time of SAFIR2, the presence of sulphate-reducing and methane-forming (or methanogenic) microbes in the Boom Clay had already been demonstrated, suggesting that such microorganisms, trapped inside the clay at the time of its sedimentation about 30 millions years ago, still exist there in a latent state (ONDRAF/NIRAS, 2001). Further research established that Boom Clay also contains microbes able to produce significant amount of nitrogenous gases from nitrates that would be released as result of the degradation of bituminised wastes (Ortiz, 2005).

The microbial activity in undisturbed Boom Clay is expected to be low as microbes are spatially restricted by the small pore sizes. Indeed, most pores in the Boom Clay are smaller than the typical size of microbes. The typical size of the microbes involved ranges from about 0.5 to 5 micrometres while the median value of the pore size in Boom Clay determined with Mercury Intrusion Porosimetry is between 10 and 100 nanometres (Figure 22) (Van Geet *et al.*, 2006). This space restriction, combined with the low rate of diffusive transport of nutrients in Boom Clay and metabolic waste products, is expected to inhibit or at least severely limit microbial activity (Aerts *et al.*, 2009b).

The investigation of diagenetic processes also suggests that microbial activity, such as the one that led to the formation of pyrite and septaria, only took place in Boom Clay at shallow depth during the early phase of deposition of the clay sediments. In unconsolidated sediments under reducing conditions, microbes reduced naturally occurring sulphates to sulphides. In the same pedo-horizon,  $\text{Fe}^{3+}$  was also reduced to

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48 ATLAS I and II: Admissible thermal loading for argillaceous storage, part of the INTERCLAY project (EU projects).

49 ATLAS III: Admissible thermal loading for argillaceous storage.

Fe<sup>2+</sup> and consequently, pyrite and calcite co-precipitated (forming pyrite framboids and septaria). Works by De Craen suggest that once formed, septaria did not further evolve in the course of the burial history up to the present day (De Craen, 1998).

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**Roadmap – Section 3.3.12 – Microbes (BC)**

ONDRAF/NIRAS will investigate the effect of space restriction on microbial activity. Because microbes are present around HADES, this experiment will aim to determine the response of microbes initially in a favourable environment (with space and nutrients) to a progressive spatial restriction, corresponding to the expected consolidation of the clay around the disposal galleries. Results of this study will be integrated in *later SFCs*.

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### **3.4. The environment can be characterised**

The geological setting of the Campine is studied since the 19<sup>th</sup> century through boreholes and seismic investigations. The peer review of SAFIR2 recognised that there is a considerable amount of information available on the regional geological environment but also highlighted the need to get more information about the long-term stability of the host formation and about the hydrogeological system (NEA, 2003). Therefore, numerous studies aiming at identifying potential forthcoming processes were initiated in various geoscientific disciplines (climate, tectonics etc.). This section presents first the geological setting of the region of interest (Section 3.4.1), then its hydrogeological setting (Section 3.4.2).

#### **3.4.1. Geological setting**

The geological Campine Basin roughly underlies the geographic Campine area located in the northeastern part of Belgium. In order to evaluate the future evolution of the Campine, significant efforts have been devoted since SAFIR2 to improve the understanding of the geological history at the regional scale.

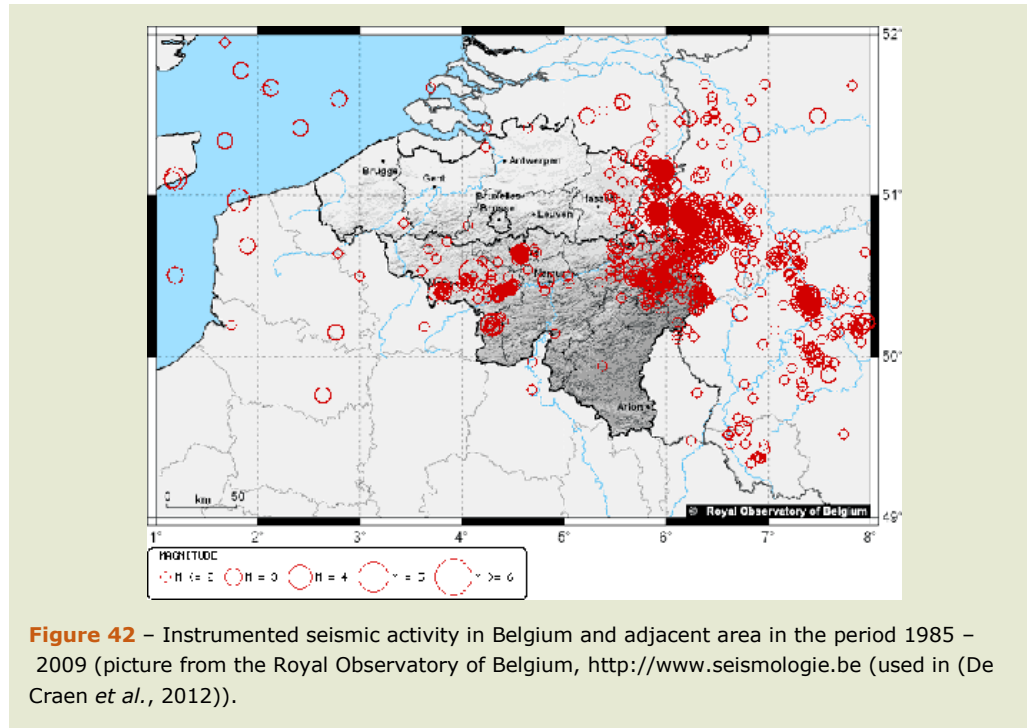
The Campine Basin is part of the tectonic framework of western and central Europe, which is mainly determined by the European Cenozoic Rift System (ECRIS) in the Alpine foreland. This system developed during the Alpine orogenic phases, and more particularly during the Eocene (about 56 to 34 million years ago) up to present times (Ziegler, 1992). ECRIS consists of a series of rifts and associated transverse faults extending from the coast of the North Sea to the Mediterranean over a length greater than 1100 kilometres (Figure 41). The Roer Valley Graben, located at the eastern border of the Campine Basin, is part of this European Cenozoic Rift System and is still active. An extensional activity and overall concomitant subsidence have been recognised for the last 25 million years (late Oligocene). The geodynamic evolution of the Campine is related to the evolution of the Roer Valley Graben, especially during the Cenozoic times.



**Figure 41** – Topographic map with the European Cenozoic Rift System highlighted (ECRS) (the physical map from website <http://geology.com/world/europe-physical-map.shtml>).

RD&D results led to the conclusion that the Campine Basin outside the central Graben can be considered as a relatively stable geological environment, compared to neighbouring areas (the rapidly subsiding Roer Valley Graben and the uplifting Ardennes) (De Craen *et al.*, 2012). In particular, the following conclusions can be drawn:

- Most of the Campine Basin is characterised by limited tectonic activity; the latter being generally related to the activity of the Roer Valley Graben which only affects the northeastern part of Belgium. Integrated seismic and borehole investigations show that the most important tectonic features of the Roer Valley Graben recognised in the Campine are the NW-SE oriented tectonic faults. The Campine region outside the Roer Valley Graben is therefore less active and less faulted.
- Therefore, the Campine Basin, outside the Roer Valley Graben, is considered as a zone of low seismic activity. The Roer Valley Graben is the most active region in northwestern Europe, as illustrated by Figure 42 that reports instrumented seismic activity in Belgium and adjacent area in the period 1985 – 2009 (ONDRAF/NIRAS, 2009g).
- In addition, the Campine is a zone without active igneous activity although much older igneous rocks have been observed in the adjacent areas (*e.g.*, in the Brabant Massif, the Ardennes Massifs, the Roer Valley Graben and the Eifel).



### The burial history of the Campine

The general burial history of the Campine area is relatively simple compared to many other geological settings. For many millions of years, before the deposition of the Boom Clay, the Campine has been a large intermittently subsiding sedimentary basin in which large amounts of sediments were deposited, and which was protected by the Brabant Massif from major orogenic compressive processes. Figure 43 shows a schematic burial history of Boom Clay and younger layers in the Mol–Dessel area. Initially, the Boom Clay was rapidly buried due to the continuous sedimentation of more sandy deposits, known as the Eigenbilzen Sands. At the end of the Rupelian, a large tectonic uplift/tilting of the entire Campine Basin took place. This tilting consisted of an uplift of the western part of the Campine Basin and a subsidence of the eastern part. Because of this tectonic activity, the burial history in the Rupel area (in the west) and in the Mol–Dessel area (in the east) is slightly different since then. Another erosion phase took place during the Late Oligocene erosion phase and the Late Miocene subsidence phase at a rate of 0.02 – 0.03 millimetres per year (Vandenberghe *et al.*, 2004). Boom Clay is currently roughly at its maximum burial depths.

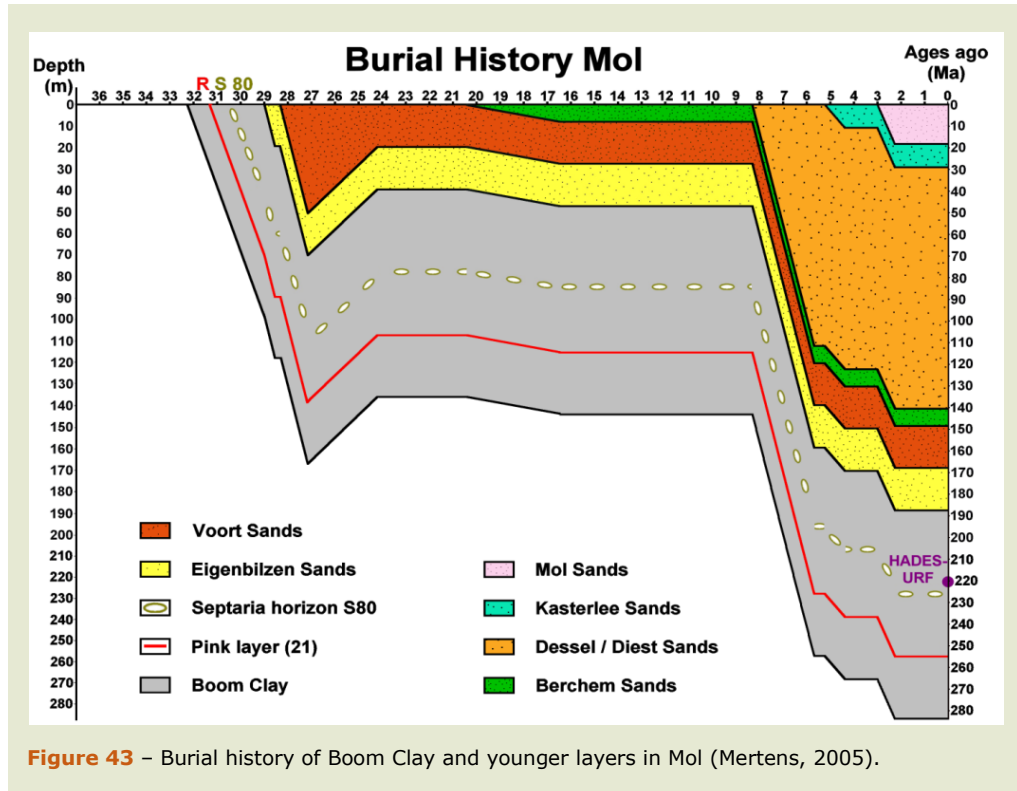
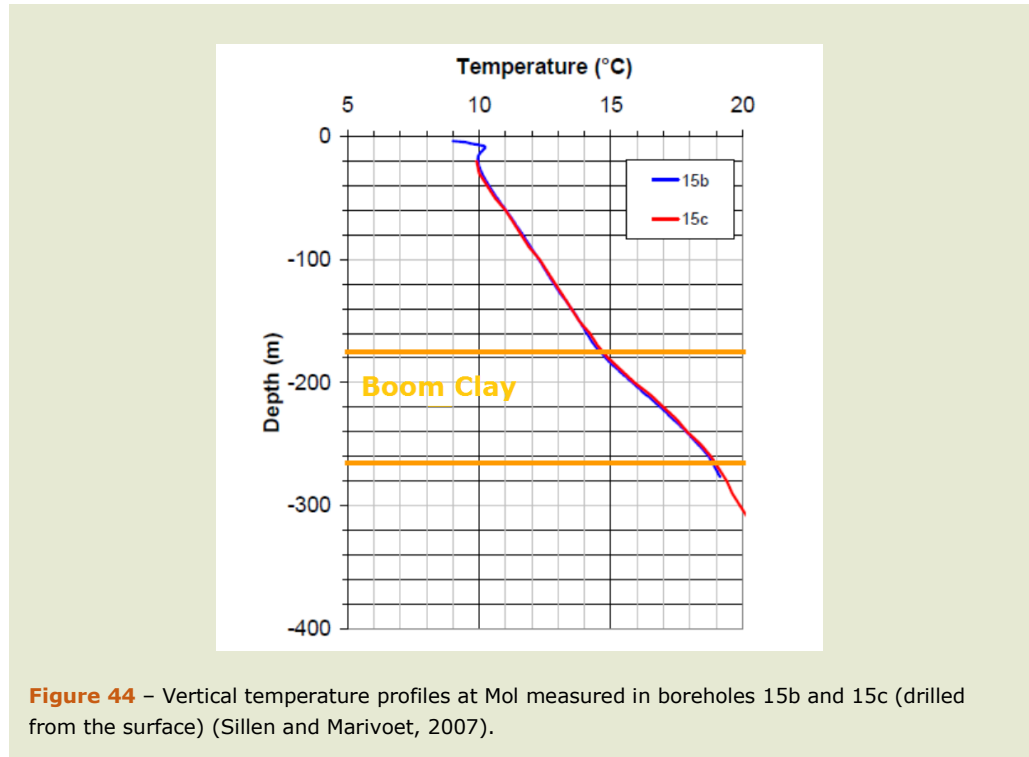


Figure 43 – Burial history of Boom Clay and younger layers in Mol (Mertens, 2005).

### The current geology of the Campine

Over the years, the sedimentation in the Campine Basin resulted in a thick sequence of sedimentary deposits, characterised by sub-horizontal to monocline layers (*i.e.*, gently dipping layers). Palaeozoic sediments reach a maximal thickness of 4 000 metres, and are mainly composed of limestones and dolomites of Lower Carboniferous age, followed by shales and sandstones of Upper Carboniferous age. During the latter period, coal beds of economic interest were formed as well (see hereafter). Mesozoic sediments are mainly composed of Cretaceous chinks and marls. The Cenozoic is characterised by a succession of sub-horizontal layers of Tertiary clays and sands and finally covered by some Quaternary sediments (Figure 17) (De Craen *et al.*, 2012).

Figure 44 shows that the geothermal gradient in the Boom Clay formation is steeper than in the surrounding aquifers, indicating that the Neogene and Oligocene aquifers are characterised by higher thermal conductivities (Sillen and Marivoet, 2007). There is no direct measurement of the thermal conductivities of the layers below and above Boom Clay. The current values of these conductivities have been derived from the thermal conductivity of Boom Clay combined with ratios between geothermal gradient values.



### Potential resources and uses of the Campine underground

Reasonably foreseeable human actions include the exploration and exploitation of the Campine underground for economical reasons. Therefore, one study focused on listing the natural resources and potential uses of the Campine underground and there is ongoing technical watch on this field, for use during the siting process

A geological environment may be of economic interest because of the presence of natural resources, which include water, mineral and energy resources. Besides natural resources, the use of deep geological layers for specific purposes may be economically interesting as well, *e.g.*, gas storage in natural geological reservoirs (De Craen *et al.*, 2012b). Table 15 summarises all natural resources and potential uses of the Campine underground.

The knowledge gathered in this field will be used for later SFCs of the programme to identify promising zones (*i.e.*, of limited economic interest) during the siting process.

**Table 15** – Resources and uses of the Campine underground.

<b>Resources/Uses</b>	<b>Location (rock type)</b>	<b>Stratigraphic age(s)</b>	<b>Depth</b>	<b>Exploitation</b>
<b>Water resources</b>				
Water	All over Campine	Neogene	Ubiquitous but with various quality/quantity levels	In exploitation
<b>Mineral resources</b>				
Clay, sand and gravel	All over Campine	Quaternary	Ubiquitous but mostly exploited at sub-surface depth	In exploitation (open pit method)
<b>Energy resources</b>				
Coal	Specific areas (paleozoic sediments)	Upper Carboniferous	~ 800 metres depth and below	Former use (Campine coal mine concession). Future use not excluded to the north of former concessions
Coal-bed methane	Specific areas (paleozoic sediments)	Upper carboniferous	~ 800 metres depth and below	Pilot project Peer '92 New pilot project foreseen in near future
Peat and lignite	Specific areas	Neogene	Sub-surface depth	Former use
Natural oil, gas, hydrocarbons	None found	Upper Carboniferous		
Shale gas	East Campine	Upper Carboniferous	~ 800 metres depth and below	Laboratory tests
Geothermal energy (shallow depth)	All over Campine	Neogene	Up to 300 metres	In exploitation
Deep geothermal energy	Specific areas	Lower Carboniferous, Cretaceous	Minimum depth 500 m or 1000 m (depending on the water's use)	Former pilot projects in Turnhout & Merksplas. Ongoing pilot study in Mol
<b>Other uses</b>				
Gas storage	Specific areas (limestone)	Lower Carboniferous	~ 900 metres depth and below	In exploitation (Gas storage and exploration concessions)
CO <sub>2</sub> storage	Specific areas	Early Triassic, Carboniferous	~ 800 metres depth and below	Currently studied

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### Roadmap – Section 3.4.1 – Geological setting (BC)

ONDRAF/NIRAS will refine knowledge of burial history of the Campine area, in particular during the last million years (to improve the resolution of data). Results of this study are not expected before SFC1 but will be introduced in *later SFCs*.

ONDRAF/NIRAS will better characterise the layers around Boom Clay (transition zone between Boom Clay and the Neogene aquifer; alternating permeable and impermeable layers of the Oligocene aquifer) in terms of geometry, for a more realistic description of the system (see roadmap Section 3.4.2). Results of this study are not expected before SFC1 but will be introduced in *later SFCs*.

The new borehole will also provide samples for the direct measurement of thermal parameters of the formations below and above Boom Clay. (These parameters are currently deduced from indirect measurements.) This knowledge will be used for re-evaluating the uplift above a repository for heat-emitting wastes (Chapter 8). The results of the samples might only be available for later SFCs.

ONDRAF/NIRAS will follow up technological watch on possible conflicts of use.

*For confidence building*, ONDRAF/NIRAS will pursue its technological watch on seismic monitoring and follow up the development of knowledge of geological settings on the Western European scale.

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## 3.4.2. Hydrogeological setting

### 3.4.2.1. Hydrogeological system

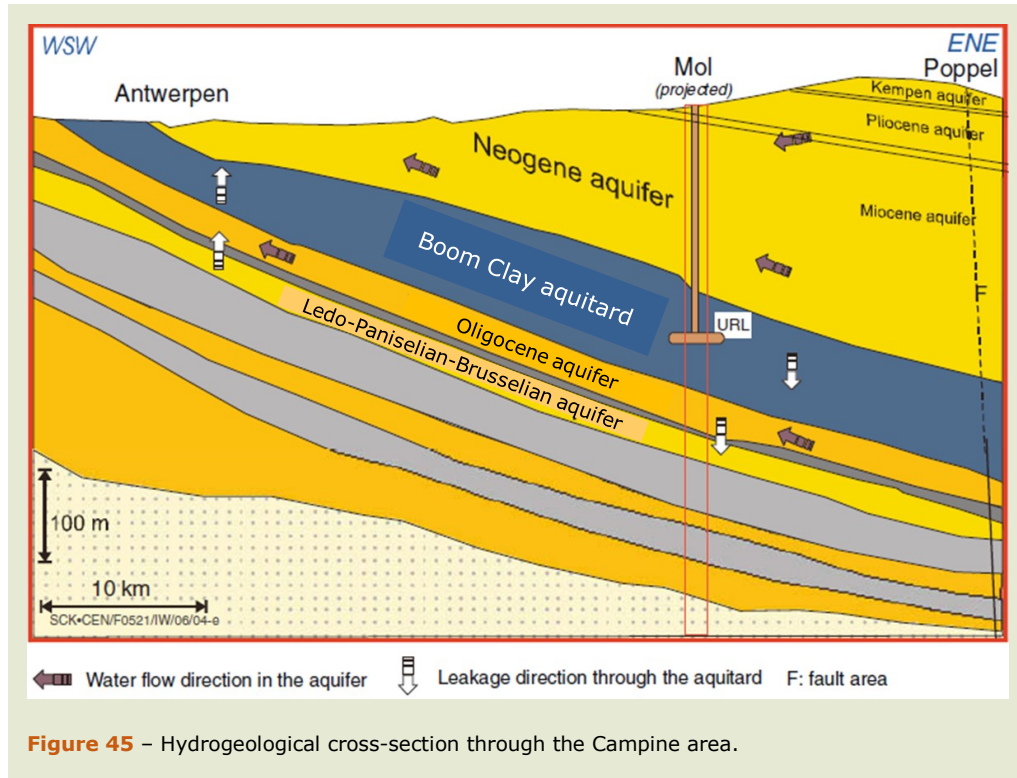
The Boom Clay plays a cardinal role in the hydrogeological system of the Campine area by separating the sedimentary units into an upper and a lower aquifer system. The upper aquifer system, called the Neogene and Quaternary aquifers, groups all of the sands overlying the Boom Clay (they are sometimes separated by some minor clay layers). The lower aquifer system consists of the Oligocene<sup>50</sup> and the Ledo-Paniselian-Brusselian<sup>51</sup> aquifers, separated by the Bartoon aquitard<sup>52</sup>, a thin sequence of lower hydraulic conductivity (see Table 8). The lower aquifer is underlain by the Ypresian clays (Figure 45) which presumably play a role of aquitard (De Craen *et al.*, 2012).

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50 Formerly known as the Lower-Rupelian aquifer.

51 Formerly known as the Ledo-Brussels aquifer.

52 The Bartoon aquitard includes the Asse Clay layer.



**Figure 45** – Hydrogeological cross-section through the Campine area.

The Neogene and Quaternary aquifer system is a dynamic groundwater flow regime, mainly fed by meteoric precipitation and regulated by the surface water bodies (rivers, canals and lakes) and river catchment dynamics, e.g., the major Meuse-Scheldt catchment in the north of Belgium. In the aquifers below the Boom Clay, the lack of sources and sinks (mainly through the outcrops of the respective formations) causes a very slow groundwater movement in generally southeast to northwest direction. This situation is disturbed by groundwater overexploitation that causes a continuous decrease of the groundwater levels in these deeper aquifers (De Craen *et al.*, 2012).

Currently, the two aquifers systems come into direct contact in the region of Diest and Averbode, owing to erosion of the clay (the Diest erosion channel). Moreover, the Boom aquitard may also be bypassed in the Roer Valley Graben where the faults may act as preferential pathways for water.

### 3.4.2.2. Hydraulic gradient

At the time of SAFIR2, there were 130 piezometers installed at 40 separate locations, mainly in the Neogene aquifer, to measure groundwater levels and their changes over time, and so determine the hydraulic gradients and the direction of groundwater flows. These measurements were – and still are – also used to calibrate hydrogeological models. The vertical gradient through the Boom Clay, that is, the difference in hydraulic head between the Neogene and Oligocene aquifers, was at that time, generally of the order of 0.02 or 2 metres of water per 100 metres of clay (ONDRAF/NIRAS, 2001).

Additional piezometers have since been installed in new locations to perform measurements beneath the Boom Clay. The current piezometric network now comprises about 150 piezometers installed at 46 separate locations, with monthly measurements of



piezometric levels. Groundwater level measurements in the aquifers above and below the host formation are summarised in the report on 30 years of regional groundwater monitoring (Labat, 2011). The gradient across the Boom Clay is rather variable at the regional scale. Higher gradients pointing downwards occur at places where the upper aquifer heads are elevated; upward gradients are found where the heads in the upper aquifer are relatively low – close to the rivers – or towards the west – close to the Scheldt estuary –. The overexploitation of the aquifers below the Boom Clay artificially increases the difference in the groundwater levels below the Boom Clay, causing important increases in the downward gradient. In Mol, the downward gradient slightly increased up to 0.04 in spring 2010, and is still increasing nowadays (De Craen *et al.*, 2012b). On the contrary, the Neogene aquifer presents no over-exploitation thanks to its considerable meteoric recharge and high hydraulic conductivity (Gedeon and Wemaere, 2009).

#### **3.4.2.3. Hydrogeological modelling**

Hydrogeological modelling aims to improve the understanding of the underground hydraulic regime in and around the Boom Clay in the Campine area. It attempts to reproduce the observations made by the hydrogeological characterisation programme, in particular the piezometric levels and the hydraulic conductivities, using mathematical models to obtain indications of the groundwater flows in the various geological formations and of the hydraulic balances between them. Hydrogeological modelling is conducted in close, permanent, and iterative association with geological and hydrogeological characterisation (ONDRAF/NIRAS, 2001).

At the time of SAFIR2, the hydrogeological models were steady-state models that neglected water pumping occurring in the aquifers below Boom Clay. Whereas the flow system above the Boom Clay was well reproduced by the model, the flow field below the clay was poorly understood and fitted observations only when assuming a higher (overall) large scale hydraulic conductivity of the Boom Clay, which did not match the measured values (ONDRAF/NIRAS, 2001).

Since SAFIR2, an update of the regional hydrogeological model for the Mol site, called NEB2002 (northeastern Belgium model), revealed the need to focus on the non-steady hydrogeological situation in the confined aquifers below the Boom Clay. This non-steady situation is due to excessive pumping which results in a continuous drawdown of the groundwater levels. Such transient situation can only be modelled with a dynamic model. Two models were then developed: the Neogene aquifer model (NAM) is a steady-state model for the upper aquifer system while the transient model (called the DAP or deep aquifer pumping model) simulates the behaviour of the confined aquifers located below the Boom Clay taking into account the transient effects due to excessive pumping (Gedeon, 2008) (Gedeon *et al.*, 2009).

The combination of the NAM and DAP models explains the observed hydrogeological behaviour of the Mol–Dessel area although some hypotheses behind the models must still be validated. The Neogene aquifer model characterises the groundwater flow in the aquifer system above the Boom Clay in a better way than previous models (Gedeon, 2008). The deep aquifer pumping model satisfactorily reproduces the main trends observed in some piezometers belonging to the three main groundwater regime groups

(strongly influenced groundwater levels, constantly lowering groundwater levels and uninfluenced groundwater levels) (Gedeon *et al.*, 2009).

Under the auspices of ONDRAF/NIRAS, these new models and the previously developed ones have been audited by a company specialised in groundwater protection and waste disposal (Colenco, 2009). Colenco concluded that it appears reasonable to consider the groundwater flow systems above and below the Boom Clay in separate models, because they are affected mostly by different features and processes and they cannot be characterised with a comparable and adequate space-time resolution.

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### Roadmap – 3.4.2 – Hydrogeological setting (BC)

The new drilling will allow ONDRAF/NIRAS to better characterise the layers around the Boom Clay (transitional formations between Boom Clay and the Neogene aquifer; alternating permeable and impermeable layers of the Oligocene aquifer) in terms of hydraulic properties, for a more realistic description of the system (see roadmap Section 3.4.1). ONDRAF/NIRAS will also better characterise the Ypresian formation in Mol, which is used as a boundary limit of the lower Rupelian aquifer in hydrogeological modelling. The first results might be included in SFC1.

*For later SFCs*, topics to focus on are the understanding of geochemical variations, equilibration time between sea water and aquifers, water dating, and integrating data from the Netherlands, in order to refine the hypotheses behind its geochemical models, as suggested by (Colenco, 2009) and (Olsthoorn, 2011).

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## 3.5. The biosphere can be stylised

The biosphere includes the atmosphere, the earth's surface and its biota (flora and fauna), aquifers, soil, surface waters and sediments (FANC, 2010). The aim of biosphere modelling is to calculate common safety indicators such as the individual dose rate or the radiotoxicity concentration in the biosphere water. *"The safety assessments must show that sufficient assurance can be provided that the radiological effects for humans and the biosphere, up to times in the distant future, won't be higher than those considered acceptable today"* (Extract from (FANC, 2010)). The FANC's biosphere guidance presents the requirements of the FANC on the treatment of the biosphere in safety assessment of any type of waste disposal facility (FANC, 2010).

However, the individual human behaviours (dietary habits and lifestyle) as well as near-surface natural processes are difficult or impossible to predict over long time scales (NEA, 2012c). These ontic uncertainties cannot be handled with any of the common strategies used for epistemic uncertainties (Knol, 2010). In consequence, there is an international consensus around using a stylised approach whenever assessment of future environmental conditions is not feasible (ICRP, 1998) (NEA, 2010b). This stylised approach means that significant assumptions are made about the various components of the biosphere (including the climate type), the interface geosphere/biosphere, the representative group and the interactions between this representative group and the environment. This stylisation results in a concise representation of human behaviour and

climate which seek to capture their most essential features while erring on the side of conservatism. Large-scale international projects, such as the BIOMASS programme from the IAEA, have resulted in the development of a methodology for converting radionuclides release from a repository into indicators of potential harm, via the use of mathematical representations of “reference” biospheres (IAEA, 2003). Implementers and regulators agree that the results from safety assessments based on this approach are qualitative indicators of safety rather than real predictions of impacts (NEA, 2002) (ICRP, 2013).

The reference biosphere developed for the area Mol–Dessel is based on the BIOMASS methodology and is consistent with international recommendations on radiation protection. It has constantly evolved since SAFIR2, becoming more refined. The RD&D programme for category B&C waste in this field is closely related to the one of category A, as the reference site for RD&D of the geological programme is located near the site for disposal of category A waste (ONDRAF/NIRAS, 2010c) (ONDRAF/NIRAS, 2011). In this model, the representative group is a self-sustaining community located at the time and place of the maximum concentration of radionuclides in the accessible biosphere. Three categories of ages (adult, child and infant) are considered in line with ICRP recommendations (ICRP, 2005) (ICRP, 2013). Contamination may occur via three exposure pathways (ingestion, inhalation and external irradiation) and from two sources of contamination: a river located nearby and a well located at the most penalising place.

The “interaction matrix” hereafter illustrates the interactions between the exposure groups and their environment represented in the biosphere model for the reference site for RD&D in Mol and for the current climate (Figure 46). By using transfer factors between the various compartments of the biosphere (*e.g.*, soil to pasture, cow to milk, etc.), the concentrations of radionuclides taken by the exposure groups can be calculated. These concentrations are converted into doses by using the dose coefficients recommended by the ICRP. The final results are expressed as dose conversion factors, that is, the annual maximum dose for a given concentration of a radionuclide in the different exposure pathways (ONDRAF/NIRAS, 2010c) (ONDRAF/NIRAS, 2011).

The model takes into account eight plant types and five animal groups. Water from the well is directly used as drinking water. It is also used for irrigation of food crops and pastures. This does not only result in the contamination of food crops for human consumption and animal feed, but also of soil. The contaminated food crops are ingested by man, resulting in a certain radiation exposure. Livestock ingest radioactive nuclides by grazing on contaminated pasture, being fed by other contaminated feed, or by being watered with contaminated well water. Meat, milk and eggs from animals are ingested by man. In the river pathway, pore water infiltrates through the bed sediment of the river and is diluted, being finally less contaminated than the water from the well. River water is also used as drinking water and for irrigation. In addition, it can also contaminate fish and sediments. In the soil pathway, the upper soil layer is directly contaminated due to its direct contact with the aquifer, resulting in contamination of crops grown on this ground. Other exposure pathways are the inhalation of dust, re-suspended in the air on fields contaminated by irrigation, inhalation of radon, exhalation from irrigated soil and external radiation on fields contaminated by irrigation (Sweeck *et al.*, 2011).

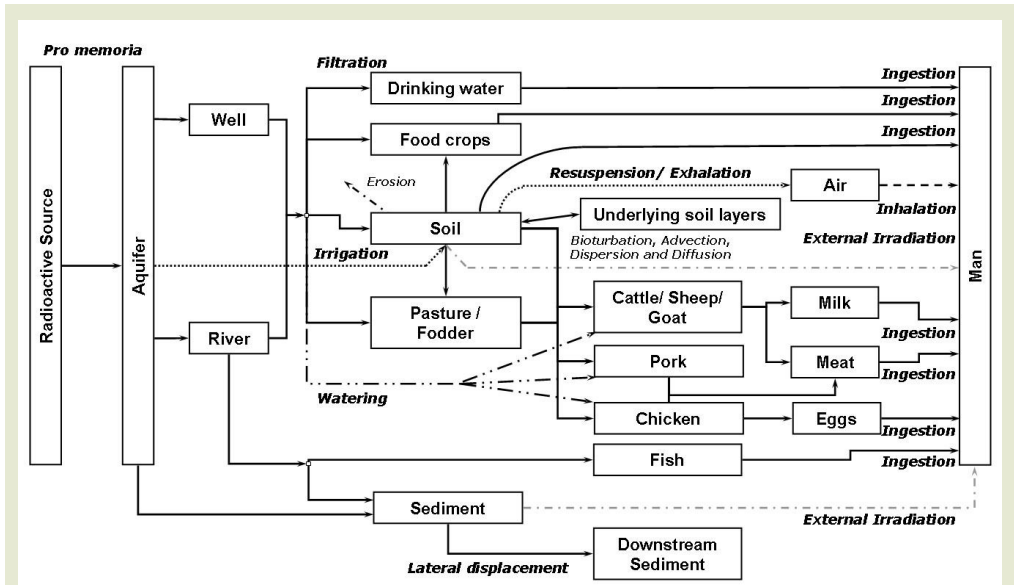


Figure 46 – Biosphere interaction matrix (Sweeck *et al.*, 2011).

Since a few years, RD&D focuses on assessing the impact of the climatic evolution, as the principal variability in the biosphere is driven by climatic change (NEA, 2002). Reference biospheres of the Dessel category A repository's environment have thus been developed for three potential climates: current climate, current climate with moderate temperature increase, and cold climate without permafrost.

Current RD&D also assesses the potential radiological impact of releases from the repository on the local fauna and flora (non-human biota) under the reference scenario for gradual leaching of category A waste (ONDRAF/NIRAS, 2010b).

### Roadmap – Section 3.5 – The biosphere can be stylised

Future developments of the biosphere stylisation within the B&C programme will take account of remarks from:

- the regulator on biosphere treatment in the category A programme, whose licence application is currently under review;
- the independent review of the current B&C biosphere approach (review under progress).

For SFC1, the B&C programme will meanwhile develop a reference biosphere for cold climate with permafrost (not considered in the frame of category A programme) and study the transferability of the transfer factors (from the soil of the reference site for RD&D in Mol to other types of soil in the Campine).

For later SFCs, ONDRAF/NIRAS will extend results from the category A programme about the potential radiological impact of releases from the repository on the local fauna and flora (non-human biota) to category B&C waste.



## 4. The evolution of the disposal system and of its environment can be bounded

The disposal system and its environment will evolve over time. Besides their characterisation, it is thus of prime importance to assess their evolution and to bound it, as stated in the part of the safety tree presented in Table 16. This chapter reviews the knowledge gained in 30 years of RD&D related to the evolution of the system and of its environment. Section 4.1 develops how potentially detrimental external and internal events and processes and associated uncertainties can be avoided or their effects limited by siting – whose process will start after SFC1 and will include societal involvement – and design. Section 4.2 presents the drivers that cannot be avoided and their consequences, focusing on remaining uncertainties.

**Table 16** – Current structure of the Safety Statements underpinning the statement “the evolution can be bounded”.

The system is known	
Indeed,	The evolution can be bounded
Indeed,	Siting and design favour stability
Indeed,	Limited number of drivers
and	Robust features
and	For those drivers than cannot be avoided, the changes in properties and conditions can be bounded
indeed	The evolution of the disposal system due to changes in its environment can be bounded
and	The evolution of Boom Clay due to repository excavation, operation and closure can be bounded
and	The evolution of the engineered barrier system with time can be bounded

## 4.1. Siting and design favour stability

Poorly indurated clay, in particular Boom Clay and Ypresian clays, displays favourable properties to ensure the functions expected of a natural barrier, *i.e.*, long-term isolation, confinement and retention of radionuclides and chemical contaminants present in a geological repository. Section 4.1.1 describes how the number and magnitude of possible perturbations to be considered in the evolution of disposal system can be limited while Section 4.1.2 presents some robust features of Boom Clay that limit the impact of unavoidable perturbations.

### 4.1.1. Limited number of drivers

In order to limit the number of perturbations to consider in the evolution of the disposal system, the design and siting processes will integrate all available knowledge. This includes the following information regarding external perturbations:

- The main driver in the geodynamic evolution (tectonic activities) that could affect a disposal system in Boom Clay and their consequences (such as faults) are identified (Sections 3.3.2 and 3.4.1). There are large zones in the Campine where the impact of these drivers should be limited.
- Climate changes are not avoidable (Section 4.2.1.1). However, their impacts decrease with depth. The siting process will consider this.
- Zones within the Campine with significant resources and uses are identified (Section 4.2.1.2) and should be avoided. The use of groundwater is ubiquitous over the whole Campine area. Possible conflict of uses will be investigated during the siting process.

The repository is designed in order to limit internal perturbations (perturbations due to the repository and the waste). For instance,

- The distance between disposal galleries with heat-emitting wastes is set in order to limit the thermal load on Boom Clay and surrounding aquifers (Section 5.2.2).
- The ESDRED<sup>53</sup> project has demonstrated the feasibility of adequately filling void spaces in a gallery, reducing the risk of host formation collapse and human intrusion (Section 5.4.1).
- The half-scale tests aim to demonstrate that the supercontainer buffer can be constructed without metallic reinforcements, limiting thus the gas production by corrosion, which could affect Boom Clay properties (Sections 3.2.3.1 and 4.2.2.5).

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### Roadmap – Section 4.1.1 – Siting and design favour stability (BC)

*During the siting process*, ONDRAF/NIRAS will perform detailed characterisation of potential site for disposal.

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53 ESDRED: Engineering Studies and Demonstration of Repository Designs (EU project).

### 4.1.2. Robust features

In addition to its favourable properties such as low permeability, Boom Clay is characterised by robust features that limit the impact of perturbations. This section discusses two of them: its self-sealing capacity (Section 4.1.2.1) and its chemical buffering capacity (Section 4.1.2.2).

#### 4.1.2.1. Self-sealing

An important feature of Boom Clay is its remarkable self-sealing capacity: fractures such as those induced by excavation works seal within weeks. Evidence of the capacity of Boom Clay to seal was first observed *in-situ* from coring and instrumentation campaigns as the clay appeared to close spontaneously against the borehole casings and underground excavations. It was confirmed by laboratory and *in-situ* experiments performed, among others, in the frame of the SELFRAC<sup>54</sup> project (Bastiaens *et al.*, 2007) (SELFRACT, 2007) (Van Geet *et al.*, 2008c):

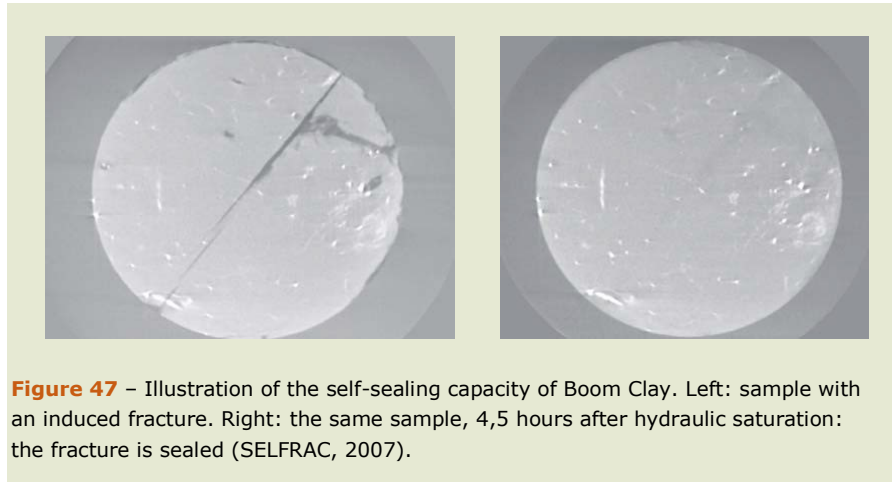
- *In-situ observations:*
  - ▶ Most fractures induced by the construction of the second shaft (1997 – 1999) are now sealed, as detailed in Inset 13.
  - ▶ During the construction of the Connecting gallery (2001–2002), about 6 metres before making the junction with the existing part of HADES URF, traces of fractures which could be clearly related to the part excavated 15 years earlier (1987), were observed. The surfaces of some fractures showed traces of oxidation but only within the last metre before the connection. Obviously, they had been effectively sealed from the air from the ventilated gallery. That observation also shows that fractures can be reactivated, indicating that healing of the fractures is limited.
- *In-situ experiments:*
  - ▶ Shortly after the construction of the Connecting gallery, a network of radial piezometers was installed around the gallery to measure the pore-water pressure distribution, its evolution with time and perform permeability tests. Measurement results less than 3 years after gallery construction indicated that all fractures existing beyond (at most) a few decimetres into the host formation were sealed.
  - ▶ Measurements of seismic parameters around an uncased borehole with a diameter of 158 millimetres that was allowed to close indicated the quasi-complete closing of the hole in about two months.
  - ▶ Measurements of seismic parameters on a fractured clay core which was instrumented and then reinstalled in an uncased borehole indicated that, after 38 days, the clay had converged around the reinstalled core and that the fractures were (from an acoustic point of view) sealed.

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54 SELFRAC: Fractures and Self-healing within the Excavation Disturbed Zone in Clays (EU project).



- ▶ **Laboratory experiments:** Tests were performed in permeameter and isostatic cells and visualised by means of X-ray computed tomography on an artificially fractured clay sample, before and after saturation. Images and density measurements indicate closure of the fracture, due only to the saturation of the sample (Figure 47). Self-sealing was confirmed by measuring the hydraulic conductivity of the sample which was of the same order of magnitude as the non-damaged sample (about  $10^{-12} \text{ m}\cdot\text{s}^{-1}$ ).



The paragraphs on oxidation (Section 4.2.2.1) contain other evidences of self-sealing. In fact, all *in-situ* observations (permeability measurements, acoustic, seismic, examination of core samples) show that fractures in Boom Clay around the underground research facility are closed within a few days or weeks after their creation, provided that the damaged Boom Clay is not kept artificially desaturated (*e.g.*, by ventilation).

#### 4.1.2.2. Chemical buffering capacity

Boom Clay displays a significant buffer capacity with regard to chemical perturbations. Indeed, the chemical perturbations affecting the pH, redox potential ( $E_h$ ) and partial pressure of carbon dioxide ( $p\text{CO}_2(\text{g})$ ) can be buffered by the minerals present, mainly pyrite and carbonates, and by organic matter. The carbonates regulate the pH and the partial pressure of carbon dioxide while the pyrite and organic matter control the redox potential.

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#### Roadmap – Section 4.1.2 – Robust features (BC)

For *SFC1*, ONDRAF/NIRAS will check whether the host rock retain its self-sealing capacity even after perturbation by an alkaline plume (Section 0). A first assessment of the possible effects of combined perturbations will also be carried out.

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## **4.2. For those drivers that cannot be avoided, the changes in properties and conditions can be bounded**

Despite careful development of the design and selection of the site, the conditions on the disposal system and the intrinsic properties of the various components of the disposal system may change during the period of concern (up to several hundred thousand years). In line with the Safety Statement tree (Table 16), the RD&D programme aims thus to identify the potential drivers and to bound the resultant changes affecting the disposal system. These potential drivers might be external to the disposal system (Section 4.2.1) or internal, that means due to the presence of repository and affecting Boom Clay (Section 4.2.2). Section 4.2.3 details the evolution of the different parts of the engineered barrier system with time.

### **4.2.1. The evolution of the disposal system due to changes in its environment can be bounded**

This section presents the external drivers that could affect the evolution of the disposal system, that is the natural external events and processes (Section 4.2.1.1) and the human actions (Section 4.2.1.2).

#### **4.2.1.1. Natural external events and processes**

The long-term evolution of the Campine will result from the combination of various events (and their consequences) related to geodynamic evolution and climate changes, presented hereafter.

#### **Geodynamic evolution**

As stated in Section 3.4, the features observed today in the regional geological setting are explained by many geological processes (tectonic activity, glacio-eustasy, etc.). The geodynamic evolution of the Campine for the next million years can be partly evaluated based on the understanding of its past evolution (*i.e.*, type of geodynamic setting). The overall European geodynamic tectonic setting has been investigated in order to reach an adequate level of knowledge allowing the identification of a range of possible evolutions. On that basis, the overall extensional activity is likely to continue in the future, and the geodynamic evolution of the Campine Basin will be closely related to the evolution of the Roer Valley Graben (RVG). However, Boom Clay will certainly remain roughly at the same depth as today, but the thickness of the coverage layers could be slightly reduced (or increased) by a few tens of metres, similarly to what happened during the last million years, as shown by the burial curve of Boom Clay at Mol (De Craen *et al.*, 2012).

The Roer Valley Graben is one of the most seismically active zones onshore in Northwest Europe and the part of the Campine adjacent to the RVG has a higher seismic activity than the surrounding zones, in contrast to the western part of the Campine, known to be a zone of low seismic activity<sup>55</sup>. Seismic events may induce the re-activation of pre-

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55 See the seismology section of the site "Royal Observatory of Belgium" <http://seismologie.be> (Last visit: 29 May 2012).

existing faults the Roer Valley Graben. The RVG is sufficiently mature for the major faults to accommodate most of the deformation (Van Baelen *et al.*, 2006). Consequently, creation of major faults is not expected to occur in the western part of the Campine. The tectonic activity might result in the differential uplift and subsidence of individual blocks (De Craen *et al.*, 2012). Regarding the structural integrity of the repository, the influence of an earthquake at depth is generally limited in comparison with what might be observed at the surface (see Inset 11) (Dowding *et al.*, 1978) (Belgatom, 2003) (Bastiaens, 2003) (Lenhardt, 2009) (Nagra, 2010) (Passagez, 2011) (De Craen *et al.*, 2012). The effect of these processes on the properties and conditions in the disposal system must be further characterised. Next to the geological record, informing about the potential perturbations that might occur in the future, also the effect on the engineered barrier system should be studied.

**Inset 11 – Underground, they survived (Nagra, 2010)**

The city of Tangshan in China provides an example of the limited damaged in the underground compared to the surface. In 1976, an earthquake of magnitude 7.8 destroyed about 80% of all buildings (mainly made of bricks) in the city and killed several hundred thousands of people. In the underground, the situation was different, with only minor defects to caverns, catacombs and mines. None of the 30 000 miners present at 800 metres below the surface died.

Future igneous activity is not expected to occur in the Campine, although it cannot be excluded. Should igneous activity occur, magma will probably preferentially rise along pre-existing faults of the Roer Valley Graben. Moreover, possible effects on the clay properties would be limited to a few tens of metres from the igneous intrusions (Benvegnu *et al.*, 1988) (ONDRAF/NIRAS, 1994). Due to the presence of aquifers, it is likely that, in the case of magmatic activity, phreato-magmatism would occur (*i.e.*, diatremes, maars).

Schittekat *et al.* (1983) observed doming structures in the top of Boom Clay during the Kennedy tunnel construction in Antwerp near the Scheldt estuary. These shallow depth structures were interpreted at that time as resulting from a “diapiric uprising” of the clay due to a differential loading (*i.e.*, incised valley). Hobbs *et al.* studied various stress state scenarios in order to evaluate the long-term stability of the Boom Clay in function of depth. The analysis of the critical stress scenarios suggests that, while close to failure in the near-surface situation, Boom Clay is geomechanically stable at depths relevant for geological disposal (Hobbs *et al.*, 2011).

Future diagenetic processes related to temperature and pressure variations in Boom Clay are not expected to significantly change the Boom Clay properties within the next one million years. There are no significant physical/mineralogical changes expected due to subsidence/uplift (De Craen *et al.*, 2012).

## Climate changes

It is expected that climate changes will continue to occur in the future, especially at the timescale considered for the long-term management of category B&C waste (several hundred thousand years and beyond).

The PHYMOL<sup>56</sup> project, carried out in 1997–1999, investigated the impact of the past climatic evolution on the hydrology and how such an evolution could be extended towards the future (PHYMOL, 2000). This project considered that climate changes were driven by astronomical and solar forcings for the last 125 000 years. The climate effects were evaluated for the next 125 000 years based on the same forcings. The PHYMOL project concluded that, although ice caps reached the Netherlands during some severe glaciations (e.g., Late Saalian), they did not reach Belgium. Simulations of the future-climate evolution indicated no glacial inflow into the Mol–Dessel area.

Current knowledge of past climate changes, the outcomes of the discussions held at the Intergovernmental Panel on Climate Change<sup>57</sup> and the results of improved climate modelling which include anthropogenic CO<sub>2</sub> forcing in addition to astronomical and solar forcings developed in the frame of BIOCLIM project (BIOCLIM, 2003) led to conclude that, in the future, alternating warm interglacial periods and cold glacial periods would continue to occur for the next one million years, as during the Quaternary. Due to global warming and associated sea-level rise, flooding of the Campine cannot be excluded. Moreover, the first cold glacial period will be delayed and less severe. Cold weather similar to quaternary glaciations should not occur before 400 000 years due to the anthropogenic CO<sub>2</sub> contribution while the strongest future glacial maximum comparable to the Last Glacial Maximum is simulated to take place at about 890 000 years (De Craen *et al.*, 2012).

Assessing the effects of cold climate states is the subject of additional studies, such as:

- Huybrechts modelled an ice sheet development for the climatic conditions at 890 000 years in order to check if such cold conditions could lead to the development of an ice cap reaching northeastern Belgium. He concluded that the ice sheet extend should be comparable to those observed during past glacial maxima (that means, should not reach the northeast of Belgium) (Huybrechts, 2010).
- Govaerts *et al.* evaluated the penetration depth of permafrost for climatic conditions similar to the Last Glacial Maximum (with and without snow and vegetation cover) and concluded that the minimum would be about 50 metres and could reach 200 metres during the coldest stages of a glacial period (Govaerts *et al.*, 2011).

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56 PHYMOL: Palaeohydrogeological study of the Mol site (EU project).

57 Website <http://www.ipcc.ch/> (Last visit: 8 April 2013).

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#### **Roadmap – Section 4.2.1.1 – Bounded evolution, natural external events and processes (BC)**

*For later SFCs*, ONDRAF/NIRAS will continue its research on the long-term stability of Boom Clay. It will also continue refining and integrating knowledge of the burial history, through, among others, increasing the stratigraphic resolution and integrating all relevant geological studies about the Campine basin (including work from VITO, Belgian Geological Survey, Universities, neighbouring countries etc.).

*For later SFCs*, ONDRAF/NIRAS will monitor the evolution of the knowledge basis about the climate changes. It will reassess results from previous projects (such as the BIOCLIM project) in the light of current knowledge (e.g., carbon cycle). ONDRAF/NIRAS will study the influence of climate changes on Boom Clay properties and on hydrogeology (e.g., assessing the impact of pore water composition on the sorting of radionuclides in groups of elements with similar migration and retention behaviour, transport and retention processes).

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#### **4.2.1.2. Human actions**

Human actions are by essence hardly predictable. However, reasonably foreseeable human actions in the Campine include the exploration and exploitation of the underground for economic reasons. Table 15 lists the resources and uses of Campine underground.

The direct exploitation of mineral resources (for instance Boom Clay) will not affect a disposal system in Boom Clay, as these resources are available in large quantities at the surface or shallow sub-surface<sup>58</sup>.

The exploration and exploitation of other resources (such as water, geothermy and gas storage) require drilling of boreholes. Therefore, drilling is one of the main actions that can be expected. Faninbel drew up the inventory of the existing drillings in the Campine in order to assess the drilling risks in areas compatible with geological disposal in Boom Clay (Faninbel, 2011). It highlighted that the depth of the drillings increases with time, and shift towards the north with time. The exploitation of water may affect the hydrogeological system, as already evidenced by the continuous depletion of the Oligocene aquifer over time due to excessive pumping of water from this aquifer.

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#### **Roadmap – Section 4.2.1.2 – Bounded evolution, human actions (BC)**

*For confidence building*, ONDRAF/NIRAS will follow up potential uses of the Campine underground as this might play a role during the siting process. It will follow up the evolution of human interest in deep aquifers, development of pumping technology and

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58 In UK, the white paper "Managing Radioactive Waste Safely A Framework for Implementing Geological Disposal" states that industrial minerals (except evaporates) are a "low resource value, limiting the potential for economic exploitation at depth" and should thus not be applied as exclusion criteria for geological disposal (Defra, 2008).

pumping activity (number and depth of boreholes, pumping rate, etc.). It will also check future interest in coal and coal bed methane extraction, in geothermy, and in gas storage in deep geological reservoirs.

*During site selection*, ONDRAF/NIRAS will assess the consequences of foreseeable human actions in the context of conflict of use.

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#### **4.2.2. The perturbations of Boom Clay due to the excavation, construction, operation and the post-closure evolution of the repository can be bounded**

Building, operating and closing a repository in Boom Clay will induce time and space dependent perturbations of the clay (Tsang *et al.*, 2011). Furthermore, the post-closure long-term evolution of the waste and other EBS components can induce additional perturbations. This section presents the different drivers of perturbations, their impact on Boom Clay and the roadmap to reduce remaining uncertainties.

##### **4.2.2.1. Excavation and repository construction and operation**

The excavation of repository shafts and galleries inevitably perturbs the host formation. The extent of the perturbation depends on the host-formation properties and on the excavation technique (Blümling *et al.*, 2007).

At the time of SAFIR2, feasibility to excavate in unfrozen Boom Clay in Mol had already been demonstrated (Section 5.2). Since SAFIR2, special attention has been paid to the development of an excavation technique limiting the extent of the damaged zone. The resulting excavation technique, used for the construction of the Connecting (2001–2002) and of the PRACLAY (2007) galleries, is considered representative of the excavation of future disposal galleries. The galleries were constructed by an industrial method using a tunnelling machine, ensuring a smooth, circular excavation profile and the rapid placement of the lining. This method limits the required over-excavation and subsequent convergence. The high suction potential of Boom Clay also contributes to stabilise the excavation front and helps to limit the extent of the damaged zone (Section 3.3.10.6).

An extensive *in-situ* measuring programme has been set up since the start of the HADES URF construction in order to assess the mechanical perturbations induced by the excavations. Piezometers, flat jacks, various stress and displacement sensors, strain gauges provide information on the hydro-mechanical response of the clay. During excavation phases, fracture patterns have been characterised in detail at the front and along the sidewalls before emplacement of the support elements (Bastiaens *et al.*, 2007) (Van Marcke and Bastiaens, 2010). After excavation, long-term seismic and acoustic emission measurements are used to track the evolution of sealing processes. Extensions of this measuring programme occurred in parallel with excavation of new parts of HADES URF. At some locations, displacements, stresses and pore pressures have been monitored continuously for more than 30 years. Laboratory experiments (reproducing expected *in-situ* stress paths), blind predictions (which precede *in-situ* experimentation) and post-experiment modelling complete the *in-situ* programme.

The hydro-mechanical behaviour of Boom Clay is reasonably understood. Results, detailed hereafter, show that the same mechanisms consistently explain perturbations resulting from excavation of the Connecting and PRACLAY galleries and the results of many tests at different scales. They also demonstrate that the perturbations of the safety-relevant properties due to excavation have a limited extent. Comparison between the Connecting and the PRACLAY galleries, excavated in similar conditions suggests that the extent of all excavation-related perturbations is proportional to the excavated diameter.

### Stress evolution

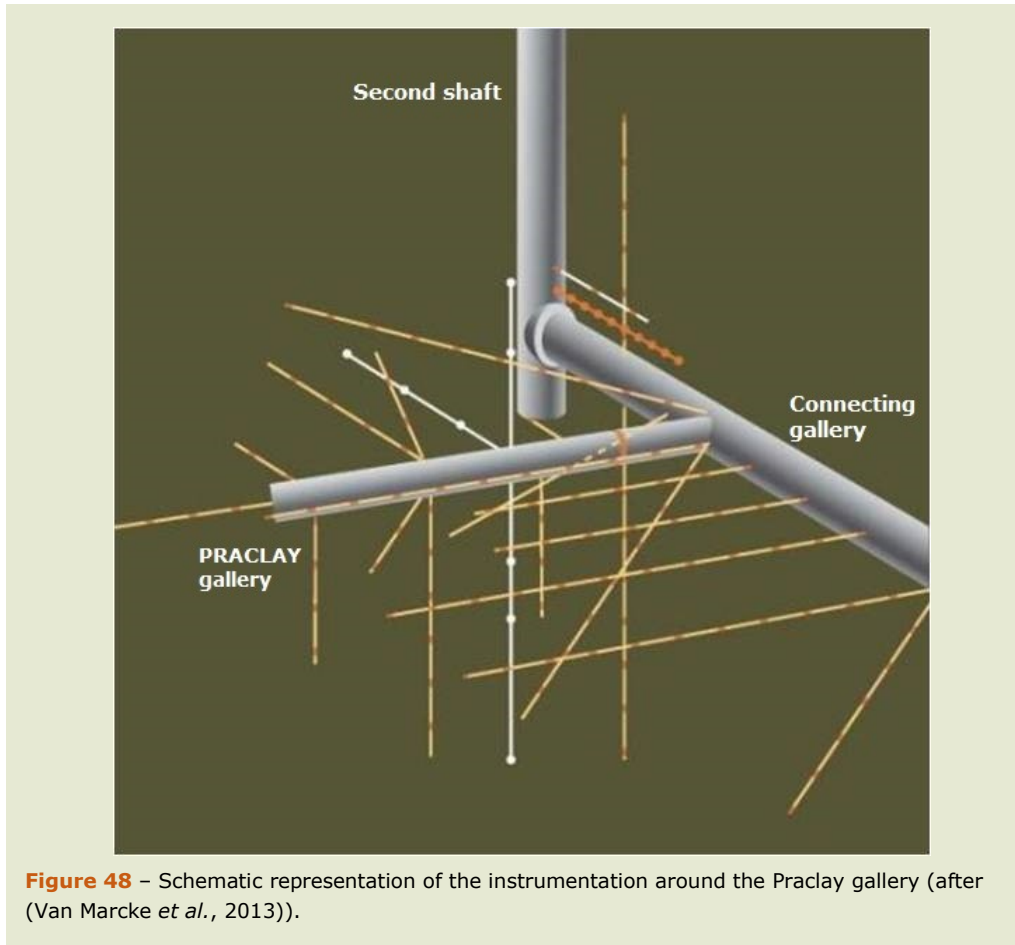
The excavation induces stress redistribution in the host formation as the clay converges towards the void left by the removed material. Classically for cylindrical excavations such as galleries and shafts, the radial stress  $\sigma_r$  decreases from the original, *in-situ* stress value to a lower value or even zero at the excavation sidewall depending on the radial convergence<sup>59</sup> of the clay towards the axis of the gallery that is allowed by the excavation technique, the time at which the support is installed and the stiffness of this support (Panet, 1995). Conversely, the circumferential stress  $\sigma_\theta$  increases with the convergence and consequently so does the deviatoric stress  $\sigma_\theta - \sigma_r$ . Except in the vicinity of the excavation front where the stress field is complex, the mean stress remains about constant provided that mechanical properties of the clay and *in-situ* stresses are reasonably isotropic.

As the deviatoric stress increases with convergence, shear failure of the clay may eventually develop near the excavation, leading to a decrease of both radial and circumferential stresses (NF-PRO, 2008).

During the excavation of the Connecting and PRACLAY galleries (MINE-BY-Tests), the measured displacements, total stresses and total stress changes are mostly consistent with this description, although a marked anisotropy is evident from the observations (Van Marcke *et al.*, 2009). The Connecting gallery was excavated from the second shaft towards the part of the underground research facility already built from the first shaft. This provided an opportunity to install in advance pore pressure, stress and displacements sensors in boreholes drilled from the end of the Test Drift towards the direction of approach of the Connecting gallery. Instrumentation boreholes were also drilled in advance from the Starting Chamber at the base of the second shaft so that various sensors could be installed around the future location of the Connecting gallery. Likewise, instrumentation was later installed around the zone to be excavated for the PRACLAY gallery in boreholes drilled from the Connecting gallery (Figure 48).

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59 Convergence, here radial, is defined as the displacement of an elementary volume of material from its original position towards the axis of the excavated gallery or shaft as a consequence of the excavation.



In the axial direction, experimental observations during the excavation of the Connecting gallery, confirmed by modelling, show that the mean total stress starts to increase about 8 metres ahead of the excavation front. This mean total stress increase results in increasing pore-water pressure. As the excavation front approaches further the point of measurement, at a distance of about 6 metres, the mean total stress begins to drop, corresponding to a plastic deformation of the clay.

The measured convergences and stresses on the lining are mostly in line with those calculated during the design of the excavation and construction of the Connecting and PRACLAY galleries using a simple engineering model (see Section 3.3.10.2). Including transverse anisotropy of *in-situ* stress and Young's modulus ( $E_{\text{horizontal}} > E_{\text{vertical}}$ ) in more advanced geomechanical models further improves the fitting of numerical results to *in-situ* observations of the hydro-mechanical behaviour of Boom Clay (see also paragraph on pore-water pressure variations hereafter).

After the emplacement of a lining, stresses around a gallery or shaft continue to evolve, albeit much more slowly than during the excavation. Generally, the load on the lining tends to increase with time:

- as the linings of the Connecting and PRACLAY gallery and of the Test Drift are not watertight, drainage of the clay slowly decreases the pore-water pressures around the underground laboratory. This results in a slow increase of effective stresses



and an increasing load on the linings. This will also be the case for a repository, during the operational period;

- over years, decades or more, Boom Clay creep will tend to reduce the deviatoric component of stresses around galleries, i.e., the circumferential stress  $\sigma_\theta$  will tend to decrease while the radial stress  $\sigma_r$  will tend to increase, again increasing the load on the lining.

The combined effects of drainage and creep have been measured in HADES and are illustrated in Section 3.3.10.7 (Figure 40).

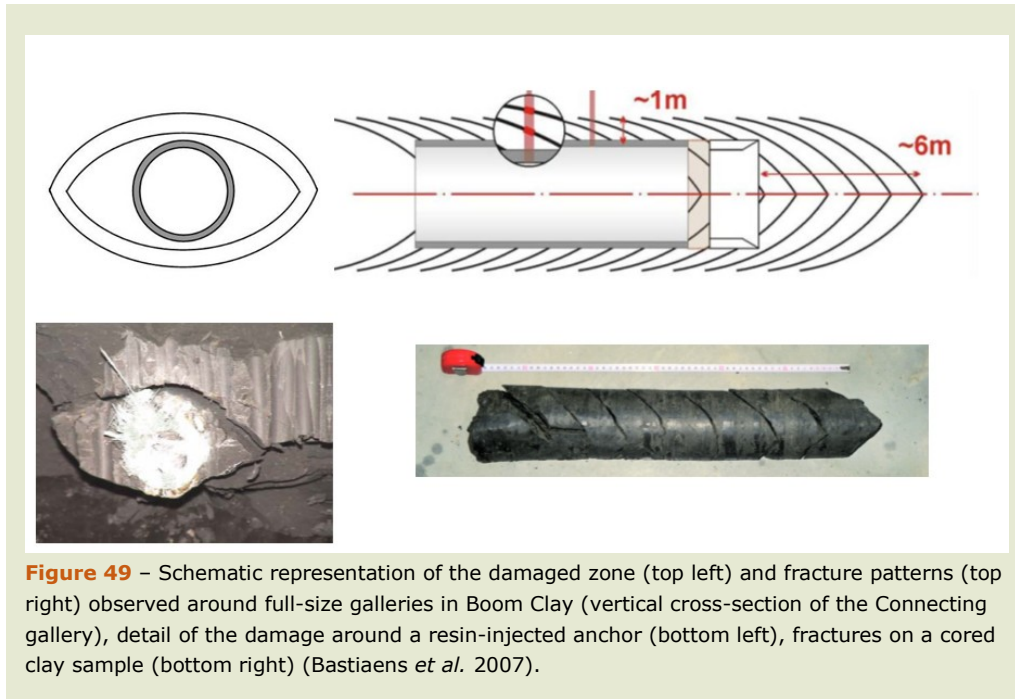
### Extent of the plastic zone and fractures

During the excavation of the Connecting gallery, it was observed that the fractures originated about 6 metres ahead of the excavation front. Close to the front, some opening of these fractures was observed because of limited movements of blocks of unloaded clay. Once fully developed, the vertical extent of open fractures, as determined by cored borings behind the rear end of the shield used for gallery excavation and construction, is about 1 metre. The distance between successive fractures is a few decimetres. The project SELFRAC led to substantial progress in fracture characterisation (SELFAC, 2007).

In case of rapid installation of the concrete lining, convergence can be limited to a few centimetres, thus further development of the fractures is effectively avoided. In the case of the Connecting gallery, the total radial convergence of the Boom Clay was about 0.09 metre on the excavated radius (2.5 metres) (Bastiaens *et al.*, 2003). The total radial convergence measured around the PRACLAY gallery was even lower.

All observed fractures are created by the excavation. This statement is based on two observations: all observed discontinuities could be traced back to underground work (Mertens *et al.*, 2004) and samples of different scales (cores, galleries) present a similar fracture pattern (see hereafter). Indeed, the fracture pattern is similar in the Connecting and the PRACLAY galleries and, at a lower scale, along cores extracted by drilling (Figure 49).

The pattern consists of two conjugated fracture surfaces: one in the upper part dipping towards the excavation direction and the other in the lower part dipping towards the opposite direction. They intersect at mid-height of the gallery where their dips reach 60° to 70°. These fracture surfaces are curved. The dips decrease to values as low as 30° with increasing vertical distance to the axis. Transversally, the zone with fractures is eye-shaped. Interestingly, an eye-shaped zone with large material deformations could also be observed in hollow cylinder laboratory tests simulating at smaller scale the excavation of gallery (François *et al.*, 2012) (Labiouse *et al.*, 2013). The long axis of this zone is parallel to the bedding planes, suggesting that material anisotropy may play an important role in the creation of this characteristic fracture pattern.



Soon after emplacement of a lining, fractures created by an excavation in Boom Clay start to close. There is no unsealed fracture network beyond (at most) a few decimetres into the host formation around HADES URF, thanks to the large self-sealing capacity of Boom Clay (Bastiaens *et al.*, 2007) (Section 4.1.2.1).

### Pore-water pressure

Excavation leads to changes in the pore-water pressure due to the volumetric deformation of the clay. Assuming that the repository will be constructed using techniques and materials similar to those used for the Connecting and PRACLAY galleries, not be watertight, the lining will not be watertight. During the operational period, the pore-water pressures will decrease in the whole massif due to drainage towards the galleries. After repository closure, within several decades, the pore-water pressure will evolve towards equilibrium with the pressure of the far field.

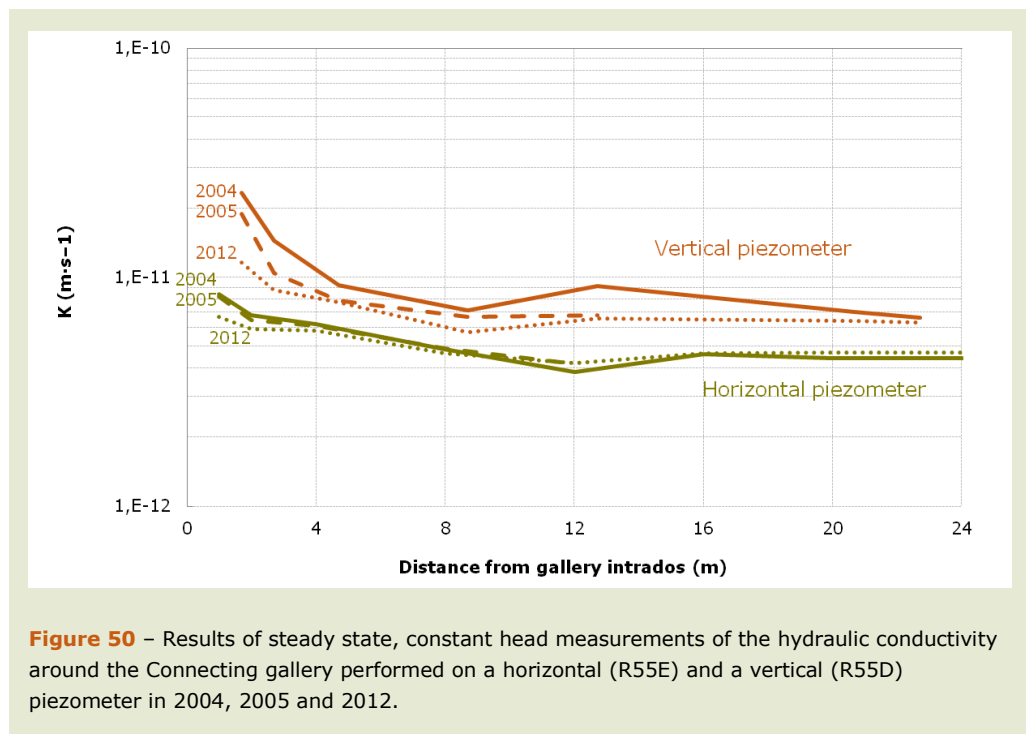
Significant volumetric deformations are not unexpected in the plastic zone and piezometric measurements performed during and after excavation of the Connecting and PRACLAY galleries indeed show a decrease of pore-water pressure, corresponding to stress relief of the clay in that zone. At close distance to the excavated zone, atmospheric pressure can sometimes temporarily be measured in some observation filters, meaning that these are connected by an open fracture to the gallery being built. In other filters close to the excavation, absolute pressure drops to zero have been observed revealing that the stress relief is such that suction appears.

While there is a general trend of pore pressure decrease in the plastic zone, limited, temporary increases of pore pressure can be observed close to the left and right sides of a gallery being excavated, corresponding with the passage of the excavation front (Wileveau and Bernier, 2008). This is probably linked to anisotropic deformations of the clay in that zone. During excavation of the Connecting gallery, small pore pressure

variations were also recorded almost instantaneously as far as 75 metres from the excavation front. These variations are believed to be due to an elastic volumetric deformation of the clay, resulting from the anisotropy of its mechanical properties.

### Hydraulic conductivity

Excavation induces a temporary increase of the hydraulic conductivity of Boom Clay. This increase is limited and generally less than one order of magnitude. Moreover, permeability in zones that have been affected by the excavation tends to evolve rapidly towards that of undisturbed clay as a consequence of the self-sealing capacity of Boom Clay. This has been evidenced at different scales, *in-situ* and in laboratory tests during the SELFRAC and TIMODAZ projects (SELRAC, 2007) (Yu *et al.*, 2011) (Chen *et al.*, 2012). Figure 50 illustrates these results, showing the evolution of hydraulic conductivity measurements around the Connecting gallery after its excavation.



The difference in far field permeability in Figure 50 is a result of the anisotropy of this property in Boom Clay<sup>60</sup>. It can be seen from the figure that, a few months after excavation<sup>61</sup>, permeability increase was less than a factor three below the gallery (R55D) and about a factor two on the East side of the gallery (R55E) and that permeability is still decreasing today, albeit more slowly than during the first months.

60 Cylindrical filters in a vertical piezometer (such as R55D) essentially measure the horizontal permeability while filters in a horizontal piezometer (such as R55E) measure a combination of the horizontal permeability and of the vertical permeability.

61 Some time was needed to install these piezometers from the newly built gallery.

## Oxidation

During the construction and operation of a geological repository, the presence of air in the open galleries inevitably leads to oxidation of the host formation. Little was known about the extent of this perturbation at the time of SAFIR2. Thanks to the current RD&D programme, it is now clear that the extent of oxidation around the galleries in Boom Clay remains more or less limited to the extent of the initially fractured zone. In the case of the Boom Clay, this is about 1 metre.

Knowledge of the extent of the oxidised zone in Boom Clay comes from *in-situ* observations and measurements and laboratory measurements (De Craen *et al.*, 2008b). In undisturbed Boom Clay pore water, sulphate and thiosulphate are generally not detected. When Boom Clay is oxidised, the oxidative dissolution of pyrite will result in the presence of sulphate and thiosulphate in the pore water. Thiosulphate, however, is metastable and will further react to form additional sulphate. Hence, sulphate is a good indicator for Boom Clay oxidation (De Craen *et al.*, 2004b) (De Craen *et al.*, 2008b). Some parts of HADES URF have been ventilated for more than 30 years and sampling from radial boreholes drilled in different parts of the gallery allows studying the evolution of the extent of the oxidised zone.

A petrographic study performed after the construction of the Connecting gallery indicates that the Boom Clay only oxidises on the fracture walls: the only evidence of pyrite oxidation, under the form of newly formed minerals, was indeed on the fracture surfaces, microfractures, and discontinuities (Van Geet, 2003b). Macroscopic investigation of samples from the northern Starting Chamber in the second shaft also clearly indicated the presence of Fe-oxides (rusty halos) around fractures (Van Geet, 2003b). A microscopical study of this clay indicated that oxidation products (mainly Fe-oxides and gypsum) were always associated with the fractures and that they were never observed in the clay matrix itself. Further experimental and modelling research in this field in the frame of the European project NF-PRO<sup>62</sup> confirmed these observations. Results of dedicated drillings in a nitrogen environment (to avoid oxidation during drilling) show that the Connecting gallery and the Test Drift present similar radial oxidation profiles despite being excavated at 15 years interval. Calculations indicate that oxygen dissolution and diffusion in the clay during ventilation does not affect the extent of the oxidised zone, even if the ventilation period lasts for tens of years. Very conservative calculations took into account only oxygen transport (diffusive and advective) (no reaction with the Boom Clay, which is completely unrealistic as Boom Clay is extremely susceptible to oxidation). Even with such assumption, results show that oxygen in-diffusion into the Boom Clay is a slow process that is moreover counterbalanced by pore water flow beyond the distance of about 1 metre (advective transport) towards the gallery (Van Geet *et al.*, 2006b). More realistic calculations included reactive transport (kinetic dissolution of pyrite; the other minerals being in equilibrium). These calculations suggest that dissolved oxygen in-diffusing into the clay is very rapidly consumed by the pyrite (Inset 12). This is consistent with the petrographic observations reported earlier (De Craen *et al.*, 2011).

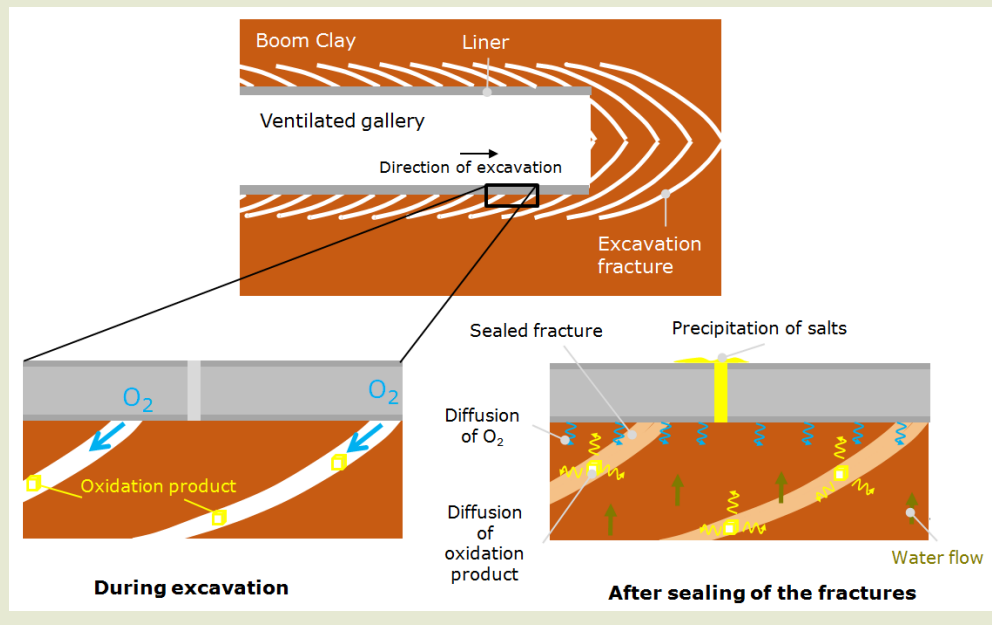
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62 NF-PRO: Understanding and Physical and Numerical Modelling of the Key Processes in the Near Field and their Coupling for Different Host formations and Repository Strategies (EU project).

### Inset 12 – Conceptual model on the oxidation in Boom Clay

RD&D results led to the development of a conceptual model on the oxidation of Boom Clay during excavation and its evolution during ventilation (schematically represented in figure hereafter) (De Craen *et al.*, 2008b):

1. During excavation open fractures are created up to about 1 metre and fast oxidation around the fractures occurs (Bastiaens *et al.*, 2005) (SELFRACT, 2007).
2. In Boom Clay, sealing of the fractures occurs fast (Section 4.1.2.1). The oxidation products are then trapped within this first metre around the gallery.
3. A combined diffusion-advection regime is present around the open galleries. Oxidation products are re-distributed and mostly transported by pore water flowing towards the gallery.
4. The dissolution and diffusion of additional oxygen from the ventilated gallery into the undisturbed Boom Clay is extremely slow as pore water flows in the opposite direction. Oxygen diffusion (into to clay) and advection (towards the gallery) cancel each other at about 1 metre.



Besides the oxidation of pyrite, the presence of oxygen may lead to the oxidation of dissolved organic matter and of kerogen, which results in breaking the aromatic chains into shorter ones, creating thus more mobile organic matter (Blanchart, 2011) (Blanchart *et al.*, 2012) (Blanchart *et al.*, 2012b).

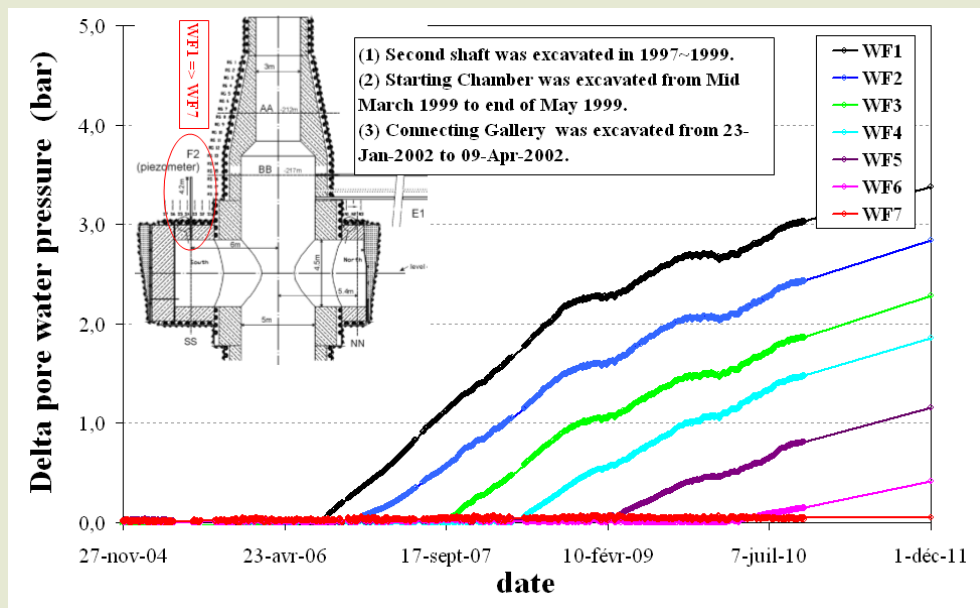
Related observations:

- A flush of sulphate (produced during oxidation) linked to the continuous water flow towards the gallery is visible in HADES URF as sulphate salts accumulate on the walls of the ventilated gallery. The sulphate-reducing microbes transforms this sulphate into sulphide, as measured in samples of Boom Clay pore water extracted from interstitial space behind the Connecting and the PRACLAY galleries (Aerts *et al.*, 2009b) (Lydmark *et al.*, 2010). This microbial activity may occur in the beginning of the operational period. However, it is expected to progressively diminish by lack of available space and diffusion-limited transport of nutrients.
- XRD patterns showed the sporadic presence of jarosite in some samples extracted from the clay close to the Connecting gallery lining soon after its excavation.

**Inset 13 – Oxidation does not hinder self-sealing (EURIDICE, 2009)**

Before the construction of the Connecting gallery, two Starting Chambers were excavated to allow the assembly of the excavation machine, leading to significant fracturing around the shaft. The fractures were open up to a depth of 2 metres behind the initial front of the Starting Chamber, as demonstrated by the oxidation of pyrite on the shear planes and by the seismic campaign (Bastiaens *et al.*, 2003). The way of excavation of this Starting Chamber was not optimised to limit the extent of perturbations and thus created a large zone of convergence. This hindered a fast self sealing as observed around gallery excavations. However, this way of working allowed checking the influence of more severe oxidation on the self-sealing capacity of the Boom Clay.

The multi-piezometer F2 was installed in a borehole drilled vertically upward from the southern Starting Chamber in 2001, thus shortly after its excavation, in a zone with open fractures. It contains seven filters for a total length of 4.2 metres. During its first years of operation, it measured atmospheric pressure illustrating a connection to a fracture network in contact with the atmosphere in the gallery and/or shaft (open fracture network). During about 2 years, the open fracture network was in contact with air. In 2006 however, the pore-water pressure started to increase indicating the self-sealing of the zone despite its oxidation (EURIDICE, 2009). This self-sealing firstly occurred in the filter the most distant from the chamber (WF-1) and propagated to all filters but one (as on 30 November 2011, see figure hereafter).



**Desaturated zone of Boom Clay**

The extent of the desaturated zone around the galleries is limited to a few centimetres at most, due to the high suction potential of the clay (strong water retention potential):

- The PHEBUS<sup>63</sup> project, devoted to the phenomenology of hydrological transfer between atmosphere and underground storage, concluded that the desaturation

63 PHEBUS: Phenomenology of hydrological transfer between atmosphere and underground storage (EU project).

zone around the galleries is limited and that the clay remains mostly saturated during the ventilation phase (Robinet and Pasquiou, 1998).

- When the temporary lining was removed from the part of the PRACLAY gallery where the seal was to be installed, the extent of the desaturated zone behind the lining was limited to a couple of centimetres (Van Marcke *et al.*, 2013).

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#### **Roadmap – Section 4.2.2.1 – Bounded perturbations resulting from excavation and repository construction and operation (BC)**

For *SFC1*, because of their potential impact on retrievability, ONDRAF/NIRAS will continue to follow up the evolution of the stresses on the lining in HADES and investigate in particular the respective roles of consolidation and creep. It will further study the mechanical properties of Boom Clay within the damaged zone, because they may condition the reaction of the clay to the swelling of Eurobitum (Section 4.2.3.4). These mechanical properties are also of importance in case of possible transport of free gas (Section 4.2.2.5).

ONDRAF/NIRAS pursues studies whose results will be integrated in *later SFCs*. Interpretation of data collected during excavation of the Connecting gallery and PRACLAY gallery using 3D-models has started. Work is also going on to refine the characterisation of material and *in-situ* stress anisotropy and their influence on the hydro-mechanical behaviour of the Boom Clay around excavations (see roadmap Section 3.3.10).

For *confidence building*, ONDRAF/NIRAS will investigate the localisation mechanisms occurring in the clay during excavation, linking these to the observed fracture patterns in the EDZ and to the anisotropy of mechanical stresses and mechanical properties.

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#### **4.2.2.2. Thermal output of the category C waste**

The *in-situ* temperature at HADES URF level is about 16°C. The emplacement of heat-emitting waste in a repository will induce thermal perturbations in the host formation during the so-called thermal phase. In the B&C programme, the thermal phase is defined as the period during which the temperature of the host formation is expected to lie above the range of temperatures within which nominal radionuclide migration properties can be relied upon<sup>64</sup>, that is to say, above 25°C. Because the largest temperature increase within the Boom Clay is always located at the interface with the EBS, this definition means that the thermal phase ends when the temperature at the outer boundary of the EBS returns below 25°C (Van Geet, 2008).

Determining the thermal properties of the host formation is essential to assess the disturbances induced by the presence of heat-emitting waste. At the time of SAFIR2, the

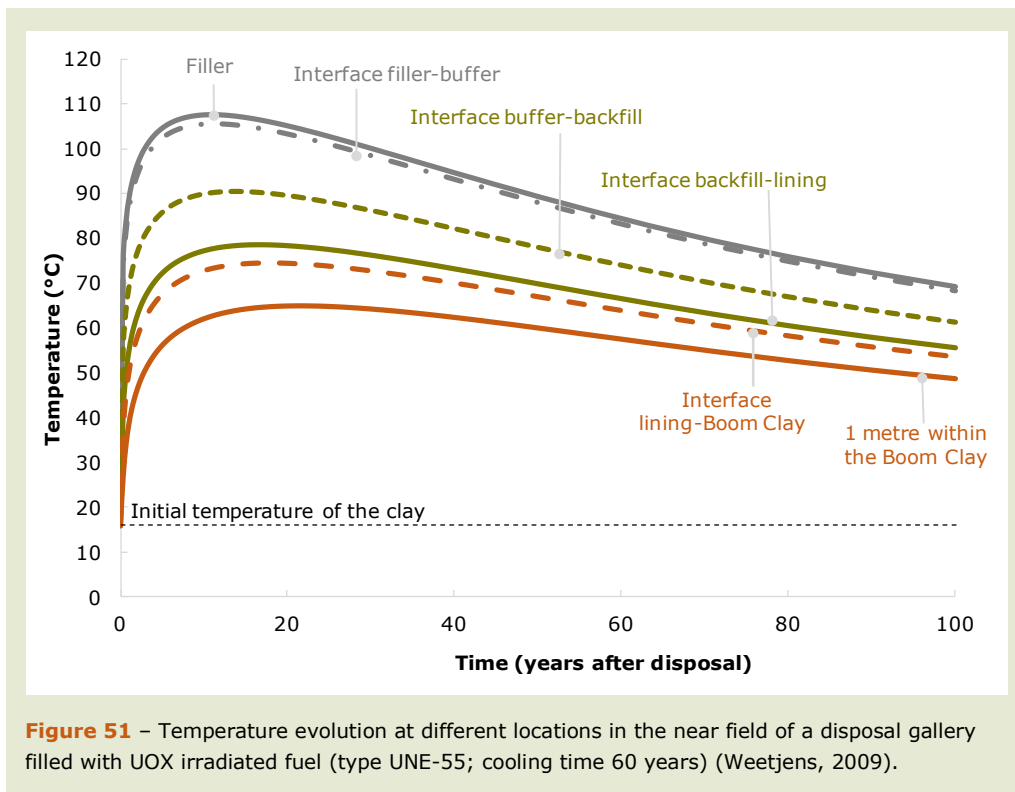
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<sup>64</sup> The thermal phase criterion is fixed at 25°C because the values for the radionuclide migration parameters have been established with sufficient confidence within the temperature range between 16°C (*in-situ*) and 25°C (laboratory).

thermal conductivity of the Boom Clay was estimated to be  $1.7 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ . Later on, back-analysis of experiments conducted *in-situ* (ATLAS I to III) indicated that the thermal conductivity is anisotropic, with a horizontal thermal conductivity of about  $1.7 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  and a vertical thermal conductivity of about  $1.35 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  for the saturated Boom Clay (Chen *et al.*, 2011).

The current repository has been designed in order to limit the temperature at the overpack on the one hand and at the interface Boom Clay-upper aquifer on the other hand. Several parameters may be modified to accommodate the heat output: the numbers of primary disposal packages in a supercontainer (valid for vitrified high-level waste and UOX irradiated fuel) and the distance between supercontainers within a disposal gallery (which controls the near-field temperature) and the distance between disposal galleries (which controls the far-field temperature). For all practical purposes, the resulting evolution of the temperature distribution in Boom Clay does not depend on thermal properties of the EBS, due to the comparatively low thermal capacity of this latter (Weetjens and Sillen, 2005).

The near-field temperature evolution has been assessed for the current reference design by Weetjens (Weetjens, 2009). Heat transport simulations are done with an axisymmetric model of a (infinitely) long gallery full of supercontainers, without interspaces between them. In the case of UOX irradiated fuel for which a waste cooling time of 60 years before disposal is assumed, simulations show that the temperature of the Boom Clay close to its interface with the gallery lining peaks at about  $78^\circ\text{C}$  ( $\Delta T$  about  $62^\circ\text{C}$ ) around 20 years after disposal (Figure 51). Given the spacing of galleries for category C waste, the influence of neighbouring galleries is still negligible at that time.

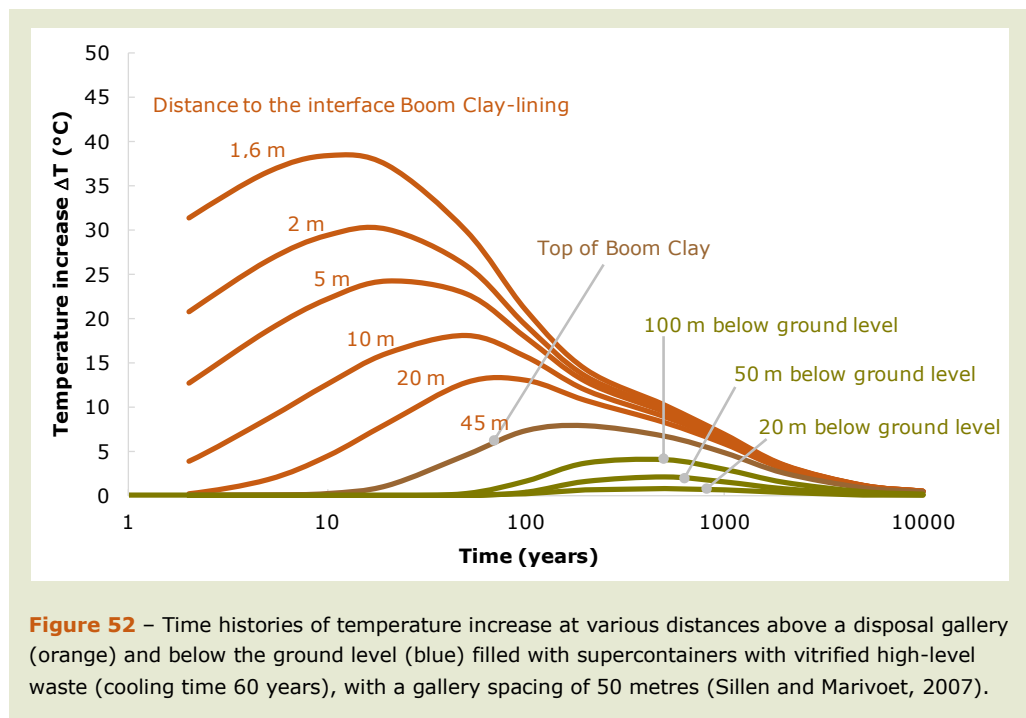


**Figure 51** – Temperature evolution at different locations in the near field of a disposal gallery filled with UOX irradiated fuel (type UNE-55; cooling time 60 years) (Weetjens, 2009).



To assess the long-term evolution of temperatures in the clay, a model that represents interactions between different galleries is required (Sillen and Marivoet, 2007). While the temperature peaks rapidly at the interface between the EBS and the Boom Clay, it then decreases gradually as the heat source decays. The temperature returns to temperatures inferior to 25°C after about 700 years for vitrified high-level waste (VHLW, Figure 52) and after a few thousand years in the case of irradiated fuel depending on burn-up and fuel type (UOX or MOX). The observed differences in duration to reach the end-of-thermal phase criterion temperature for the different waste forms are due to the significant differences in the actinide inventory (especially  $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$  and  $^{241}\text{Am}$ ) and hence in the amount of decay heat released by the different waste forms (Weetjens, 2009).

As can be seen in Figure 52, the maximum temperature increase at the interface Boom Clay-upper aquifer does not exceed 10°C after about 150 years for vitrified high-level waste (Sillen and Marivoet, 2007), which satisfies the environmental criterion. (In the case of Boom Clay, the temperature of its upper aquifer – the Neogene aquifer – may not exceed 25°C (Ecorem, 2008) (Chapter 8).)



RD&D is going on for 30 years in order to assess the impact of the thermal output on Boom Clay properties and processes. In particular, attention is paid to properties and processes that may be permanently affected by the thermal load. (During the thermal phase, all radionuclides are still contained by the overpack in the reference scenario.) In the TIMODAZ project, the influence of temperature on the evolution of the disturbed zone and the impact of that evolution on the performance of the disposal system have been investigated. Current results are detailed hereafter. They show that most effects of thermal loading and unloading are temporary.

### Effect on clay fraction

The thermal load will not affect Boom Clay's clay fraction. This statement is supported by multiple lines of evidence in the field of geology, including natural analogues:

- Based on available experimental and natural analogue data, Wersin *et al.* reviewed data on thermally-exposed bentonite. They identified two main processes due to the heat: illitisation, which is the transformation of smectite to illite, and cementation by precipitation of SiO<sub>2</sub>. They conclude that several conditions, among which a temperature of 150°C, are required before significant illitisation and cementation occur (Wersin *et al.*, 2007).
- Pusch *et al.* confirmed the validity of a semi-empirical model that shows that there is no significant illitisation of dense smectite-rich clay during the thermal phase of a repository for a standard value of the activation energy and a temperature lower than about 100°C (Pusch *et al.*, 2010).

In the framework of the B&C programme, there is no observation of mineralogical changes that can be attributed to thermal loading of the clay. At the time of SAFIR2, the CERBERUS<sup>65</sup> experiment indicated that no significant changes in Boom Clay mineralogy occur with temperature (for the temperature range that will be reached around the disposal galleries containing heat-emitting wastes). This experiment studied *in-situ* the effects of disposal of heat-emitting waste on Boom Clay. Such a package was simulated by electrical heaters that increased the temperature in the argillaceous formation to over 100°C in places. After five years of heating, the mineralogy and geochemistry of the Boom Clay are not significantly modified by radiation or by a temperature increase (ONDRAF/NIRAS, 2001).

The same conclusion was achieved in the frame of the TIMODAZ project: samples of Opalinus and Boom Clay did not present significant mineralogical modifications after being exposed a year at 90°C under conditions representative of those present in a disposal system (Honty *et al.*, 2012b).

### Effect on permeability

The effect of temperature on the permeability of clays has been investigated in both constant volume and constant isostatic stress conditions. Tests in a nearly-constant volume permeameter performed on Boom Clay and Opalinus Clay by SCK•CEN for TIMODAZ show that, while the hydraulic conductivity increases with temperature due to the decrease of water viscosity, the intrinsic permeability remains basically unchanged (Chen *et al.*, 2010) (Delage *et al.*, 2012). Tests performed under various confining stresses also show that the intrinsic permeability does not increase with temperature (Delage *et al.*, 2000). In fact, some tests performed in constant effective stress conditions suggest that the permeability may even decrease because of thermal consolidation of the samples (Baldi *et al.*, 1991).

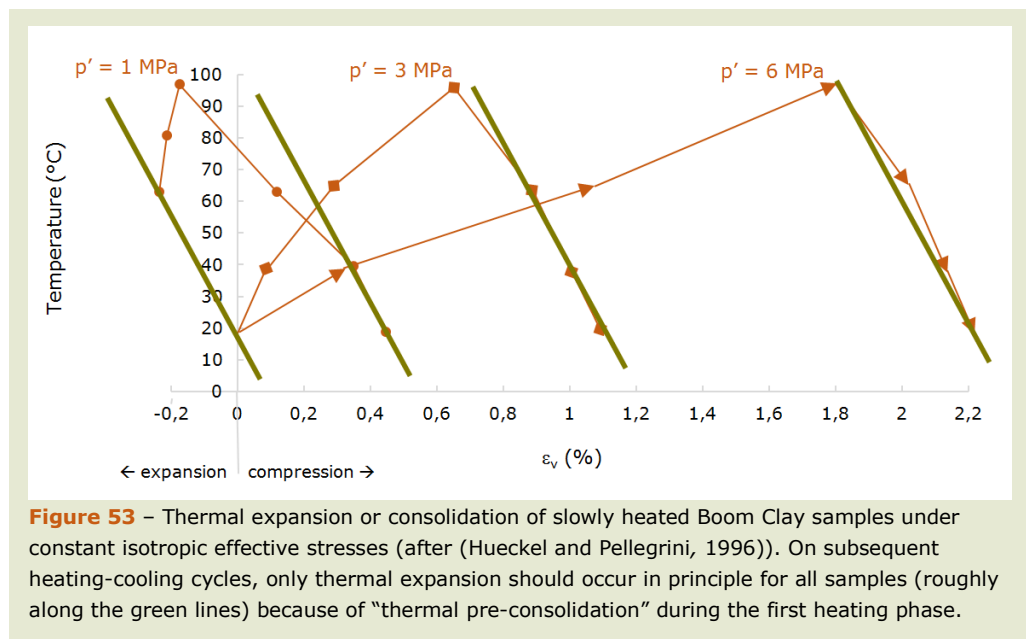
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65 CERBERUS: Control Experiment with Radiation of the BElgian Repository for Underground Storage) (EU project).

### Effect on mechanical properties of the clay

Boom Clay is thermo-plastic, which means that its elastic domain tends to become smaller as temperature increases. In other words, all other things being equal, a sample of Boom Clay which is in hydro-mechanical equilibrium at a given confining stress may start to develop plastic deformations when the temperature is increased, even if this temperature increase is gradual enough and the sample is adequately drained to avoid any significant pore-water pressure change and thus also in absence of significant change of the effective mean stress. This thermo-plastic behaviour has been studied by (Baldi *et al.*, 1991) and (Hueckel and Pellegrini, 1996) among others before SAFIR2. Additional tests have been performed by (Delage *et al.*, 2000) (Delage *et al.*, 2004) in support of the development of constitutive models aiming at reproducing the thermo-hydromechanical (THM) behaviour of Boom Clay (see (Hueckel *et al.*, 2009), for a discussion of such a model). Laboratory tests performed during these studies have shown that for drained samples and gradual temperature increases, the thermal load can result in a thermal expansion or a thermal consolidation (or an expansion followed by a consolidation above a threshold temperature), depending on the pre-consolidation stress applied on the sample before heating, as illustrated in Figure 53 (Hueckel and Pellegrini, 1996).

It has also been observed that an increase of the temperature also increases the creep rate of Boom Clay (Section 3.3.10.7) (Le *et al.*, 2012).



### Effect on stresses and pore-water pressures

In repository conditions, the temperature increase rate is determined by the waste type (amounts and decay rates of heat-emitting radionuclides) and by the thermal properties of the clay (thermal conductivity and capacity). Close to the repository, the temperature increase is quite fast and, due to thermal expansion of water and the low permeability of clays, some increase of the pore-water pressure around the disposal galleries is unavoidable. Modelling of true repository conditions is necessary to investigate whether

this increase of pore pressure combined with thermal stresses and thermo-plasticity can lead to additional damage or damaged zone extension. Measurement results from the simple *in-situ* heater test ATLAS (De Bruyn and Labat, 2002) (Garitte *et al.*, 2012) suggest that the effective stresses will remain compressive as the total stresses tend to increase with the pore pressures. Large heater experiments such as PRACLAY should allow confirming the small-scale tests and modelling results in repository-representative configurations (Sillen, 2012).

While the hydro-mechanical behaviour of clays can be quite subtle under thermal loading, the available models show that a consistent theoretical framework exists to explain the observations as shown by (Hueckel *et al.* 2009).

### **Effects on self-sealing capacity**

In TIMODAZ, self-sealing laboratory experiments using pre-fractured clay samples have been performed at elevated temperatures (tests up to 80°C). Compared to tests at ambient temperature, no reduction of the sealing capacities of clay samples was observed. On the opposite, laboratory test results indicate a faster sealing of the fractures (Chen *et al.*, 2013).

The sealing capacity of Boom Clay is linked in part to its swelling capacity, which relies on the clay mineralogy, especially the content of smectite that is not expected to be significantly modified as mentioned earlier (Honty *et al.*, 2012b). At higher temperature, pore water is more mobile as viscosity decreases, which might accelerate the sealing process. As mentioned earlier, creep is also enhanced by an increase of temperature and it may also contribute to the faster self-sealing.

### **Effects on organic matter decomposition**

The heating of Boom Clay leads to a degradation of its organic matter. As large organic molecules are broken in smaller ones, the hydrosoluble fraction increases (Blanchart, 2011) and CO<sub>2</sub> is also produced (Deniau *et al.*, 2005). This production of CO<sub>2</sub> can potentially perturb the chemistry of the Boom Clay pore water. This perturbation will depend on the quantity of produced CO<sub>2</sub>, the buffering by Boom Clay components such as carbonates and the diffusive transport of species whose concentrations are locally increased due to CO<sub>2</sub> (Deniau *et al.*, 2005).

Interestingly, the quantities of CO<sub>2</sub> produced by heating slurries of bulk Boom Clay or by pyrolysis of bulk clay components are higher than the production of CO<sub>2</sub> by pyrolysis of kerogen isolated from the Boom Clay (Michels *et al.*, 2010). This suggests that the presence of minerals found in Boom Clay either enhances the thermal decomposition of organic matter or that these minerals also release some CO<sub>2</sub> when heated. Modelling and additional experiments are being carried out to test these hypotheses.

## Uplift

The disposal of heat-emitting waste will lead to the thermal expansion of the Boom Clay and of the surrounding geological layers. Although there are currently no regulatory limits for uplift – increase of the elevation of the ground –, Sillen and Marivoet performed an assessment of this thermal expansion, considering the disposal of irradiated fuel and vitrified high-level waste in a repository corresponding to the current design (Sillen and Marivoet, 2007). The maximum uplift of the ground level above the geological repository is estimated to be about 10 centimetres in case of irradiated fuel disposal and 15 centimetres in case of vitrified high-level waste and occurs respectively about 125 years and 60 years after disposal. This uplift should be relatively uniform over the repository area (no localised differential uplift). However, only thermo-elastic calculations have been performed so far. Including the thermoplastic behaviour of Boom Clay in the models will probably lead to lower uplift estimates but the uncertainty in such uplift calculations would be considerable based on the data available today. More information on this field is expected from the PRACLAY experiment.

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### Roadmap – Section 4.2.2.2 – Thermal output (BC)

ONDRAF/NIRAS will include the first results from the PRACLAY Heater Test (Annex A4) *in SFC1*. This test intends to confirm the capacity of Boom Clay and the gallery linings to support the thermal load imposed by heat-emitting waste and, in particular, to verify that the clay will not be destabilised by the thermal transient and that its permeability will not be significantly affected.

*For SFC1*, ONDRAF/NIRAS will also re-evaluate the uplift above a repository for heat-emitting wastes using a more realistic model and results from laboratory experiments. For later SFCs, the model will be further adapted to include knowledge gained from the PRACLAY Heater Test and from the thermal properties of layers surrounding the Boom Clay (see roadmap Section 3.4.1).

ONDRAF/NIRAS will start studies whose results will be integrated *in later SFCs*:

- It will check the validity of the thermo-hydromechanical (THM) models of Boom Clay behaviour at the scale of disposal galleries, by comparison with the measurements around the PRACLAY gallery and further develop them if necessary.
  - It will study the thermal decomposition of organic matter upon heating and production of CO<sub>2</sub>, in order to clarify the role of the buffering capacity of Boom Clay with respect to the CO<sub>2</sub> produced. Will the production of small organic molecules by the thermal degradation of organic matter significantly increase the amount of mobile organic matter in Boom Clay?
  - It will investigate the possible dissolution/precipitation of carbonates near a gallery with heat-emitting waste.
-

#### 4.2.2.3. Alkaline plume

The interaction between the host formation and the high-pH materials used to build the repository will lead to the formation of an alkaline plume around the repository. Research has been carried out to characterise and understand this plume and predict its extent.

The experimental programme involved laboratory migration experiments, *in-situ* tests of cement-clay interactions, and batch tests to study the alteration of clay mineralogy at an alkaline pH. These experiments aimed to study the alkaline plume perturbation in the Boom Clay in terms of mineralogical alteration, evolution of pore-water chemistry and solute transport properties. They also provide input data for modelling.

The nature of the alkaline plume is relatively well understood: the hyperalkaline concrete pore fluid will diffuse into the host formation and react with Boom Clay minerals and pore water:

- Within the disturbed zone, the alkaline plume will dissolve clay minerals and result in precipitation of calcium-silicates-hydrates phases (C-S-H phases), zeolites, and calcite phases (Honty *et al.*, 2010c). In particular, experiments show dissolution of smectite by the cement water with high alkali concentrations and high pH (13.5). Experiments show that pyrite was well preserved after Boom Clay cores were infiltrated with cement waters. The original  $\text{NaHCO}_3$  type of pore water will turn to  $\text{Ca}(\text{OH})_2$  dominated water with an elevated pH.
- Laboratory percolation experiments indicate that natural organic matter near the cement-Boom Clay interface may be remobilised and flushed away from the interface into the Boom Clay.
- The  $\text{CO}_2$  will diffuse, driven by the relatively high partial pressure within the Boom Clay, towards the cementitious repository and react with the high concentration of calcium from concrete to form calcite at the interface of the repository and the Boom Clay (Wang *et al.*, 2010).

Reactive transport simulations have been performed based on the experimental results (Wang *et al.*, 2010) complemented with literature data. These simulations take into account geochemical processes including mineral dissolution/precipitation, ion-exchange, surface complexation and transport processes including advection and diffusion. First, short-time and small-scale simulations have been carried out to support the interpretation of laboratory percolation experiments with concrete waters at different pH through undisturbed Boom Clay cores. Then, long-time and large-scale simulations were carried out to determine the possible spatial extension of the alkaline plume around a disposal gallery.

In addition to detailed simulations of the evolution of the alkaline plume, simple mass balance estimations were also performed to determine the maximum extent of Boom Clay that might be disturbed by the EBS, considering that all cement degrades and that its degradation products fully react with Boom Clay components. This use of mass balance constraints helps to increase the confidence in estimating the extent of an alkaline plume perturbation caused by complex processes and highly coupled phenomena (Wang *et al.*, 2010).

### Extent of alkaline plume

The alkaline plume will grow very slowly and its extent will be limited. In fact, it cannot be observed (yet) around the sections of HADES URF with concrete lining. During the ECOCLAY II<sup>66</sup> project, samples from the interface between a 10-year old shotcrete shield and oxidised Boom Clay at the end of the Test Drift have been submitted to mineralogical analyses for determination of the extent of the alkaline front. “*No clear cement/clay interface could be studied at the level of several micrometres*” (ECOCLAY II, 2005).

The results of reactive transport simulations based on the reference supercontainer design indicate that the zone perturbed in Boom Clay, that means the zone with a pH higher than 8.5 (initial pH is 8.3), should not extend beyond 2.5 metres at most after 100 000 years in contact with cement (Wang *et al.*, 2010). This order of magnitude is consistent with simple, conservative mass balance calculations, which indicate a maximum extent of about 3 metres. The results of reactive transport simulations are sensitive to values of parameter which are not always well characterised. Using less conservative values of these parameters, much smaller extents of the alkaline plume are calculated. These results can be compared with results from Gaucher *et al.* whose simulations of the diffusion of an alkaline plume from concrete into a bentonite clay barrier indicate that the extent of the perturbation after 100 000 years is limited to a few centimetres (Gaucher *et al.*, 2004).

### Properties of the disturbed zone and impact on solutes transport

- Hydraulic conductivity: A slight increase (less than a factor two) of the hydraulic conductivity is observed in percolation experiments with young-cement water at pH 13.2. The opposite is seen in experiments with evolved-cement water at pH 12.5, that is, a slight decrease (about 20%) in hydraulic conductivity. These slight variations in hydraulic conductivity are in line with the observed alterations in the experimented clay cores. They are explained by the expected evolution of the porosity.
- Porosity: Calculations suggest that there is a slight increase of porosity, followed by a decrease to a value lower than the original one:
  - ▶ The porosity first increases due to the dissolution of minerals;
  - ▶ Porosity occlusion in the long term: the total volume of minerals as a result of cement-clay interaction is generally higher than the original dry volume of the clay so the pore volume of the altered clay becomes smaller than the original porosity of the unaltered clay. This decrease in porosity is observed in laboratory experiments and natural analogues.
- Retention
  - ▶ Actinides and lanthanides are strongly sorbed on host formation minerals under a hyperalkaline condition. Newly formed secondary minerals as a result of cement-clay interactions such as C-S-H and zeolite phases are

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66 ECOCLAY II: Effects of Cement on Clay barrier performance (EU project).

- strong sorbents for radionuclides. Co-precipitation of radionuclides with carbonation products such as calcite will immobilize radionuclides.
- ▶ There are indications that strontium is not retarded within the zone disturbed by the alkaline plume. By extension, the sorption of alkaline earth elements might thus be reduced (compared to undisturbed clay).
  - ▶ The alkaline plume is expected to flush out the organic matter, which could affect the transport of some radionuclides (Section 3.3.9).
- $E_h$ : The original reducing redox potential of the Boom Clay is not expected to be negatively impacted by an alkaline plume as experimental results show no signs of oxidation of pyrite, the primary redox buffering mineral of the Boom Clay.
  - Diffusion coefficient: There is no observable effect on diffusion in experiments regarding with tritiated water and iodine used as tracers. Comparable apparent diffusion coefficients ( $D_{app}$ ) are obtained from experiments with hyperalkaline water and from experiments on undisturbed Boom Clay.

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### Roadmap – Section 0 – Alkaline plume (BC)

For *SFC1*, ONDRAF/NIRAS will check whether the host rock retain its self-sealing capacity even after perturbation by an alkaline plume (roadmap Section 4.1.2).

For *confidence building*, ONDRAF/NIRAS will assess the consequences of the alkaline plume on the hydro-mechanical properties of Boom Clay. It will analyse the porosity changes in the zone affected by the alkaline plume and the properties of the interface EBS/clay.

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#### 4.2.2.4. Disposal of Eurobitum

The Eurobitum wastes are essentially composed of a mixture of salts (mostly  $\text{NaNO}_3$ ) and hard, blown bitumen. Upon hydration with groundwater, this waste swells and can exert significant pressures on its surroundings while it will simultaneously release large amounts of dissolved  $\text{NaNO}_3$ . A discussion on how the RD&D programme can address these perturbations of the clay and the associated interdependent processes can be found in (Valcke *et al.*, 2009). Salient results of the programme are briefly presented below.

#### Effects of the $\text{Na}^+$ and $\text{NO}_3^-$ releases

The contact between pore water and Eurobitum will result in leaching of the embedded hydrosoluble salts, mainly  $\text{NaNO}_3$ . The effect of a  $\text{NaNO}_3$  plume on the transport properties of the radionuclides in the clay is studied in combined  $\text{NaNO}_3$  percolation and radionuclide pulse injection tests. Batch tests (both in abiotic and biotic conditions) assess the influence of a  $\text{NaNO}_3$  plume on the redox properties. Some of these percolation experiments last for more than 10 years.



All tests results suggest that the perturbation of the Boom Clay due to the NaNO<sub>3</sub> plume is limited. The Boom Clay is transformed into a clay with a high-sodium occupancy, as expected. Reactive coupled transport modelling was used to describe the experimentally observed elution curves for cations at the outlet of a percolation cell (Martens *et al.*, 2011), with use of cation exchange parameters previously determined on non-perturbed Boom Clay (De Craen *et al.*, 2004). The model could fairly well reproduce the observed cation concentrations.

The increase of ionic strength with increasing NaNO<sub>3</sub> concentration has a limited effect on the permeability: percolation experiments reveal a limited, temporary increase of permeability (by a factor two at most) at the beginning of the injection of NaNO<sub>3</sub> water. Tracer tests with tritiated water, iodine and bicarbonate also show limited variations of the migration parameters. Abiotic batch tests show that there was no significant reduction of nitrate in the clay in the absence of microbes (Mariën *et al.*, 2011), and thus no significant oxidation of Boom Clay components. Biotic batch tests are still going on to assess the effect of microbes in disposal conditions.

The influence of sodium will be limited under real disposal conditions. Concentration of Na<sup>+</sup> and NO<sub>3</sub><sup>-</sup> lower than those used in the laboratory experiments are expected and concentration variations will proceed much slower than in these experiments. Weetjens *et al.* calculated the maximum concentrations of Na<sup>+</sup> and NO<sub>3</sub><sup>-</sup> in the repository near field, assuming congruent release at constant rate of Na<sup>+</sup> and NO<sub>3</sub><sup>-</sup> and diffusive transport (Weetjens *et al.*, 2010). Results show that the perturbation due to sodium is limited: the calculated sodium concentration at the gallery interface with Boom Clay is only about 4 times higher than the background sodium concentration in Boom Clay, due to its sorption on C-S-H phases of the cement in the near field and on clay, and decreases rapidly with distance.

The influence of nitrate has also been assessed. With realistic NaNO<sub>3</sub> source terms, the calculated NO<sub>3</sub><sup>-</sup> concentrations reach a maximum between 0.5 and 1 mol·L<sup>-1</sup> at the gallery interface, and rapidly decrease with distance (The concentration is as low as 0.1 mol·L<sup>-1</sup> at a distance of 5 metres in the Boom Clay) (Weetjens *et al.*, 2010). In these simulations, nitrate is considered to be not sorbed on concrete nor Boom Clay. On the opposite, assuming a (unlikely) fast and complete oxidation of the clay components by nitrate, Bleyen *et al.* have calculated the extent of Boom Clay that could be affected due to oxidation by nitrate is less than 3 metres. In the case of a slow reaction over the whole thickness of the Boom Clay, less than 1% of the Boom Clay redox capacity would be destroyed (Bleyen *et al.*, 2013).

Regarding actinide migration properties, geochemical calculations are under way. Preliminary results suggest that nitrate does not affect the speciation, nor the solubility of uranium (IV/VI) and neptunium (IV).

The NaNO<sub>3</sub> plume is not expected to strongly interact with the alkaline plume, due to their different timing of occurrence, combined with the low concentration of additional sodium in the clay (as it is sorbed in the EBS) and the absence of reactivity of nitrate with the main species present in the alkaline plume.

The investigation of the effects of the NaNO<sub>3</sub> plume on Boom Clay mechanical properties is under way.

### Effects of the swelling of Eurobitum

After disposal, upon availability of water, hygroscopic salts embedded in the bituminised waste will absorb water, resulting in the swelling of the waste and subsequent geo-mechanical perturbation of the clay. The osmosis-driven water uptake and swelling of Eurobitum is fairly well understood (Valcke *et al.*, 2009) (Mariën *et al.*, 2012) (Mariën *et al.*, 2012b). The complex set of processes is studied through small-scale water uptake experiments in constant volume or (nearly-) constant stress conditions. The Boom Clay and the EBS surrounding the bituminised waste being deformable, the actual conditions in a repository should indeed lie between these two extremes. These tests are performed in oedometer cells (see also Section 4.2.3.4 for a more detailed description of the processes involved in the water uptake and swelling). The test results confirm that water uptake by Eurobitum is a very slow process – the hydration front in experiments running for years has moved from less than one centimetre –. The experiment has also shown that Eurobitum waste has a high swelling potential and, provided that the bitumen matrix acts as a semi-permeable membrane all along the hydration process, fully hydrated waste forms may possibly exert large pressures on – or induce large deformations to – their immediate surroundings (Valcke *et al.*, 2010). In order to optimise the linear loading of disposal galleries (drums per m'), a constitutive model of the swelling Eurobitum is being developed (Mokni *et al.*, 2011), based on the small-scale laboratory swelling experiments. In parallel, the capacity of the clay to withstand the swelling pressures and deformations imposed by the waste is further investigated by EURIDICE.

Based on the results of water uptake experiments and insight gained from modelling, three successive phases are identified in the interaction between Eurobitum and Boom Clay in disposal conditions:

- 1/ Free swelling phase after closure of the gallery. The volume of the waste will increase until the free volume in the drums (about 20%) is filled.
- 2/ Restricted swelling phase. Once the free volume in the drums is filled, an increasing osmotically-induced pressure will be exerted by the bitumen on the Boom Clay through the intermediate of monolith B, backfill and lining, which will result in a gradual deformation of the formation surrounding the disposal gallery.
- 3/ Reconsolidation phase. During this phase, the concentration of the NaNO<sub>3</sub> solution in the highly leached waste and the osmotic efficiency of the deformed bitumen matrix is low enough for the waste to be recompressed by the surrounding materials. The stress on Boom Clay is then progressively reduced as it re-converges around the now shrinking waste (surrounded by degraded EBS components).

A major finding of the RD&D programme is that the geo-mechanical perturbation due to the uptake of water by the salts will not induce unacceptable damage to Boom Clay, from a mechanical viewpoint, as long as the number of drums per cross-section is limited. A so-called Eurobitum characteristic is calculated representing the osmotic pressure that can be generated by the waste as a function of its swelling assuming conservatively that all NaNO<sub>3</sub> crystals in the Eurobitum participate at once in the water uptake process and that the bitumen matrix acts as an ideal semi-permeable membrane (Valcke *et al.*, 2010). This Eurobitum characteristic describes the evolution of the swelling pressure exerted by the bituminised waste on its surroundings as a function of its volume increase: if no deformation is allowed, this pressure can be very high (about 43 MPa) but the swelling pressure decreases if some swelling of the waste is allowed.

Similarly, a Boom Clay characteristic is calculated, describing the relationship between the radial stress exerted on Boom Clay by the swelling waste (via the EBS components) and the corresponding radial displacement of the EBS/clay interface, which can be converted in an increase of the diameter of the gallery and thus also in an increase of the volume of the swelling Eurobitum. The maximum contact stress at the interface between the EBS and the clay can then be calculated for different number of drums per monolith based on these characteristic curves and equilibrium considerations.

Combining these simplified calculations with the other studies allowed concluding that the disposal of five drums per gallery cross-section is acceptable. This value of five drums is conservative as the mechanical perturbation of the Boom Clay by the swelling waste is overestimated. Indeed, bitumen is considered to behave as a perfect semi-permeable membrane to calculate the osmotic pressure of the waste and it is assumed that all NaNO<sub>3</sub> crystals contribute at once in the water-uptake process (Mariën *et al.*, 2013).

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#### **Roadmap – Section 4.2.2.4 – Disposal of Eurobitum (BC)**

The knowledge of the impact of disposal of Eurobitum on Boom Clay is sufficient for the purpose of SFC1. Modelling has indeed shown that, when the number of drums per monolith B is limited, the swelling of bitumen does not induce additional damage to the clay.

Several long-term studies are going on, whose results will be integrated *in later SFCs*:

- To confirm the compatibility of the bitumen matrix with disposal in Boom Clay. It focuses on the evolution of the swelling pressure of bitumen in repository conditions. This test will allow determining the number of Eurobitum drums to be placed per monolith B in a more realistic way.
- To continue investigating the effects of nitrates – including those resulting from microbial-mediated reactions –, on Boom Clay and to verify that the results obtained for each component separately are still valid for a natural Boom Clay mixture.
- To check whether near-field conditions around a disposal gallery with Eurobitum waste can affect the speciation of radionuclides sensitive to redox potential, as this may affect their transport properties.
- To confirm that the mechanical properties of Boom Clay and of Boom Clay affected by a NaNO<sub>3</sub> plume are comparable.

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#### **4.2.2.5. Gas**

The generation of gas is inevitable after closure of the disposal gallery, due to anaerobic corrosion of metals, radiolysis, microbial degradation of organic waste and radioactive decay. Preliminary assessments performed for SAFIR2 indicated that gas transport was a potential issue. Initially, gas generated in the near field of a geological repository in clay will dissolve in the pore water and will be transported away from the repository by

diffusion as dissolved species. However if the gas generation exceeds the capacity for diffusive transport of dissolved gas, a free gas phase will be formed, leading to a gas pressure build-up (Yu and Weetjens, 2009) and eventually to gas breakthrough events. During gas breakthrough, some water could be displaced by the gas phase. Depending on the timing of gas breakthrough, dissolved radionuclides and contaminants could be driven through the disposal system and, ultimately, out of the clay faster than by the normally expected diffusive transport of these radionuclides and contaminants.

The peer review of SAFIR2 advised to consider the issue of gas from the disposal of category B waste as a priority in the RD&D programme (NEA, 2003). ONDRAF/NIRAS has then developed a multi-step, iterative, cross-disciplinary approach to evaluate the gas issue consisting of several steps for representative waste types:

1. Identification of main gas sources;
2. Quantification of gas production and production rate;
3. Estimation of the diffusive removal capacity of the system for dissolved gas;
4. Comparison of results from points 2 and 3.

If the comparison in (4) indicates that, for some waste and EBS combinations, the formation of a free, pressurised gas phase seems unavoidable, a conceptual model for free gas transport may be needed. Thus, in parallel to these steps, RD&D on possible transport modes of free gas through Boom Clay and EBS components is currently being carried out, among others in the EU project FORGE<sup>67</sup>. Results of the four-step approach above are detailed in (Yu and Weetjens, 2012b) and are synthesised hereafter for different types of waste.

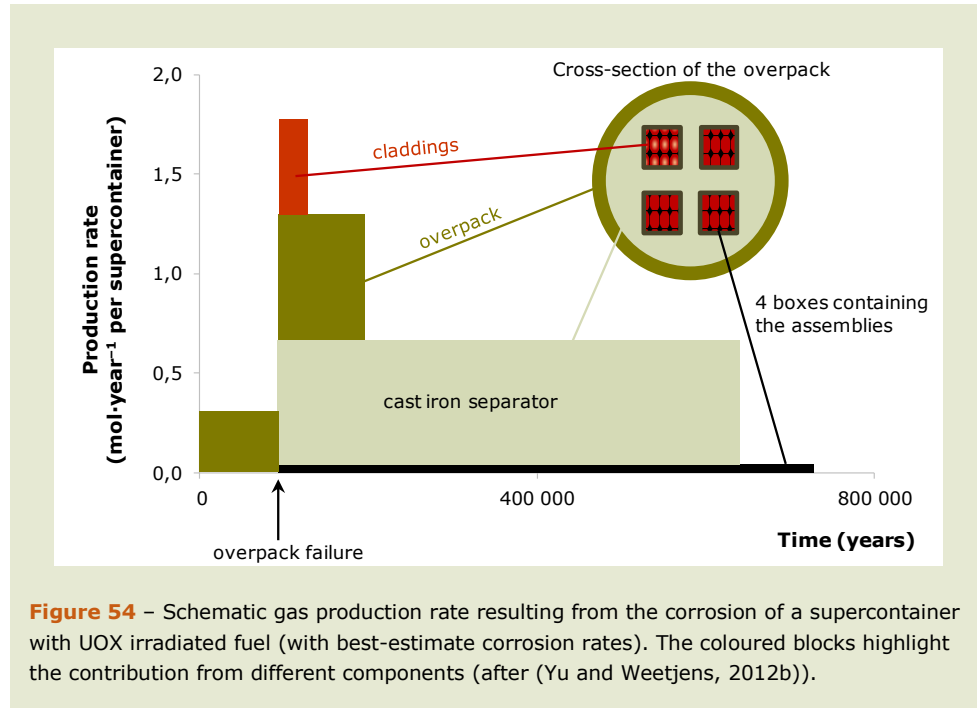
### Category C waste

With the current reference design, simulations show that the dominant source of gas for category C waste is the corrosion of the metallic components of the EBS, which releases hydrogen (Yu and Weetjens, 2012b):

- For supercontainers with UOX irradiated fuel, gas production mainly comes from the anaerobic corrosion of the carbon steel overpack, the cast iron separator, the stainless steel boxes containing the assemblies and metals contained in the fuel assembly. The peak rate of the gas production occurs after perforation of the overpack and corresponds to the start of the corrosion of the Zircaloy cladding due to its large reactive surfaces. In these calculations, the following corrosion rates of carbon steel in alkaline conditions (pH = 12.5-13.5) were used: 0.01 micrometre per year (Minimum), 0.1 (Best Estimate or "BE") and 1 (Maximum) micrometre per year. (Remark: Based on current knowledge, data found in the literature and data generated during the ONDRAF/NIRAS RD&D experimental programmes, a uniform corrosion rate lower than  $0.1 \mu\text{m}\cdot\text{year}^{-1}$  is proposed for carbon steel exposed to the supercontainer concrete buffer environment under anoxic and unirradiated conditions, see Section 4.2.3.3.)

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67 FORGE: Fate of Repository Gases. Investigation of process of gas generation and transport and their potential impact on a disposal system (EU project).



- For supercontainers with high-level vitrified waste, the main sources of gas are the anaerobic corrosion of the overpack and the waste packages. The peak rate of the gas production occurs after perforation of the overpack.

Modelling was performed to estimate the maximum diffusive migration capacity of the system at various radial distances from the gallery axis. The apparent diffusion coefficient of dissolved  $H_2$  in the pore water is based on physical analogy with helium (He), for which an accurate value has been recently obtained using a new laboratory test setup (Jacops *et al.*, 2010).

- Evaluation of the hydrogen diffusion process for the supercontainer with irradiated fuel demonstrates that for the case with the Min gas production rate, there will be no free gas formed in the system. With the best-estimate gas production rate, a free gas phase can be formed within the concrete buffer for some time after perforation of the overpack, but not in the Boom Clay. Only in the case of the maximum corrosion rates (which are now considered over-conservative, see Section 4.2.3.3) might the free gas phase penetrate into the Boom Clay, when the corrosion of Zircaloy and cast iron frame starts. The evolution of the hydrogen concentration in the near field is also numerically simulated for a supercontainer with UOX irradiated fuel by implementing the best-estimate source term in a simple one-dimensional radial solute transport model. The results show that the solubility limit of hydrogen is exceeded within the supercontainer buffer (but again, not in Boom Clay) shortly after perforation of the overpack, *i.e.*, at the start of the Zircaloy, Inconel and cast iron corrosion.
- For supercontainers with high-level vitrified waste, evaluations of the source term of hydrogen and its diffusive transport indicate that for the case with the best-estimate and minimum gas production rates, there should be no free gas formed in the system. A free gas phase is only likely to be formed within the EBS for the maximum gas production rates (which are now considered over-conservative, see Section 4.2.3.3). In additional two-phase numerical simulations, numerical results

indicate that the free gas phase would in that case remain within the EBS without penetrating into the Boom Clay.

### Bituminised waste

Once disposed in a geological repository, the presence of Eurobitum waste will lead to a continuous production of gas by anaerobic corrosion, radiolysis and microbial activity:

- Anaerobic corrosion of metals. Bitumen is included in steel drums that will corrode. The main gas produced by anaerobic corrosion is  $H_2$ . Other metallic parts may be present in the repository, such as reinforcement bars of the monolith B (if any).
- Radiolysis of the bitumen. The main gas produced by radiolysis is  $H_2$ . The other gas,  $CH_4$ ,  $NO$  and  $CO$ , represent a small fraction of the total produced gas. The total quantity of gas produced by radiolysis is lower than the one produced by corrosion. However, the gas production rate due to radiolysis can significantly exceed that of anaerobic corrosion in the beginning of the post-closure period.
- Microbial activity (degradation of bitumen and leached organic molecules ( $CO_2$ ), and denitrification of nitrate and nitrite producing nitrous gas such as  $N_2$ ,  $N_2O$ ). A microbial-induced reduction of nitrate that is released from the bituminised waste may lead to the production of nitrogenous gases. The precise gas,  $N_2O$ ,  $N_2$  and/or  $NH_4^+$ , depends on the type of active microbes. The contribution of microbial activity to the total gas production is subjected to large uncertainties as many types of reactions may occur (both production and consumption of gases). Experimental results demonstrated that Nitrate Reducing microbes can grow and become active in disturbed Boom Clay. It is, however, uncertain whether the microbes can be (very) active under the prevailing harsh conditions for microorganisms in the repository. More research is going on in this field.

Li Yu *et al.* have evaluated the hydrogen production rates due to radiolysis and corrosion, in the current repository design. They have then compared these rates to the capacity of the Boom Clay to evacuate the dissolved gases by molecular diffusion. Two cases were considered, depending on the presence of metallic reinforcement bars in the monolith B. Results indicate that, in the case without reinforcement bars, the capacity for diffusive removal of dissolved  $H_2$  stays higher than the production of  $H_2$  (best estimate case) (Yu *et al.*, 2012).

Calculations of the diffusive removal capacity by the clay for produced  $N_2O$  indicate that the solubility of  $N_2O$  in water at 23 bars is sufficiently high to avoid the generation of a separate gas phase. Calculations of the diffusive removal capacity of the clay for  $N_2$  are under way.

### All other category B waste

Category B waste contains many different types of waste of complex inventory. With the current reference design, simulations show that three sources of gas may significantly contribute to the gas production of category B waste: corrosion of the metallic components of the EBS, radiolysis and (bio-)chemical degradation of organic compounds.

Modelling indicate that the gas generation from some category B waste might be higher than what can be evacuated by diffusion of the dissolved gas, leading to the formation of a gas phase. For instance, simulation of the gas production from CSD-C, with metallic reinforcement of the monolith B, indicates that “*a free gas phase will be formed with best estimate and maximum gas production rates*” (Yu and Weetjens, 2012b). RD&D for SFC1 in the field of gases thus focuses on three points:

- To screen out the wastes for which diffusive removal of gas is sufficient;
- To understand which gas transport modes occur when the diffusive removal capacity is exceeded (two-phase flow, pathway dilation or gas-induced fracture) (mostly experimental, modelling options are very limited);
- Meanwhile, to assume that gas releases from the problematic wastes can be handled with little or no impact on radionuclides transport: sub-horizontal fractures (that is no effect on vertical radionuclide transport), evacuation of gas (but not water) through EBS or damaged zone (that is no effect on vertical radionuclide transport) or possibly stylised scenarios (how much contaminated free water can be pushed out of the near-field by gas and what would be the radiological impact).

The FORGE project investigates process of gas generation and transport and their potential impact on a disposal system. It includes laboratory and *in-situ* experiments, as well as numerical modelling of different aspects of gas generation, and potential effects of excessive gas pressure on the EBS and host formation (Yu and Weetjens, 2009).

While two-phase flow has been considered before as a possible representation of the transport of free gas through Boom Clay, it now seems increasingly likely that some pathway dilation or even the creation of new pathways (or reactivation of discontinuities in the excavation-damaged zone) will be necessary for free gas to penetrate into water-saturated Boom Clay (Yu and Weetjens, 2009). Once possible gas transport modes and pathways will be identified, the amount of (possibly contaminated) pore water that can be displaced by gas flow should be evaluated. In the frame of FORGE, Jacops et al have carried out gas breakthrough tests in the laboratory through small clay cores (Jacops *et al.*, 2012). Compared to the volumes of gas involved in the breakthrough events, the volume of displaced water was found to be minimal in these tests (less than 1%). These tests were however performed without control or measurement of the stresses in the samples. As this is identified as an important limitation (pathway dilation and creation almost certainly depend on the stress field), tests under controlled stresses are being planned.

As the reinforcement bars in the monolith B may be an important source of gas generation, alternative non-metallic reinforcement methods could help to decrease gas production in the system to acceptable levels (Yu and Weetjens, 2012b). Research in the field of feasibility is underway in order to limit the quantity of metallic materials left in the repository after disposal (Section 5.2.2).

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### Roadmap – Section 4.2.2.5 – Gas (BC)

Gas transport by dissolution and diffusion is now well understood and characterised. The main uncertainty surrounding the effect of gas on Boom Clay concerns the transport modes of a free gas phase. The development of a free gas phase is probably unavoidable for some waste types.

For SFC1, ONDRAF/NIRAS will evaluate the gas source terms for a selection of wastes and associated EBS, considering the evolving conditions in the disposal system (see roadmap Section 3.1). For later SFCs, it will check possible gas sink terms (consumption by microbes, hydrate formation (in presence of zirconium), etc.).

Laboratory experiments and *in-situ* tests are being conducted in order to investigate the possible free gas transport modes and to confirm that no significant pore water displacement is associated with the transport of free gas (if any). Results of these studies will be integrated *in later SFCs*.

ONDRAF/NIRAS will continue its work, the results of which will be integrated *in later SFCs*, on the development and validation of conceptual models for the transport of free gas through the disposal system (through the clay, through EBS components and along interfaces), in order to assess the consequences of such transport.

If necessary, ONDRAF/NIRAS will investigate design options that would simplify the description of the evolution of the system with respect to gas production and transport. For instance, ONDRAF/NIRAS could use an engineered gas transport system made of adapted/suitable backfill and seal materials (see Sections 5.4.1 and 5.4.2).

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### 4.2.2.6. Microbes

The possible impact of microbes in the damaged zone must be assessed<sup>68</sup>, as in this case, the viable indigenous microbes can be activated by more favourable growth conditions:

- Sulphate-reducing microbes reduce the sulphate produced by the oxidation of pyrite into sulphide, as measured in samples of Boom Clay pore water extracted from interstitial space behind the Connecting and the PRACLAY galleries (Aerts *et al.*, 2009b) (ONDRAF/NIRAS, 2010a). In laboratory experiments providing very favourable conditions for microbial growth, Boom Clay and its pore water from HADES URF contain viable, rapidly inducible microbial populations capable of producing significant amounts of sulphide gases (ONDRAF/NIRAS, 2010a). In disposal conditions, this microbial activity may occur in the beginning of the operational period. However, it will progressively diminish by lack of available space and diffusion-limited transport of nutrients after the closure of the galleries.

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68 For category B waste containing organic compounds, the possible impacts of microbial activity in the waste packages should also be investigated.



- In presence of methane-producing microbes, degradation of the organic matter and radiolysis lead to the production of methane. Experimental results indicate that these microbes could also transform the hydrogen produced by the anaerobic corrosion of metals and radiolysis into methane, once the oxidised species of sulphur are reduced (and sulphate-reducing microbes become inactive). There is experimental evidence that the presence of methane-producing microbes in the Boom Clay (and sulphate-reducing microbes to a lesser extent) can reduce the net volume of gas produced, as the microbes use four molecules of hydrogen in their metabolic reactions to form one molecule of methane (Ortiz *et al.*, 2002) (Jacobs *et al.*, 2010).
- A microbial-induced reduction of nitrate that is released from the bituminised waste may lead to the production of nitrogenous gases. The precise gas, N<sub>2</sub>O, N<sub>2</sub> and/or NH<sub>4</sub><sup>+</sup>, depends on the type of active microbes. This nitrate reduction simultaneously occurs with oxidation of organic matter (ONDRAF/NIRAS, 2010a). In laboratory experiments carried out by Microbial Analytics AB and providing very favourable conditions for microbial growth, it was demonstrated that Boom Clay and its pore water sampled from the HADES URF contain viable, rapidly inducible microbial populations capable of producing significant amounts of nitrogenous gases (ONDRAF/NIRAS, 2010a). It is, however, uncertain whether the microbes can be (very) active under the prevailing harsh conditions for microorganisms in the repository. More research is going on in this field.

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#### **Roadmap – Section 4.2.2.6 – Microbes (BC)**

*For SFC1*, ONDRAF/NIRAS will investigate the limitations of microbial activity in Boom Clay due to space restriction. To bound the possible evolution of the disposal system, ONDRAF/NIRAS will perform “envelope calculations” (*e.g.*, supposing the complete conversion of sulphate to sulphide) estimating the maximal amount of reaction products due to microbial activity.

*For later SFCs*, additional experimental work about microbial activity may lead to a more realistic description of the possible evolution of the system.

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### **4.2.3. The evolution of the engineered barrier system with time can be bounded**

The engineered barrier system (EBS) will evolve with time. This section details the evolution of the different parts of the EBS, starting with the cementitious materials (Section 4.2.3.1), then the seals (Section 4.2.3.2), the overpack (Section 4.2.3.3) and ending with the evolution of the currently most studied wastes (Section 4.2.3.4). Section 4.2.3.5 analyses the evolution of the system in terms of criticality.

#### **4.2.3.1. The evolution of the cementitious materials with time can be bounded**

The EBS contains large quantities of cementitious materials, whose properties evolve with time, as detailed in report "Evolution of the near field of the ONDRAF/NIRAS repository concept for category C wastes" (Wickham, 2008). For SCF1, focus is on the characterisation of these materials' properties and of their behaviour within the disposal system. Several parameters may affect the concrete properties.

The level of gamma radiation will rapidly decrease. In the most penalising case in terms of dose rate (VHLW), the gamma radiation rate at the interface between the overpack and the buffer would not exceed  $25 \text{ Gy}\cdot\text{hr}^{-1}$  (Bouniol, 2007). A first estimate of the duration of radiolysis effects in the supercontainer is about 300 years, which is ten times the half-life of  $^{137}\text{Cs}$ , the main source of gamma radiation (Bouniol, 2005). Radiolysis of concrete pore water will influence redox conditions and will generate hydrogen, oxygen, and other oxidising radicals. However, the effects of these oxidising radicals will be transient.

Poyet calculated the initial degree of saturation of the freshly cured concrete buffer to be approximately 80% (Poyet, 2005). The ingress of Boom Clay pore fluid, in time, will lead to a complete saturation of the concrete buffer. Coupled thermo-hydraulic calculations, indicated that it would only take a couple of years to reach full saturation of the concrete buffer close to the overpack, considering an initial saturation degree of 80% (Weetjens *et al.*, 2009b). However, the real evolution of the buffer is expected to differ: there are numerous evidences reported in the literature that clogging of the concrete buffer will occur, limiting the saturation of the buffer and subsequent transport of aggressive species (Kamali *et al.*, 2008) (Richet *et al.*, 2004) (Sneyers *et al.*, 2001). Until recently, the RD&D programme did not take this clogging into account, as a conservative assumption and for the simplicity of calculations. The use of an envelope would further reduce the flux of Boom Clay water towards the overpack. Clogging and/or the envelope (if present) will significantly delay the saturation of the buffer.

In the case of category C waste, heat and radiation are introduced into the system, leading towards a temperature elevation and irradiation of the different concrete layers. The near-field temperature evolution has been assessed for the current reference design by Weetjens (Section 4.2.2.2) (Weetjens, 2009). Results for UOX (UNE-55) and MOX (MOX-50) irradiated fuel indicate that, with the current reference design, the interface overpack/buffer may experience a temperature higher than  $100^\circ\text{C}$  for several decades but not exceed  $120^\circ\text{C}$ . The surface temperature of the overpack will then gradually drop below the thermal phase criterion temperature ( $25^\circ\text{C}$ ) within 200, 1 500 and 3 000 years for vitrified high-level waste, UOX and MOX irradiated fuel respectively.

Current RD&D evaluates the consequences of such a temperature excursion above 100°C.

For category C waste, a key component of the cementitious EBS is the concrete buffer, designed to establish and maintain a chemical environment around the overpack that is favourable to achieving the desired performance (containment of the radioactivity during the thermal phase). pH being the most important property controlling the corrosion behaviour of the overpack, ONDRAF/NIRAS launched a modelling programme to assess its evolution. This two-part work programme, based on very conservative assumptions, concluded that the pH at the overpack surface is and will likely remain alkaline for a geological time span.

The pH is first controlled by the alkali hydroxides present in the cement clinker. The alkali hydroxides release high amounts of  $\text{Na}^+$  and  $\text{K}^+$  ions into the pore solution and of an equivalent concentration of anions, the most dominant being  $\text{OH}^-$ . Many measurements of the  $\text{OH}^-$  concentration in the pore solution of Portland cement pastes (OPC), mortars and concretes have been reported in the literature (Bertolini *et al.*, 2004). The reported  $\text{OH}^-$  concentrations lie between 0.25 and 0.90 mol·L<sup>-1</sup>. This corresponds to a pH-value between 13.2 and 13.8 at 25°C (Wang, 2009). When the alkali hydroxides have been leached out by diffusion, the pH is controlled by portlandite ( $\text{Ca}(\text{OH})_2$ ). Portlandite is thus the major component contributing to the pH buffering capacity of the concrete (portlandite is a main hydration product of CEM I cement used in the concrete formulation, which contains about 30% in weight of cement). Calculations about the pH evolution were done specifically to check if the pH around the overpack would stay high enough to impose passivity conditions (over conservative assumptions). These calculations underestimate the real timescale as the model neglects clogging, porosity reduction and envelope (which might be present, see Section 3.2.3.1).

The temperatures achieved in the concrete buffer with the disposal of VHLW and UOX irradiated fuel will not compromise passivation. Literature reports that the pH required to guarantee passivation at temperatures that could be reached for several decades in case of disposal of MOX is lower than 10 – 10.5, thus below the expected pH in the buffer (Nakayama and Akashi, 1991) (Fukuda and Akashi, 1996) (Fukaya and Akashi, 1999). This is backed up by current experimental results. However, tests at 130°C will be performed to confirm these data.

Inside sound concrete, there is no literature mentioning degradation by microbes (West *et al.*, 2002) (Roux *et al.*, 2006) (De Cannière *et al.*, 2011).

More research is under way to assess the thermo-hydromechanical (THM) evolution of the buffer concrete, to confirm in particular the absence of through-going cracks.

Transferability of radionuclides solubility database established for category A waste to category B&C waste is being assessed (ONDRAF/NIRAS, 2010d). As geochemical conditions are not well defined in the concrete, a broad range of conditions ( $E_h$ , pH) are considered for assessing solubility values for the category B&C project.

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### Roadmap – Section 4.2.3.1 – Evolution of the cementitious materials (BC)

For *SFC1*, ONDRAF/NIRAS will perform a first assessment of the evolution of the EBS, regarding:

- the ageing processes within the buffer (decalcification and pH evolution);
- the thermo-hydro-mechanical evolution of the buffer (e.g., thermal stress field due to thermal gradient, influence of temperature on the structural characteristics and properties of concrete, confirmation of the absence of through-going cracks).

After this assessment, ONDRAF/NIRAS will study the interactions between the waste components and the cementitious materials of the EBS (for instance the acidification processes resulting from biodegradation or radiolysis (in particular carbonation)) and their potential impact on properties. Results will be integrated in *later SFCs*.

For *later SFCs*, ONDRAF/NIRAS will look at the consequences of the ageing processes in cementitious materials on fluid and solute transport parameters (see roadmap Section 4.2.2.5).

ONDRAF/NIRAS will, for *later SFCs*, check the influence of waste components, their degradation products and additives (such as superplasticiser) on contaminants transport in the EBS.

For *SFC1*, ONDRAF/NIRAS will propose a backfill compatible with retrievability. (The requirements must still be defined in collaboration with other stakeholders. For later *SFCs*, adaptations might thus be required.) Later *SFCs* will integrate any study about the evolution of backfill properties, if needed.

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### 4.2.3.2. The evolution of the seals with time can be bounded

ONDRAF/NIRAS has installed two seals in Boom Clay (Section 5.4.2). The experimental (vertical) shaft in HADES URF is sealed with a mixture of powder and pellets of FoCa clay. The diameter of the seal shaft is about 2.2 metres and its height 2.24 metres. The (horizontal) PRACLAY gallery is sealed with an annular ring of compacted bentonite placed against the Boom Clay and a stainless steel structure enclosing the bentonite. This seal presents a diameter of 2.4 metres and a length of 1 metre<sup>69</sup>.

The hydro-mechanical evolution of the seals is recorded, through registration of total stress, water pressure, displacements and relative humidity, during and after the hydration process. The same conclusions can be drawn from the two experiments:

- It is feasible to construct seals, with a hydraulic conductivity similar to the Boom Clay (Section 5.4.2).

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<sup>69</sup> The PRACLAY seal was necessary to create the desired boundary conditions for a large-scale heater test (Annex A4). Its design was oriented to this specific application and it was not intended as a prototype for a seal in a disposal facility, where the requirements placed on the seal would be different.

- Hydration time is longer than expected and saturation mechanisms are not yet fully understood.

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#### **Roadmap – Section 4.2.3.2 – Evolution of the seals (BC)**

For SFC1, ONDRAF/NIRAS will define requirements on the seals, taking into account the current concerns of other stakeholders, and select a design fulfilling these requirements. (These concerns will be formalised during the societal dialogue and/or interactions with the regulator.) The RD&D on THMC (thermo-hydro-mechanical and-chemical) behaviour of the seals will then resume. Preliminary results might be available for SFC1, in function of the selected design.

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#### **4.2.3.3. The evolution of the overpack with time can be bounded**

The overpack is designed to assure the containment of the wastes during the thermal phase. Assessing its evolution with time is thus of prime importance. ONDRAF/NIRAS has launched a RD&D corrosion programme to collect evidence that the integrity of the carbon steel overpack will not be jeopardised at least during the thermal phase. In the frame of this programme, SCK•CEN has developed a methodology to demonstrate and defend this concept. The methodology is based on the assumption, validated by the corrosion expert panel, that, under the predicted conditions within the supercontainer, the carbon steel overpack is expected to undergo uniform corrosion through the mechanism of passive dissolution (ONDRAF/NIRAS, 2004) (ONDRAF/NIRAS, 2004b) (Kursten, 2010). It consists of three steps:

- To evaluate the corrosion evolutionary path, which defines the time-dependent corrosion behaviour of the carbon steel overpack and is closely tied to the evolution of the environmental conditions surrounding the overpack.
- To determine, in view of these boundary conditions, the corresponding corrosion rates and mechanisms.
- To validate the “exclusion principle”, which means that only uniform corrosion occurs under the predicted geochemical boundary conditions, excluding all other forms of corrosion (Kursten *et al.*, 2011) (Kursten *et al.*, 2011c).

The RD&D programme first focused on determining the evolution of the environmental conditions and the uniform passive corrosion rate before extending to the exclusion of localised corrosion.

#### **Evolution of environmental conditions**

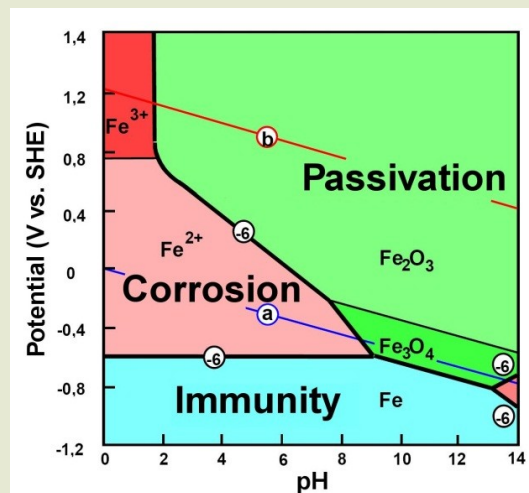
The corrosion depends on the properties of the overpack (raw material, heat-affected zones and welds) and on the corrosivity of the environment to which it is exposed, which evolves with time. The parameters potentially affecting the corrosion behaviour of the overpack are the pH, temperature, radiation level, corrosion potential of the overpack and concentration of aggressive species. (The saturation degree of the concrete is not included because full saturation is not required for keeping the system in a passive

state.) The evolution of the listed parameters with time and their influences on corrosion behaviour are detailed hereafter (Kursten, 2010), (Kursten *et al.*, 2011).

The pH of the concrete pore solution is imposed by the concrete buffer (Section 4.2.3.1). According to the Pourbaix diagram for iron at 25°C, this high pH will maintain the passivation of the overpack. The (simplified) Pourbaix diagram for iron at 25°C on Figure 55 presents a map of the regions of thermodynamic stability of iron and its corrosion products in aqueous environments. The green-coloured area represents a region of passivity for iron. The pH expected in the buffer lies in that region (Kursten, 2010).

The temperature evolution is imposed by the waste. It will decrease as heat output of the radioactive waste decreases. The near-field temperature evolution has been assessed for the current reference design by Weetjens (Section 4.2.2.2) (summary in Section 4.2.3.1) (Weetjens, 2009).

The radiation levels are imposed by the waste. At the overpack surface, the maximum radiation rate will not exceed  $25 \text{ Gy}\cdot\text{h}^{-1}$  (in the most penalising case (VHLW) and will decrease with time (Bouniol, 2007). Radiolysis generates hydrogen, oxygen and other oxidising radicals whenever pore water is present. Modelling results showed that radiolysis, through production of oxidising species, would lead to oxidation of incoming sulphide, thus limiting largely their potential harmful influence. Process modelling indicates that radiolysis could potentially prolong the aerobic period by three hundred years. Experimental results in saturated conditions show that irradiation does not impact the uniform corrosion rate while the corrosion potential corresponds to an anaerobic corrosion mode; the cathodic reaction being controlled by water (Winsley *et al.*, 2011).

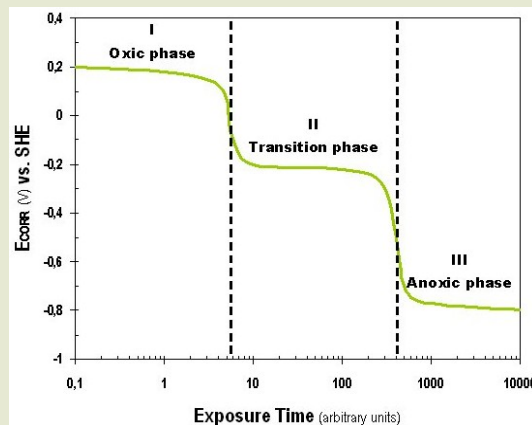


**Figure 55** – Simplified potential-pH diagram for iron at 25°C showing areas of immunity (no corrosion), passivity and corrosion, together with the possible reaction/corrosion products produced (Kursten, 2010).

The corrosion potential of the overpack, a key parameter with regards to corrosion, depends on the type of metal, the environmental redox conditions and the temperature. Figure 56 shows a schematic representation of the expected evolution of the corrosion potential  $E_{\text{corr}}$  at the surface of the carbon steel overpack (Kursten, 2010). Three phases are identified: a (short) oxic phase, a transition phase from oxidising to reducing

conditions and a (long) anoxic phase (Kursten *et al.*, 2011) (MacDonald *et al.*, 2011) (Saleh *et al.*, 2011) (Winsley *et al.*, 2011):

- The corrosion potential during the initial oxic phase is controlled by the level of oxygen dissolved in the concrete buffer since the supercontainer will be fabricated, assembled and emplaced under atmospheric conditions. Measurements on concrete pore fluids suggest positive oxidising potentials of around +100 to +200 mV(SHE) (Atkins and Glasser, 1992).
- The redox conditions inside the supercontainer will become reducing due to corrosion of the carbon steel overpack (and envelope, if present) (modelling performed by D.D. MacDonald, results to be published). During the anoxic phase, the oxidant in the system controlling the cathodic reaction is water, and corrosion under these conditions yields hydrogen gas. Tests performed by AMEC (former SERCO) with and without irradiation under anoxic conditions showed that hydrogen is produced (in line with the measured  $E_{corr}$ ).
- A transition phase from oxidising to reducing conditions will occur in the supercontainer (Kursten *et al.*, 2011).



**Figure 56** – Expected evolution of the corrosion potential of a carbon steel overpack surrounded by the concrete buffer of the supercontainer (arbitrary units) (Kursten, 2010).

The chemical composition of the concrete pore solution is first imposed by the concrete buffer and then influenced by aggressive species from Boom Clay. The non-perturbed Boom Clay pore water in HADES URF does not contain significant amount of aggressive species for the designed repository (Van Geet *et al.*, 2006). However, the introduction of potentially aggressive species for the carbon steel overpack, from ingressing Boom Clay pore waters, may not be excluded. (The concentration of aggressive species (chloride and reduced sulphur species) within the concrete buffer is bounded by requirements on concrete composition (Section 5.1.1).) These potentially aggressive species for the designed repository include: chloride ( $Cl^-$ ), thiosulphate ( $S_2O_3^{2-}$ ), sulphides ( $S^{2-}$ ) and sulphates. SCK•CEN performed calculations in order to assess when and in which concentrations aggressive species from the Boom Clay pore water would reach the surface of the overpack (Govaerts and Weetjens, 2010b). The sulphide concentration used as reference case (150 ppm) is in line with results from (Aerts, 2009) who writes that the maximum expected sulphide concentrations around the gallery due to SRB activity would be in the range of 150 to 300 ppm. These calculations are based on conservative assumptions: no clogging, no retention of aggressive species on concrete

components, highest ever-measured concentration of each type of aggressive species. Furthermore, in one pessimistic (unrealistic) case, all pyrite in the EDZ is assumed to be oxidised into sulphate, which in turn is totally transformed into sulphide by microbial activity. Even with such assumptions, results indicate that aggressive species will arrive at the overpack surface long after emplacement and that only a third of the concentration of aggressive species will reach the overpack (maximum concentrations at the overpack surface are reached after a few hundred years up to one thousand years).

### **Determination of the uniform passive corrosion rate**

In order to collect multiple lines of evidence, the RD&D programme on corrosion involves several research teams, specialised in complementary investigation methods:

- SCK•CEN has compiled and analysed data from literature on the corrosion rates for systems comparable to the supercontainer in different environments (oxic alkaline solutions, anoxic alkaline solutions (in disturbed environments, containing for instance Cl anions and in non-disturbed environments) (Kursten, 2010).
- The experimental programme performed at Pennsylvania State University (USA) aims at studying the electrochemistry of the carbon steel overpack in the concrete buffer environment, including in presence of aggressive species (Kursten *et al.*, 2011). The main goal of this research is the understanding of carbon steel electrochemical behaviour in a cementitious environment. The group of researchers also assesses the uniform corrosion rates of carbon steel in simulated concrete pore solution by measuring the steady state value of the passive current density (potentiostatically), in short-term (about 20 hours) and over one year experiments.
- The main emphasis of the experimental programme performed at AMEC (former Serco TCS) (UK) is put on studying the influence of gamma irradiation on the long-term anaerobic uniform corrosion rate and electrochemical behaviour. Serco TCS performs several types of tests: hydrogen evolution measurements, electrochemical techniques and weight loss measurements.
- In support to the experimental programme, CEA evaluates by modelling the potential impact of radiolysis on the buffer (in terms, among others, of hydrogen production).
- SCK•CEN has initiated tests to assess whether the overpack material (including welds and heat-affected zones) is susceptible to stress corrosion cracking and hydrogen embrittlement.
- UC Berkeley explores the pitting corrosion of carbon steel in concrete pore water (with and without aggressive species at room and elevated temperatures).

Results show a good correlation between measurements of the passive uniform corrosion rate from different laboratories and with different measuring techniques (hydrogen evolution measurements, weight loss measurements and passive current density measurements at steady state) (Kursten *et al.*, 2011). Experimental results indicate that the uniform corrosion rate decreases with time. This feature is valid for concrete and other environments such as clays and granite, under aerobic and anaerobic conditions, as shown by long-term laboratory and archaeological studies (Kursten, 2010). Results also indicate that the anaerobic uniform corrosion rate does not vary with

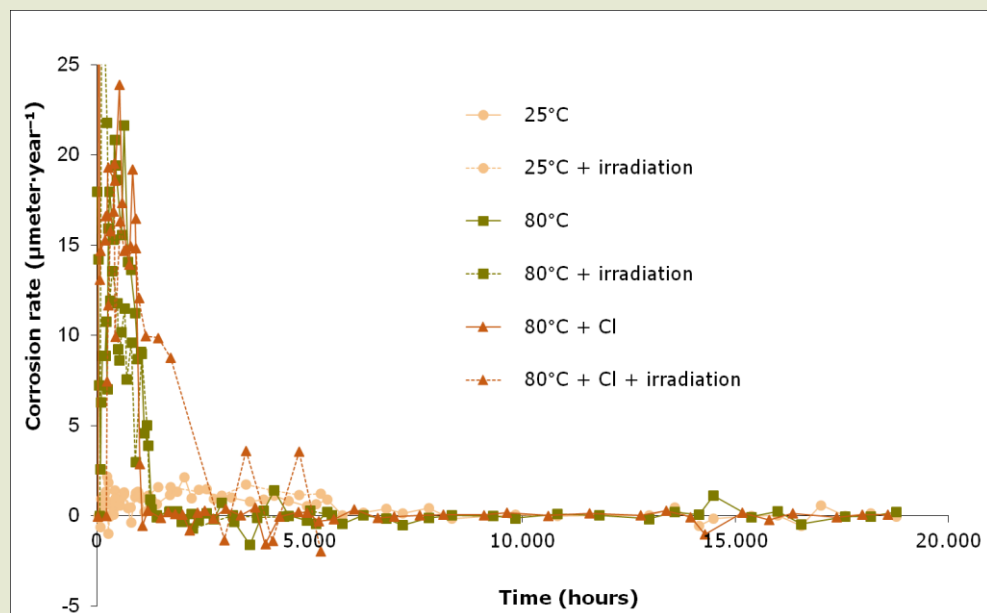


temperature (temperatures tested: 25°C and 80°C), chloride concentration (100 mg·L<sup>-1</sup>) or gamma irradiation (25 Gy·h<sup>-1</sup>) (Inset 14). Furthermore, the quick repassivation of the steel after scratching indicates that the system has a marked tendency for passivity even at 80°C (Smart *et al.*, 2004).

**Inset 14 – Measure of the instantaneous anaerobic uniform corrosion rate for carbon steel in supercontainer environment.**

SERCO TCS measured the anaerobic uniform corrosion rate from hydrogen gas evolution experiments, for carbon steel immersed in concrete pore solutions representative of the supercontainer buffer environment. The method of testing gives instantaneous values of corrosion rate. After an initial high value, which is an experimental artefact, the anaerobic uniform corrosion rate rapidly dropped to a very low level and is still decreasing (ongoing test, test duration higher than 20 000 hours). It was also observed that the uniform corrosion rates do not change with temperature (25 and 80°C), chloride concentration (100 mg·L<sup>-1</sup>) or gamma irradiation (25 Gy·h<sup>-1</sup>).

When the total amount of hydrogen gas produced over the entire measuring period is converted into an overall corrosion rate, the obtained value corresponds very well with the integrated value calculated from the weight loss measurements (Kurstén *et al.*, 2011).



**Figure 57** – Anaerobic uniform corrosion rate (from hydrogen gas evolution measurements) for carbon steel in concrete pore solution (YCW) under unirradiated (solid lines) and irradiated conditions (25 Gy·h<sup>-1</sup>) (broken lines) as function of temperature and chloride concentration (100 mg·L<sup>-1</sup>) (after (Winsley *et al.*, 2011).

Based on current knowledge, data found in the literature and data generated during the ONDRAF/NIRAS RD&D experimental programmes, a uniform anaerobic corrosion rate lower than 0.1 µm·year<sup>-1</sup> is proposed for carbon steel exposed to the supercontainer concrete buffer environment under anoxic and unirradiated conditions (Kurstén, 2010). The last available data and the expected evolution of the disposal system indicate that the uniform anaerobic corrosion rate could be in the range of nanometres per year (to be published).

### **Exclusion of localised corrosion**

Metals whose corrosion resistance depends on maintaining a stable passive film can exhibit an increased susceptibility to localised forms of corrosion if the protective film is locally disrupted (Kursten, 2009). In accordance with the “exclusion principle”, there is ongoing RD&D to exclude all types of corrosion that are not uniform and passive. The RD&D programme currently assesses the susceptibility of the carbon steel overpack to hydrogen embrittlement, stress-corrosion cracking and pitting corrosion. This latter can only occur under the combined action of the following factors: (i) a material susceptible to this type of corrosion, (ii) a mechanical load, and (iii) a suitable environment (in terms of concentration of aggressive species and corrosion potential) (King, 2007).

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#### **Roadmap – Section 4.2.3.3 – Evolution of the overpack (BC)**

*For SFC1*, ONDRAF/NIRAS will pursue its work on assessing the evolution of the overpack, in order to collect evidence that the integrity of the carbon steel overpack will not be jeopardised at least during the thermal phase. ONDRAF/NIRAS will continue its work to demonstrate that the combination of aggressive chloride and sulphur species does not affect uniform and localised corrosion (within the defined corrosion evolutionary path).

*For SFC1*, a model is under development to assess the long-term evolution of the corrosion products layer, of the corrosion potential and of the uniform corrosion rate. Experiments are ongoing to determine the parameters of the model.

ONDRAF/NIRAS will perform localised corrosion tests to assess the susceptibility of the carbon steel overpack (with welds and heat-affected zones) to localised corrosion under conditions relevant for the supercontainer, in order to demonstrate the validity of the exclusion principle. (This includes assessing the impact of temperature excursion above 100°C on the potential occurrence of stress-corrosion cracking.) The first results might be included in SFC1. The earlier mentioned model will be extended to include pitting by chlorides *for later SFCs*.

ONDRAF/NIRAS has initiated studies to check whether the corrosion behaviour of the overpack is still determined by passive corrosion at high temperature (up to 130°C) (this is of importance for the disposal of MOX irradiated fuel). SFC1 will integrate the first results from these studies. The complete results will be integrated *in later SFCs*.

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#### **4.2.3.4. The evolution of the wastes with time can be bounded**

The waste components will evolve with time. After failure of the overpack (category C waste) or the monolith (category B waste), they will progressively degrade due to interaction between the waste and the pore water, resulting in a release of radio-nuclides. Assessing the release rate of contaminants from the waste components and understanding their dissolution behaviour is important as, for some waste types, they contribute to the long-term safety. For SFC1, RD&D focuses on the dissolution of

irradiated fuel and of vitrified high-level waste, and on the compatibility of bitumen with geological disposal.

### **Irradiated fuel dissolution**

The irradiated fuel is made of different parts presenting different dissolution behaviours. This section first describes the matrix dissolution, the Instant Release Fraction, the cladding and structure releases and the effect of gas content of an irradiated fuel assembly on its dissolution rate.

#### **Matrix dissolution**

Studies on the dissolution of depleted and alpha-doped  $UO_2$  started at SCK•CEN in 1996. At that time, the environment of the waste packages was a clayey environment (with a pH similar to undisturbed Boom Clay). Adopting the supercontainer concept led to major changes in the RD&D programme. After failure of the overpack, the waste components will progressively degrade and dissolve due to interaction between the waste and the EBS components. Many parameters will influence the dissolution of the irradiated fuel waste, the most important one being the redox conditions of the environment, which evolve with time. The fuel matrix dissolution consists of the sum of oxidative U(VI) dissolution and non-oxidative dissolution, as shown by many studies at neutral pH (Lemmens, 2010). Oxidative dissolution requires the presence of oxidising species. Anaerobic corrosion of the iron-based overpack results in the build-up of a  $H_2$  atmosphere.

The RD&D programme launched by ONDRAF/NIRAS focuses as well on the irradiated fuel behaviour in presence and absence of hydrogen (in experiments with real irradiated fuel at laboratory KIT (Karlsruher Institut für Technologie)) as on the behaviour of depleted and alpha-doped  $UO_2$  in de-aerated conditions (SCK•CEN).

Experimental results from KIT and SCK•CEN are coherent and in line with literature (Nagra, 2004) (Andra, 2005) (Nagra, 2005) (SKB, 2005) (Poinssot *et al.*, 2006) and lead to the following conclusions:

- There is a threshold below which the effect of alpha-radiolysis of water on  $UO_2$  dissolution is negligible.
- If the overpack breaches before the radiation level is lower than the threshold, the contact of irradiated fuel with water will result in oxidative dissolution of the fuel.
  - ▶ The oxidative dissolution is annihilated by hydrogen, produced by the corrosion of the overpack.
  - ▶ Should hydrogen be absent (or present at too low partial pressure), the oxidative dissolution rate of irradiated fuel at high pH is of the same order of magnitude as at near-neutral pH, or even slightly lower.
- If the overpack breaches when the radiation level is lower than the alpha-threshold, assuming reducing conditions, very low residual oxidative dissolution rates are conservatively assumed.

These results are detailed hereafter.

The laboratory KIT analyses real irradiated fuel samples with a burnup of about 50 GWd·tHM<sup>-1</sup>. This laboratory measured the dissolution rate of this irradiated fuel in anoxic conditions, in pore water at pH 12.5 with and without magnetite granulates/Fe and Ti chips and at pH 12.5 and 13.5 in presence and absence of hydrogen gas (Loida *et al.*, 2009) (Loida *et al.*, 2012). The irradiated fuel dissolution rates reported by KIT are based on the strontium release (dissolution indicator) and expressed as “Fraction of Inventory in the Aqueous Phase” (FIAP<sup>70</sup>), which is the amount of a dissolved radionuclide divided by the total amount of this radionuclide initially present in the fuel sample. The release rate of strontium is considered as an indicator of the irradiated fuel matrix dissolution rate because most of the strontium inventory is distributed homogeneously in the matrix and it is scarcely involved in retention processes (Loida *et al.*, 2009). The tests from Loida are performed on pellets that are still clad. In the future, tests will also be performed on “declad” fuels, at high pH with hydrogen. Tests with fresh irradiated fuel are to be considered as worst case in absence of hydrogen because of the high activity still present in the medium generates oxidising species by radiolysis, which enhance the oxidative dissolution of the matrix (Andra, 2005) (Ferry *et al.*, 2005).

Results indicate that the dissolution rate of irradiated fuel at high pH is the same than the one at near-neutral pH. Using a solution rich in NaOH, KOH and Ca(OH)<sub>2</sub> at pH 12.5, irradiated fuel corrosion experiments were conducted over 378 days. Under anoxic conditions, parallel experiments were performed (a) in the absence of Fe phases and (b) in the presence of solid Fe phases representing the overpack corrosion products, without externally applied hydrogen. Both types of experiments resulted in relatively low matrix dissolution rates, around 10<sup>-7</sup> per day, according to the fractional release of strontium. Solution concentrations of redox-sensitive elements (technetium and actinides) are close to or below the detection limit, indicating that those elements are present as tetravalent reduced species. These results are similar to results obtained at near neutral pH: matrix dissolution rates obtained in the course of several international irradiated fuel corrosion studies in various types of pore water were found to be scattering in the range between 10<sup>-6</sup> per day and 10<sup>-7</sup> per day after about 100 days at neutral pH (Loida *et al.*, 2009). Experiments also demonstrate that hydrogen significantly reduces the dissolution of irradiated fuel at high pH. Recent studies have shown that in the presence of sufficient H<sub>2</sub> overpressure (3.2 bars), the dissolution rate of the irradiated fuel matrix cannot be measured anymore, being lower than the detection limits at pH 12.5-13.5 (Loida *et al.*, 2012). This beneficial effect of hydrogen had already been demonstrated at near neutral pH for UOX fuel as well as for MOX fuel (Ollila, 2011). The effect of hydrogen is also confirmed for MOX irradiated fuel (Carbol *et al.*, 2009).

SCK•CEN performs experiments on depleted and on alpha-doped UO<sub>2</sub>, at pH ranging from 13.5 to 11.7. Depending of its level of doping, the alpha-doped UO<sub>2</sub> is representative of an irradiated fuel after a few hundred years of storage up to about 100 000 years old fuels. The dissolution rates in the SCK•CEN tests are measured in static and dynamic tests by following the <sup>233</sup>U and/or the <sup>238</sup>U total concentration in solution (Lemmens, 2010). Measurements are made on powders and small pellets. Interpretation of results requires knowledge of the surface area of the used materials. For SFC1, values of the effective surface area of irradiated fuel are extracted from

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70 FIAP for other key radionuclides have also been measured.

literature. As the initial effective surface area does not depend on the disposal design, literature data from other waste RD&D programmes may thus be applied to the Belgian irradiated fuel, provided that their irradiation history is similar (as the surface area depends on the burnup). In line with the conclusions of the MICADO<sup>71</sup> project, the effective specific surface area is considered as constant and is equal to the effective surface area when the fuel is removed from the reactor core at the end of irradiation cycles (MICADO, 2010). As mentioned earlier, there is an alpha-activity threshold below which alpha radiolysis does not impact the dissolution of irradiated fuel. This threshold is probably reached after a few tens of thousands of years (in absence of hydrogen) at high pH but it is not (yet) clear whether the residual rate will be as low as for depleted UOX (ongoing tests). The most reliable data measurable with depleted UO<sub>2</sub> in contact with high pH water (pH = 13.5) give a dissolution range between 0.1 – 0.2 µg·m<sup>-2</sup>·d<sup>-1</sup>.

The results from KIT and SCK•CEN are in line with those from the MICADO coordinated action. In this action, reference ranges for surface normalised dissolution rates were proposed for reducing conditions with and without hydrogen gas. In presence of hydrogen, the rates range between 0.2 and 5 µg·m<sup>-2</sup>·d<sup>-1</sup> (for low surface area) and between 0.02 and 5 µg·m<sup>-2</sup>·d<sup>-1</sup> (for high surface area). The value of 5 µg·m<sup>-2</sup>·d<sup>-1</sup> is not reliable as it was measured in a dynamic experiment, with a hydrogen flow rate too slow to block all radiolysis effects. It is however kept in the assessment of uncertainties (MICADO, 2010). The residual rates in absence of hydrogen (after complete corrosion of metallic elements) lie between 0.03 and 2.6 µg·m<sup>-2</sup>·d<sup>-1</sup> for reducing conditions at near-neutral pH.

#### Instant Release Fraction

Besides the progressive and relatively slow release of the radionuclides present within the fuel matrix, some radionuclides, present in “open volumes” inside a fuel rod, *i.e.*, essentially the gap between the fuel and the cladding, in the cracks in the fuel, and in the instantaneously accessible grain boundaries, are released “immediately” (relatively to the geological timescale) at overpack failure. The instant release fraction (IRF) depends on the radionuclide distribution within the irradiated fuel rods, which in turn is function of the history of irradiation, and tends to increase with high power operation and increasing fuel burnup. The radionuclide distribution also depends on the intrinsic evolution of the irradiated fuel microstructure before overpack failure. Data on IRF exist in the literature for UOX irradiated fuel (for example, Ferry *et al.*, 2008). The European Union project FirstNuclides<sup>72</sup> whose overall objective is to improve understanding of the IRF from high burnup UOX irradiated fuel has started in 2012, with the participation of the SCK•CEN as technical contributor and of ONDRAF/NIRAS in the End Users Group. (FirstNuclides will also include research on MOX irradiated fuel, although this is not included in the initial objectives.)

#### Claddings and structure releases

Radionuclides from the fuel rod claddings and the assembly guide tubes, made of Zircaloy, are released in 2 waves: those present in the oxidised layers at cladding surface are expected to be rapidly released and are thus part of the instant release fraction (IRF) while the radionuclides in the unoxidised cladding are released at the

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71 MICADO: Model uncertainty for the mechanism of dissolution of irradiated fuel in a nuclear waste repository (EU project).

72 FirstNuclides: Fast / Instant Release of Safety Relevant Radionuclides from Spent Nuclear Fuel (EU project).

Zircaloy corrosion rate (Lemmens, 2010). The thickness of the oxidised layer accounts for less than 20% of the total cladding thickness (Boulanger, 2010).

There is currently no specific research on the release of radionuclides from other structural parts of the assemblies, which is considered congruent to their corrosion. These structural parts contain more than 90% of stainless steel; the rest being Inconel and Zircaloy (Boulanger, 2010).

#### Effect of gas content of an irradiated fuel assembly on its dissolution rate

Boulanger has evaluated the gas content of a Belgian irradiated fuel assembly to check whether it could affect its dissolution rate (Boulanger, 2010). At discharge from the reactor, an UOX irradiated fuel assembly with a burnup of 45 – 50 GWd·tHM<sup>-1</sup> typically contains:

- between 150 and 250 litres of “free” gas, directly available for release at loss of cladding tightness. In most cases, more than 70% volume of this gas is helium from pre-pressurization of the fuel rods at fabrication; the remaining fraction being Xe (mainly), Kr and He fission products (and a minor amount of He from alpha decay) released from the fuel matrix by thermal diffusion during in-reactor operation.
- between 600 and 700 litres of fission gas (Xe, He, Kr) confined in the fuel matrix and in the closed porosity of the fuel.

After discharge, the gas inventory of the fuel rods increases with time, due to alpha decay but the total gas inventory of UOX irradiated fuel will not significantly evolve during the thermal phase. The helium produced by alpha decay is expected to be mostly confined in the fuel matrix (at least for UOX fuel). According to Ferry *et al.*, the generated helium will not modify the microstructure of the UOX irradiated fuel (Ferry *et al.*, 2010). Based on the available data, it is expected that the gas will not affect the dissolution rate of UOX irradiated fuel.

#### Vitrified high-level waste dissolution

At the time of SAFIR2, research focused on the interaction of glass with clay. Studies identified the basic processes likely to occur during glass dissolution (ONDRAF/NIRAS, 2001). The CORALUS<sup>73</sup> test and NF-PRO<sup>74</sup> project further refined the glass dissolution model and model parameter for clay conditions (CORALUS, 2007) (Godon *et al.*, 2008). Introduction of the supercontainer concept led to major changes in the RD&D programme, as glass is surrounded by a high pH environment. Some knowledge of the NF-PRO project can be transferred for high pH environment: results indeed suggest that the mechanisms of glass dissolution are not fundamentally different at neutral and high pH, although their relative importance may differ (Lemmens, 2011).

Several stages are observed during glass dissolution. There is first congruent dissolution characterised by a high initial rate. Then, there is formation of a gel, made by the

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73 CORALUS I to IV: Integrated *in-situ* tests on the corrosion of alpha active glass in contact with dense clay at high swelling pressure. Leaching from glass and migration in clay of radionuclides.

74 NF-PRO: Understanding and Physical and Numerical Modelling of the Key Processes in the Near Field and their Coupling for Different Host formations and Repository Strategies (EU project).

recondensation of dissolved species, which decreases the dissolution rate by several orders of magnitude to a residual dissolution rate. The mechanisms controlling this rate might be the diffusion within the passivating reactive interface (PRI) and/or the (slow) precipitation of secondary phases. There is no consensus about the mechanistic interpretation for this low residual glass dissolution rate. For pH higher than 10.5, glass alteration resumption has been observed and is correlated to rapid precipitation of secondary phases (zeolites). The pH is a key parameter in glass alteration because  $\text{OH}^-$  species catalyse the hydrolysis of the silica network. *The growth of the zeolites consumes Si and Al, thus depleting the medium and diminishing the protectiveness of the gel* (Godon *et al.*, 2008). On the long term, the dissolution rate could still decrease to a low rate similar as at neutral pH, on the condition that the altered layers at the glass/cement interface are thick and dense enough to maintain a pH gradient between the concrete bulk (high pH) and the pristine glass (near-neutral pH). Although this effect may be realistic, it is not yet supported by sufficient scientific evidence (Lemmens, 2011).

The current experimental programme focuses on the understanding of glass dissolution mechanisms and on measuring glass dissolution rates in a high pH and aqueous environment (with and without addition of cement). In simple systems with penalising conditions, it is indeed highlighted that the lifetime of silica glass is shortened in a high pH environment, compared to a neutral one (Lemmens, 2011) (Ferrand, 2013). It also showed that in presence of cement, the glass dissolution is controlled by the reaction of the released silica with portlandite, forming C-S-H phases. This reaction will continue as long as portlandite is available and accessible. It is not clear yet whether, and to which extent, dissolution at high pH will be dominated by secondary phases on the long-term.

Values of the effective surface of the glass, which is the surface of the glass accessible to water (where radionuclides are assumed to be congruently released), are currently based on literature. The initial surface area is an intrinsic property of the waste. After disposal of the glass, the value can however evolve with time, influenced by environmental factors. Due to a lack of experimental data concerning the evolution and the behaviour of cracks at high pH, the selected cracking factors are based on the literature data for neutral pH (Ferrand, 2011).

### **Bituminised waste degradation**

The bitumen are a very important type of category B waste as about 3 000 m<sup>3</sup> of waste should be disposed of. The waste contains (as a percentage of weight), next to 60% bitumen, 20 to 30% sodium nitrate ( $\text{NaNO}_3$ ) and 4 to 6% calcium sulphate ( $\text{CaSO}_4$ ). The waste further contains  $\text{CaF}_2$ ,  $\text{Ca}_3(\text{PO}_4)_2$ ,  $\text{Ni}_2[(\text{Fe},\text{Mn})(\text{CN})_6]$ , and oxides and hydroxides of Fe, Zr, and Al (4–10%). The content of radionuclides is at most 0.2% by weight. The salts, precipitates, and (hydr-)oxides are homogeneously dispersed in the bitumen matrix (Valcke *et al.*, 2009).

The physico-chemical properties of bituminised waste continuously evolve due to ageing. The extent and rate of this ageing depend on many factors like chemical composition and structure of the bitumen, time, temperature, radiation, exposure to oxygen, etc. Ageing is mainly due to oxidation and radiolysis. Because of ageing by both phenomena, bitumen becomes harder and less plastic, while there is a radiolytic production of hydrogen (the consequences of which are discussed in Section 4.2.2.5). In the case of

geological disposal, Eurobitum will be in contact with oxygen up to closure of the monolith B. The thickness of the oxidised layer of Eurobitum will depend on the time elapsed between the production of the waste and its underground disposal, and is not well known yet.

After disposal, upon availability of water, hygroscopic salts embedded in the waste will absorb water, resulting in the swelling of the waste and subsequent geo-mechanical perturbation of the clay. As the waste is hydrated, the salts embedded in the bitumen are progressively leached and released into the EBS and the host rock. A large RD&D programme focuses on understanding these geo-mechanical and geo-chemical perturbations (see Section 4.2.2.4).

Experimental study of the swelling and  $\text{NaNO}_3$  releases resulting from the hydration of Eurobitum occurred through water-uptake experiments. In these tests, small Eurobitum samples (diameter 38 millimetres, height 10 millimetres), either radioactive or non-active, are hydrated in water-uptake cells. The hydration occurs either in constant pressure conditions or in constant volume conditions. The hydration of Eurobitum results in an overall swelling of the samples in the constant pressure condition tests or in a stress increase in the constant volume tests. Characterisation of leached samples is performed by use of micro-focus X-ray tomography and Environmental scanning electron microscopy. These tests led to the identification of processes occurring when Eurobitum is in contact with water (Mariën *et al.*, 2013):

- an osmosis-induced water uptake;
- the dissolution of salt crystals and subsequent dilution of the salt solution, with an increase in porosity as a result;
- the release of dissolved salts;
- the recompression of highly leached layers in low-porosity layers by local consolidation;
- a creep of the bitumen matrix.

Figure 58 presents schematically the phenomenology of the water uptake and swelling in restricted swelling conditions for a binary mixture of bitumen and  $\text{NaNO}_3$ .

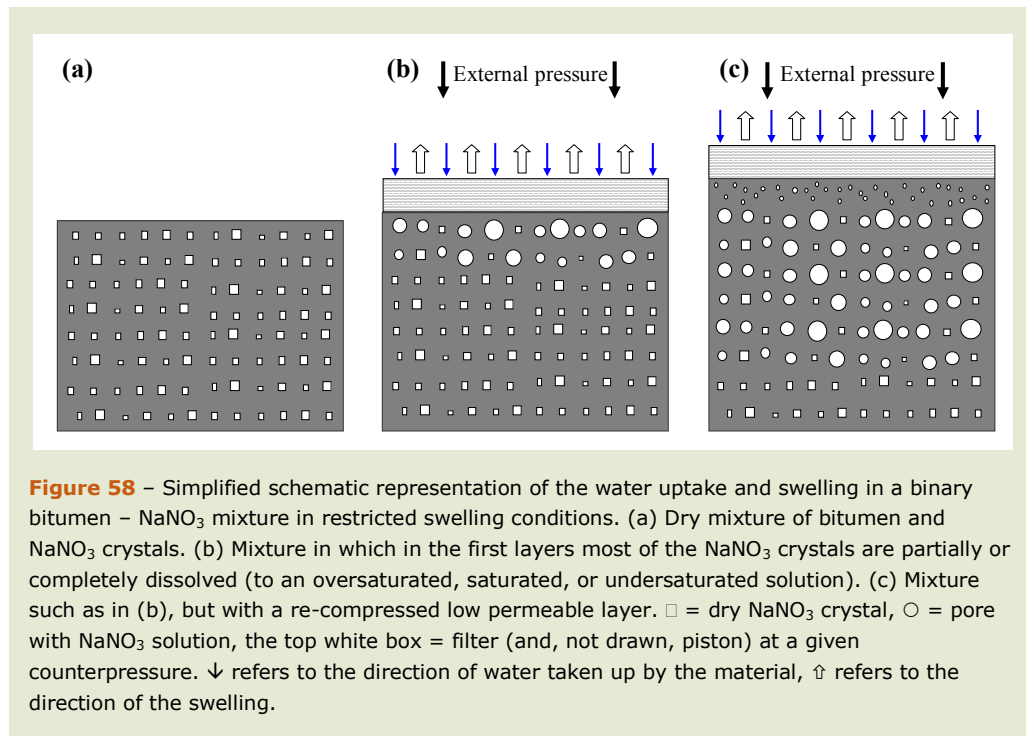
For better understanding, the SCK•CEN investigated the influence of five parameters ("parametric investigation"): the total stress on the Eurobitum samples, the water pressure, the salt content of samples, the water activity of the leachant solution (which allowed to confirm the osmosis phenomenon), the Eurobitum membrane efficiency (tests with differently aged Eurobitum samples). This parametric study revealed that the rate of swelling, pressure increase and  $\text{NaNO}_3$  leaching depends on

- the efficiency of the bitumen membrane (slightly different swelling, pressure increase and  $\text{NaNO}_3$  leaching rates were obtained for the inactive and radioactive samples);
- the waste loading of the samples;
- the boundary conditions under which the samples were hydrated, that is the water



activity of the contacting solution and the effective stress<sup>75</sup> on the sample.

Based on experimental results, UPC has developed a fully coupled hydro-chemical-mechanical constitutive model for Eurobitum that includes the osmotic flow and the solute diffusion. This model qualitatively reproduces the swelling, the pressure increase and the NaNO<sub>3</sub> leaching rates that were measured in the water uptake tests with inactive “reference” Eurobitum in contact with water, at least for a period in which the samples are only partially hydrated (at the end of 2012, no sample has reached full hydration yet).



Based on experimental results and insight gained from modelling, three successive phases are identified in the evolution of Eurobitum within its environment in disposal conditions:

1/ Free swelling phase after closure of the gallery. Initially, the salts are homogeneously dispersed in a matrix of bitumen. After disposal, the waste will come in contact with pore water. NaNO<sub>3</sub>, a dehydrated and hygroscopic salt, will absorb this water and dissolve. The bitumen surrounding the salts is an efficient semi-permeable membrane, which strongly hampers the leaching of NaNO<sub>3</sub>. Therefore, the volume of water that is taken up by the waste is higher than the volume of NaNO<sub>3</sub> that can leach out of it (that is osmosis), leading to swelling. The volume of the waste thus increases until the free volume in the drums (about 20%) is filled.

2/ Restricted swelling phase. Once the free volume in the drums is filled, an increasing osmotically-induced pressure will be exerted by the bitumen on the Boom Clay through the intermediate of monolith B, backfill and lining, which will result in a gradual deformation of the formation surrounding the disposal gallery (Section 4.2.2.4). With

<sup>75</sup> The effective stress is the total stress less the pore pressure.

time, more water is taken up, which will dissolve more  $\text{NaNO}_3$  situated deeper in the waste and dilute the  $\text{NaNO}_3$  solution in the outer layers where the salts are already dissolved. There is thus formation of pores that are filled with saline solution and that with time become interconnected, increasing the permeability of the corresponding layer.

3/ Reconsolidation phase. During this phase, the highly leached waste is compressed and the stress on Boom Clay is reduced.

The constitutive model also explains the difference of swelling behaviour between Eurobitum and the other bituminised wastes such as a Japanese one. The Japanese bituminised waste is less homogeneous and contains more hydrosoluble salts than Eurobitum. The bitumen membrane is not continuous: the osmotic barrier, which is due to the bitumen, is thus not efficient. Consequently, the Japanese bitumen does not swell.

Current work includes the development of large-scale water uptake experiments (constant stress tests at 5 bar counterpressure on samples with a diameter about 10 centimetres). Results from the large-scale water uptake tests will allow UPC to validate the constitutive model for Eurobitum. Further development of the constitutive model and study of the interaction between swelling Eurobitum and Boom Clay are the subjects of a post-doctoral research at UPC.

### Other category B waste

Until now, the Belgian geological programme focuses on the dissolution of high-level waste and of bituminised waste. Consequently, there is currently limited information regarding the dissolution of other category B waste in a disposal system built in Boom Clay.

One study analysed the degradation products of cellulose in presence of crushed Portland cement suspensions (Valcke *et al.*, 2003). Results show that the degradation-products solutions contained high concentrations of dissolved organic matter. These are attributed to the presence of non-cellulose compounds, for instance hemi-cellulose, in the pure cellulose powder because these compounds are readily extractable and/or degrade easily to low molecular weight compounds, mostly of unknown composition. Only about 5% of the total dissolved organic matter content could be attributed to the presence of iso-saccharinic acid (ISA)<sup>76</sup>. The very low total ISA concentration in the degradation product solution is the result of a strong sorption of ISA on cement. This is in line with results from other researchers. The study concluded that the presence of cemented cellulose-based waste in a final repository in Boom clay will not present problems as far as the production of chemical degradation products of cellulose is concerned.

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76 ISA belongs to the class of polyhydroxycarboxylic acids, which are known to form stable complexes with various metal cations, especially under alkaline conditions. At sufficiently high ISA concentration, the formation of water-soluble radionuclide complexes with iso-saccharinic acid might decrease the sorption and increase the solubility of radionuclides, thus potentially affecting the performance of a repository for such type of waste.

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### Roadmap – Section 4.2.3.4 – Evolution of the wastes (BC)

#### UOX

For *SCF1*, ONDRAF/NIRAS will refine knowledge of the dissolution of UOX irradiated fuel in a cement environment. ONDRAF/NIRAS will also continue to collaborate as end-user in the European Union project FirstNuclides<sup>77</sup> whose overall objective is to improve understanding of the IRF from (mainly) high-burnup UOX irradiated fuel. (The FirstNuclides project also includes studies on the leaching of MOX irradiated fuel.)

#### Glass

For *SFC1*, ONDRAF/NIRAS will refine knowledge of the dissolution of glass matrices in a cement environment, focusing on the interpretation and modelling of experimental data. Unlike irradiated fuel, glass evolution is sensitive to chemical evolution of cementitious materials.

#### Eurobitum

For *SFC1*, ONDRAF/NIRAS will collect lines of evidence about the respective leaching rates of radionuclides and nitrates. (It is expected that the radionuclides leaching rates are lower than the nitrates leaching rates.)

For *confidence building*, ONDRAF/NIRAS will also pursue confirmation experiments. They aim, among other things, to confirm that the upscaling hypotheses used in calculations are valid:

- ONDRAF/NIRAS will continue to characterise the swelling of Eurobitum and the release of salts in the range of conditions expected in a repository;
- ONDRAF/NIRAS will continue to investigate the leaching of organic molecules due to the chemical and radiolytic degradation of Eurobitum and other products and characterise the organic degradation products.
- ONDRAF/NIRAS will also launch a large-scale experiment (*whose results are expected in decades*) to confirm that the knowledge gained from small-scale laboratory tests can be transposed to the behaviour of Eurobitum waste at the scale of a disposal gallery.

ONDRAF/NIRAS will continue its investigations on gas production by degradation of Eurobitum, in particular by radiolysis and, possibly, through microbial activity. Results of this research are *not expected for SFC1*. After *SFC1*, ONDRAF/NIRAS will check whether other salts present in Eurobitum may influence its behaviour.

#### Other B waste

For *SFC1*, ONDRAF/NIRAS will make a preliminary assessment of the degradation processes (chemical, biological, gas production) in other category B waste. Indeed, some components of this waste, such as phthalates or cellulose, may influence the EBS properties (see roadmap Section 4.2.3.1). For *later SFCs*, impact of the evolution of cementitious materials on waste components will be assessed.

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77 FirstNuclides: Fast / Instant Release of Safety Relevant Radionuclides from Spent Nuclear Fuel (EU project).

#### **4.2.3.5. The evolution of the engineering barrier system with time in terms of criticality safety can be bounded**

Category C and most category B waste contain fissile radionuclides. These nuclides could cause a spontaneous and sustained nuclear chain reaction, producing large amount of energy and heat. In order to occur, criticality requires sufficient quantities of fissile isotopes in a suitable geometry and a neutron moderator such as water.

The probability of occurrence of a critical event must be limited anytime. The way to handle fissile materials during the operational period is detailed in Section 5.6.4. The fissile content of the waste primary packages is one criterion for the selection of impacting waste families that will constitute the basic input to the safety assessments (Section 3.1.3). In the long term, after widespread deterioration of the physical containment provided by the waste primary package, there is the possibility of movement of fissile material out of many waste packages and subsequent accumulation into new configurations that could in principle lead to a criticality event. The probability of occurrence of such configurations for category B waste and vitrified high-level waste is negligible.

In the case of UOX and MOX irradiated fuels from commercial reactors, avoiding criticality has been a design-driving factor since the start of the programme on geological disposal in Belgium. A Ph.D.' work under the supervision of ONDRAF/NIRAS, focused on criticality calculations, highlighted that the supercontainer design presents less criticality risks than the SAFIR2 design (Wantz, 2005). This is mainly due to the concrete layers surrounding the overpack, the cast iron basket between the boxes and the filling (with sand) of the "void" spaces inside the boxes<sup>78</sup>. The concrete layers prevent the sand from escaping, limiting thus the water fraction inside the overpack. The most important parameters affecting criticality calculations are the quantity of water (whose ingress should be limited), the burnup (the higher the burnup, the lower the risk of critical event) and the time. The calculations were performed with a supercontainer design slightly different from the current one, considering fresh (non-irradiated) fuel. More precise calculations will be performed at a later stage of the programme with the updated design, materials and dimensions.

Whether burnup credit should be used in criticality evaluations – that means performing calculations on irradiated fuel (thus less reactive) instead of fresh fuel –, remains an open question. This approach, studied by numerous waste agencies, is applicable to the Belgian inventory, according to the STARBUC<sup>79</sup> study (Lance and Boulanger, 2007). It would increase realism and reduce the over-conservatism of the results but requires a reliable characterisation of each irradiated fuel assembly. In addition, to rely on burnup credit in long-term safety analysis, it has to be shown that the relevant absorber nuclides are not separated from the fissile materials in the long term.

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78 The current reference design also includes the filling of the space between containers and overpack with an inert granular material or powder, see Section 5.1.1.

79 STARBUC study: Stratégie d'application réaliste du Burnup Credit pour le concept belge de dépôt final.

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**Roadmap – Section 4.2.3.5 – Criticality (BC)**

*For SFC1*, ONDRAF/NIRAS plans to develop a methodology for handling criticality safety for category B&C waste. It will include a review of the existing post-closure criticality studies, the analysis of the fissile inventory of all families of category B&C waste, the identification of penalising families (Section 3.1.3) and, if necessary, specific criticality calculations.

ONDRAF/NIRAS will check the methodologies of other waste management agencies on this topic. It will also follow up international activities related to the use of burnup credit for geological disposal of irradiated fuel.

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# 3

## **Part 3**

**The feasibility of geological disposal  
in Boom Clay can be assessed**



## **5. The repository can be constructed, operated and closed safely**

RD&D to underpin the feasibility of constructing, operating, closing, and where applicable, decommissioning, the proposed disposal design for category B&C waste is a key element of ONDRAF/NIRAS programme in support of the geological disposal of these wastes in Belgium. The importance of demonstrating and substantiating the feasibility of the disposal design is emphasised by the conclusions of the peer review of the SAFIR2 submission, which highlighted uncertainties relating to the feasibility of implementing the design envisaged at that time (ONDRAF/NIRAS, 2001b) (NEA, 2003).

This chapter discusses the RD&D programme that is being carried out to provide confidence in the feasibility of constructing, operating and closing the proposed repository for category B&C waste. For SFC1, the aim is to evaluate feasibility at the conceptual design level, in order to demonstrate that there is no fundamental flaw, or “showstopper” relating to implementation of the disposal design (Wacquier et al., 2011b) (Van Marcke *et al.*, 2012b). The feasibility RD&D programme is being carried out in accordance with the approach set out in ONDRAF/NIRAS feasibility strategy and feasibility assessment methodology (Section 2.3.2) (ONDRAF/NIRAS, 2011e). ONDRAF/NIRAS is confident that the approach being followed will enable them to identify and characterise uncertainties relating to feasibility, and to address these issues at the required level of detail in support of SFC1 and beyond.

This chapter presents the status of understanding and plans for RD&D in support of feasibility as of December 2012, based on the repository design presented in Section 3.2.3. Work is continuing to address remaining areas of uncertainty and to build further confidence in the feasibility of the proposed design for geological disposal in Belgium, and plans for RD&D will be updated to reflect advances in understanding as the feasibility programme progresses. There is already substantial evidence underpinning the feasibility of many of the steps that would be involved in the geological disposal of radioactive waste in Belgium. This comes from activities performed by ONDRAF/NIRAS and supporting organisations over the last three decades, as well as experience from waste management programmes considering geological disposal in other countries.

An initial report synthesising the state-of-the-art was prepared at the start of a 4-year collaborative programme of RD&D to underpin feasibility, and reflects the state of understanding in July 2010 (Galson, 2011). The position presented in this RD&D Plan reflects advances in understanding based on RD&D that has been completed since development of this state-of-the-art synthesis report.

The feasibility assessment methodology is based on the substantiation of a hierarchy of Feasibility Statements (FS) covering all steps of the disposal process, from the removal of primary waste packages from interim storage facilities, to closure of the repository (including the monitoring period) (Table 17). This chapter summarises the current status of understanding for each FS, key areas of work and key areas of uncertainty that need to be addressed presented in the form of a roadmap at the end of each section.



**Table 17** – High-level Feasibility Statements

<b>FS The proposed disposal system can be constructed, operated and progressively closed taking into account operational safety issues and with adequate funding</b>	
<b>Indeed,</b>	<b>FS 1 The engineering practicability of the disposal system is proven</b>
Indeed,	FS 1.1 The disposal waste packages can be fabricated
and,	FS 1.2 The repository for category B&C waste can be constructed
and,	FS 1.3 The repository for category B&C waste can be operated
and,	FS 1.4 The repository for category B&C waste can be closed
and,	FS 1.5 The performance of the disposal system can be monitored
<b>and</b>	<b>FS 2 The safety of workers, the public and the environment can be guaranteed during the operational phase</b>
Indeed,	FS 2.1 The non-radiological risks associated with a normal operating scenario can be mastered
and,	FS 2.2 The radiological risks associated with a normal operating scenario can be mastered
and,	FS 2.3 The risks resulting from accident scenarios and external events can be mastered
and,	FS 2.4 Fissile materials can be handled appropriately from a security, safeguards and criticality perspective
<b>and</b>	<b>FS 3 The costs for the construction, operation and closure of the repository can be</b>
Indeed,	FS 3.1 The costs for construction, operation and closure of the disposal facility for category B&C waste, including decommissioning of the site surface installations, have been evaluated
and,	FS 3.2 Waste tariffs and current funding mechanisms are adequate to cover the required costs taking into account escalation

## 5.1. Feasibility of disposal waste package fabrication

This section discusses the RD&D programme to underpin the feasibility of fabricating disposal waste packages for category B&C waste, referred to as the category B monolith, or “monolith B”, and the supercontainer respectively. The relevant FS that require substantiation are shown in Table 18.

**Table 18** – Excerpt of the FS hierarchy showing FS relating to disposal waste package fabrication.

<b>FS 1 The engineering practicability of the disposal system is proven</b>	
Indeed,	FS 1.1 The disposal waste packages can be fabricated
Indeed,	FS 1.1.1 The supercontainer can be fabricated
and	FS 1.1.2 The monolith B can be fabricated
and	FS 1.1.3 The post-conditioning facilities for category B&C waste can be constructed, operated, decommissioned and dismantled

The **post-conditioning facilities** are the surface buildings where disposal waste packages are assembled from their constituent parts and stored, prior to transfer underground for final disposal.

Discussion in Section 5.1 covers the following areas:

- The feasibility of fabricating and assembling the supercontainer for the disposal of category C waste (Section 5.1.1). This discussion relates to FS 1.1.1.
- The feasibility of fabricating and assembling the monolith B for the disposal of category B waste (Section 5.1.2). This discussion relates to FS 1.1.2.
- The feasibility of designing, constructing, operating, decommissioning post-conditioning facilities on the surface of the repository site (Section 5.1.3). This discussion relates to FS 1.1.3.

### 5.1.1. Supercontainer fabrication

Supercontainer fabrication has been (and continues to be) the subject of extensive RD&D since its selection as the reference disposal waste package for category C waste in 2004 (ONDRAF/NIRAS, 2004b) (Belgatom, 2007) (Belgatom, 2008) (Van Humbeeck *et al.*, 2008) (Areias *et al.*, 2010). This emphasis on the supercontainer within ONDRAF/NIRAS RD&D programme arises for several reasons, which include:

- The relatively recent selection of this disposal design.
- The fact that this disposal design, which envisages a large disposal waste package with integral cementitious buffer, is rather different to the disposal design for high-level waste and irradiated fuel considered by other waste management organisations worldwide, which reduces the quantity of transferable experience that is available.
- The strong emphasis placed on the performance of the supercontainer during both the operational and post-closure phases of the repository.

As discussed in Section 3.2.3.1, the main function of the supercontainer is to provide complete containment of radioactivity at least through the thermal phase which is defined as the period during which the temperature of the host formation is expected to

lie above the range of temperatures within which nominal radionuclide migration can be relied upon (ONDRAF/NIRAS, 2008a). Containment during the thermal phase is provided by a thick carbon steel overpack, which will degrade extremely slowly, in the high-pH environment promoted by the surrounding cementitious buffer. The main constraints on the buffer are listed hereafter:

- Create favourable environment to optimise overpack lifetime (corrosion), for instance by use of a high-pH cement (ordinary Portland cement) and carbonate aggregates (which eliminate alkali-silica reaction (ASR));
- Provide permanent shielding for workers ( $25 \mu\text{SV}\cdot\text{h}^{-1}$  at 1 metre from the disposal waste package);
- Provide efficient heat dissipation;
- Provide sufficient mechanical strength (handling, gallery support, accidental fall, retrievability,...);
- Not affect (negatively) the retention capacity of Boom Clay (e.g., through appropriate selection and limitation of chemical additives).

The supercontainers will be fabricated on the surface. The first stage of supercontainer assembly consists of inserting the waste packages into an overpack. In the current reference design, the radial and axial thicknesses of the overpack are respectively 30 and 60 millimetres (Wacquier and Van Humbeeck, 2009). These thicknesses take into account the thickness required for standing the mechanical stresses plus a thickness to ensure that the overpack remains intact during the thermal phase.

- The overpack for vitrified high-level waste (VHLW) will have an external diameter of about 0.5 metre and will contain 2 vitrified waste packages. The containers will be positioned symmetrically within the overpack using guides, and will be in end-to-end contact.
- The overpack for uranium oxide (UOX) irradiated fuel contains 4 separate boxes positioned in a 2×2 array, with an external diameter of about 1 metre. Three lengths will exist, to accommodate the lengths of the different assemblies (respectively 8, 12 and 14 feet). Assemblies of different burnup will be combined for not exceeding, per overpack, the mean burnup used in safety evaluations. The boxes containing the irradiated fuel assemblies will be supported within the overpack by a cast iron basket.
- The overpack for mixed oxide (MOX) irradiated fuel will contain only one box, with an external diameter of about 0.4 metre.

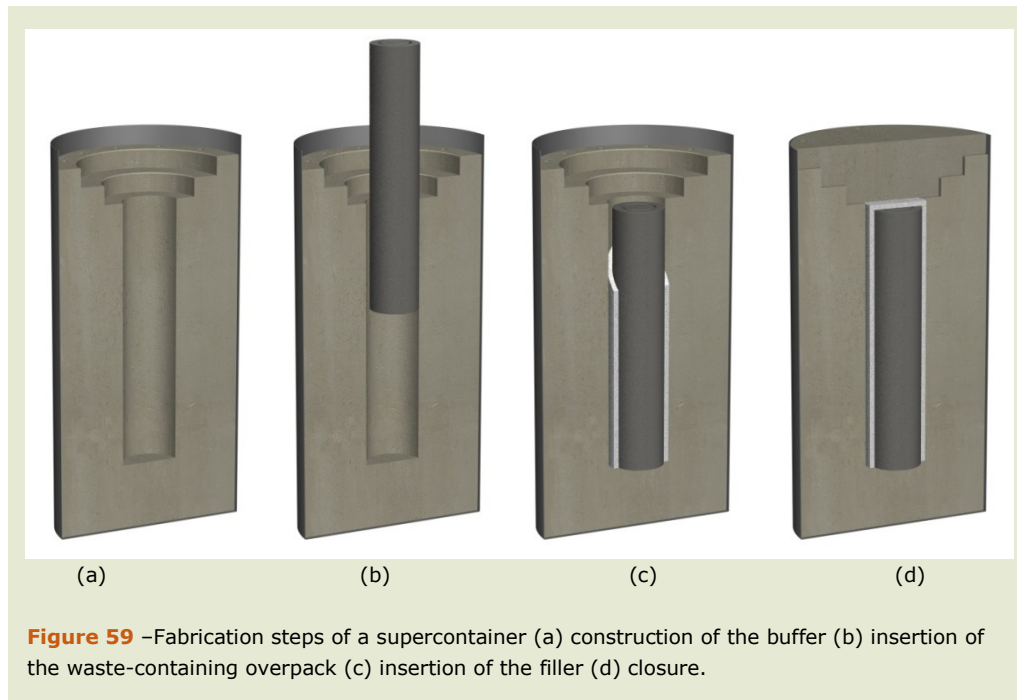
The space between containers and overpack will probably be filled with an inert granular material or powder and an inert gas before the overpack is sealed by welding (Belgatom, 2006) (Wickham, 2008).

The second stage of supercontainer assembly involves four steps (Figure 59):

- Step 1: Construction of the buffer, using the envelope as a mould. The buffer will be cast with its long axis vertical. The thickness of the buffer is determined by the shielding criterion (maximum  $25 \mu\text{Sv}\cdot\text{h}^{-1}$  at 1 metre);
- Step 2: Emplacement of the waste-containing overpack within the buffer;

- Step 3: Placement of a cementitious filler in the small annulus remaining around the overpack;
- Step 4: Closure and sealing of the supercontainer (Section 3.2.3.1).

Steps 2 to 4 will be carried out in a “hot cell” to ensure protection of workers from radiation.



The performance and evolution of the carbon steel overpack is of particular interest, given the key contribution made by this barrier towards assuring post-closure safety. ONDRAF/NIRAS has initiated studies for designing a watertight overpack able to withstand mechanical stresses at least during the thermal phase, with limited localised corrosion (Belgatom, 2006) (Herms, 2010). Corrosion of the overpack has been extensively researched, and there is a high degree of confidence that very low corrosion rates will be observed (Section 4.2.3.3). From a feasibility perspective, a related uncertainty that is being evaluated concerns the approach used to weld the overpack closed during fabrication. It is important to ensure that the welded region is not unacceptably susceptible to more rapid corrosion than the rest of the overpack, through processes such as stress corrosion cracking and hydrogen embrittlement. The conditions that could potentially affect the corrosion behaviour of the carbon steel in its environment and preventive measures that could be undertaken from the point of view of materials selection and welding procedures (in terms of strength grade, microstructure, processing, chemical composition and so on) were summarised in (Herms, 2010). Expanding on this work, samples from a plate of carbon steel are being used to test different welding techniques and to investigate the relative susceptibility of welded and unwelded carbon steel to stress corrosion cracking and hydrogen embrittlement under different environmental conditions. Preliminary results from studies carried out at a high corrosion potential are already available (Kursten, 2009), and a series of longer-running studies at a lower corrosion potential are planned over the next few years.

Other key uncertainties relating to supercontainer fabrication include:

- The impact of inserting a hot overpack (heated by the radioactive decay of the waste contained within it) into the pre-cast concrete buffer of the supercontainer. The behaviour of the supercontainer concrete under various thermal and mechanical loads was simulated within a Ph.D. thesis (Craeye, 2010). The thesis concluded that no crack formation is expected during the hardening of the concrete buffer. However, the risk of cracking after installing the overpack could not be excluded.
- The methodology for emplacing a cementitious filler between the pre-cast buffer and the emplaced overpack, and the appropriate cement formulation for this component. A good contact between the filler and the overpack helps to ensure that a continuous passive layer forms on the surface of the overpack, which promotes slow, uniform passive corrosion.
- The feasibility of closing the supercontainer, and the approach to carry out this fabrication step. At present, the use of a pre-cast concrete end piece, or a poured end piece, or some combination of the two approaches, is being considered.

These uncertainties are being investigated through a series of pilot fabrication studies by a collaboration of EURIDICE, Tractebel Engineering and the University of Ghent. These studies consist of the construction of a full-scale diameter, half-scale length mock-up of a supercontainer known as the “half-scale tests” (Areias *et al.*, 2010) (Areias *et al.*, 2013).

The first half-scale test focused on fabricating the concrete buffer and investigating the impacts on the buffer of inserting a hot overpack simulated by means of a heater (Figure 60). This test was completed in 2009 (Areias *et al.*, 2011). Visual inspection of the concrete buffer after the concrete hardening confirmed the absence of tangential and axial cracks in the buffer as predicted by earlier simulations (Craeye, 2010). An array of apparently superficial small cracks appeared however on the surface of the buffer after insertion of the heat source. A possible mechanism for the creation of these cracks is the thermal expansion of the overpack, which induces tensile stresses in the buffer that can potentially exceed the tensile strength of the concrete. The formation of these cracks will be further examined in a second half-scale test. This test will also investigate the emplacement of the filler. A third half-scale test will focus on fabrication of the concrete lid for the supercontainer.



**Figure 60** – Components of the first supercontainer half-scale test, which aimed to demonstrate the feasibility of fabricating the pre-cast concrete buffer component of the supercontainer, and the impact of inserting a hot overpack on this component. Left: Removal of the mould after casting the concrete buffer. Right: The inner formwork of the mould.

The half-scale tests will provide additional understanding from an engineering and feasibility perspective that should inform future decision-making relating to the design of the supercontainer. A key decision still to be made concerns the choice of concrete formulation to be used in the pre-cast concrete buffer. Several different formulations have been explored in previous research on the supercontainer, and as part of the category A monolith demonstration programme, including self-compacting concrete, which contains a higher quantity of superplasticiser to improve its flow properties, and traditional vibrated concretes, which require vibration during emplacement. Self-compacting concrete formulations are currently preferred for use in the supercontainer.

In future, it will also be necessary to decide whether the supercontainer envelope (which is used as a mould during fabrication of the buffer) should be intact, perforated or absent at the time of disposal, since its condition is expected to have a significant effect on saturation of the buffer, and hence, on post-closure evolution (Wickham, 2008). Both scenarios (*i.e.*, an intact or a perforated/absent envelope) will be considered from a safety perspective for SFC1. From a feasibility perspective, the presence of the envelope at disposal could facilitate the retrievability of supercontainers from the repository. The feasibility of handling the supercontainer with or without an envelope during transfer and emplacement will also need to be confirmed. This is mainly relevant for FS 1.3.2, as discussed in Section 5.3.2. Ongoing studies in this area are likely to build on recently completed work on tilting and transfer of the supercontainer as part of a Master's thesis (Jacquemin, 2011).

Based on RD&D already performed, ONDRAF/NIRAS has a good understanding of the expected performance of the supercontainer, and is confident that it can fulfil the required safety functions during the operational phase of the repository and in support

of long-term safety. However, there are still several areas of uncertainty that need to be addressed in order to confirm that this disposal waste package can be fabricated according to design and performance requirements.

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### **Roadmap – Section 5.1.1 – Supercontainer fabrication**

*For SFC1*, ONDRAF/NIRAS will address several issues regarding supercontainer fabrication. It will check how to weld the top plate of the overpack onto the overpack cylinder and how to centre the overpack within the concrete buffer. It will pursue research on the filler (define the most appropriate composition and ways to install it) and on the concrete buffer (define the most appropriate composition, ways to construct it and looking for a type of reinforcement material compatible with concrete, if needed).

*For SFC1*, ONDRAF/NIRAS will also check what are the thermal and radiological conditions and stresses in the supercontainer components (envelope, concrete buffer, filler, concrete lid and overpack) during fabrication, storage, transport, disposal and potential retrieval of the supercontainer. It will assess the time required to fabricate a supercontainer (primary waste package emplacement and supercontainer closure included).

*For later SFCs*, ONDRAF/NIRAS will focus on issues regarding the closure of the concrete buffer (design, composition, method to place it) and the envelope (need for, design, fabrication process).

*For later SFCs*, ONDRAF/NIRAS will analyse how to fill the overpack with filling material after insertion of the primary waste packages for vitrified high-level waste or irradiated fuel. (This is an optimisation issue as frit emplacement is considered to be feasible.)

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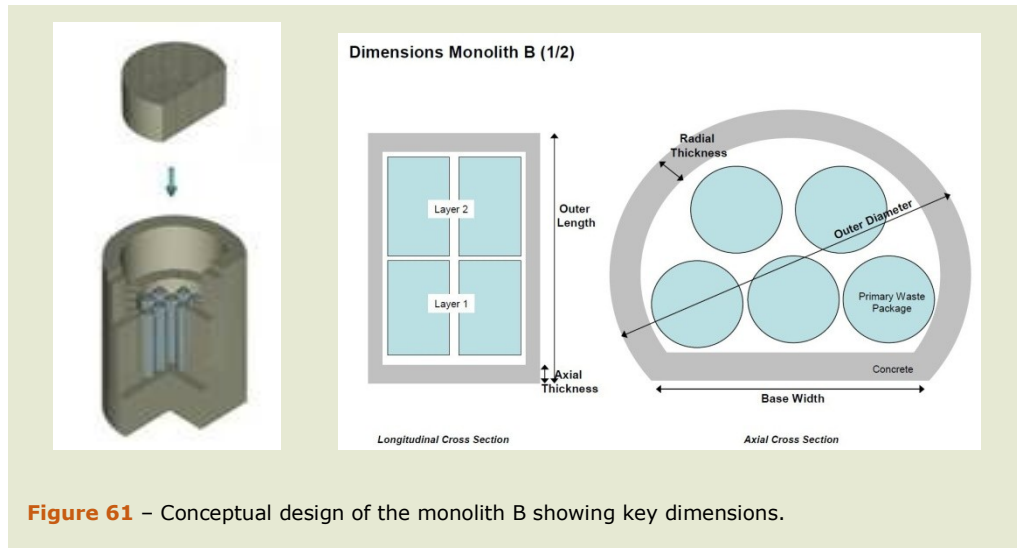
### **5.1.2. Monolith B fabrication**

The disposal packages for category B waste are called monoliths B. At the post-conditioning facility, primary waste packages are inserted in a pre-cast caisson, then mortar is poured in (eventually through the concrete lid) to fill up and close (*i.e.*, cover) the disposal package (Figure 61) (Wacquier and Van Humbeeck, 2009). One monolith B may contain primary waste packages from different families, to manage the variability of their characteristics (such as a higher heat output or activity than the mean package).

Currently, the thickness of the caisson has been determined taking into account only radiological considerations (*i.e.*, the required level of shielding provided by the concrete wall has to limit the dose rate to a maximum of  $25 \mu\text{Sv}\cdot\text{h}^{-1}$  at 1 metre from the disposal package) (Wacquier and Van Humbeeck, 2009).

Relatively little RD&D specifically focusing on the monolith B has been performed, compared with the intensive programmes of RD&D focusing on the supercontainer and on the category A monolith for packaging short-lived low activity waste (called monolith A) (ONDRAF/NIRAS, 2011d). This is partly due to the less stringent long-term performance requirements placed on the monolith B, since it is only required to fulfil

formal safety functions during the operational period (whereas the supercontainer also has specific performance requirements in support of long-term safety). Another reason is that information or understanding on the monolith A, and also on the supercontainer in terms of size, mass, component materials and envisaged assembly, is transferable to the design and construction of the monolith B.



**Figure 61** – Conceptual design of the monolith B showing key dimensions.

It is therefore considered that if the monolith A and the supercontainer are shown to be feasible to fabricate (by on-going demonstration tests such as the half-scale tests (Section 5.1.1) and demonstration of category A monolith fabrication (ONDRAF/NIRAS, 2011d)), then there will also be a high degree of confidence in the feasibility of fabricating the monolith B. An intensive RD&D programme is therefore not envisaged for the monolith B as an input to SFC1.

Some specific RD&D studies are however planned and ongoing to address issues that are specific to category B waste and the monolith B. Key uncertainties mainly result from the fact that a thicker caisson is required for packaging category B waste, compared to the monolith A, in order to provide sufficient radiological shielding to protect workers during operational activities. Thus, it remains to be demonstrated that it is feasible to fabricate, transfer and handle a thicker caisson.

A report is being prepared which synthesises current understanding relating to the design and performance of the monolith B (ONDRAF/NIRAS, 2013). This includes discussion of the transferability of experience from RD&D programmes focusing on the monolith A and the supercontainer, as well as consideration of the load cases that the monolith B is likely to be subjected to during fabrication and subsequent stages of the waste disposal process.

Another uncertainty concerns the potential need for reinforcement of caisson for monolith B. Fibre reinforcement materials (including glass fibres) have been proposed as an alternative to steel reinforcement bars (rebar) within the caisson, to help reduce the quantity of metal in the repository and hence, to reduce the associated production of hydrogen gas. Gas generation (from waste degradation, corrosion of metallic disposal system components such as reinforcement materials and radiolysis) might be a key issue affecting the long-term evolution of the repository, particularly for the disposal of



category B waste, as discussed in Section 4.2.2.5. Studies on fibre reinforcements to-date have focused on the chemical compatibility of different reinforcing materials with cementitious components (ONDRAF/NIRAS, 2013). Future work is likely to focus on the mechanical compatibility of fibre reinforcement materials with different cement formulations.

Such compatibility issues could potentially limit the transferability of some experience from the supercontainer half-scale tests, which use a self-compacting concrete formulation. There is also uncertainty relating to the feasibility of vibrating a traditional vibrated concrete type formulation satisfactorily for a caisson that is up to 60 centimetres thick (much thicker than the caisson for monolith A). Therefore, the preferred concrete formulation for the monolith B will require further careful consideration.

A significant proportion of the category B waste inventory has been encapsulated in a bitumen matrix. These bituminous wastes are expected to swell over time, as they absorb water from the surrounding environment (Section 3.1.3). The degree of swelling expected may affect future decision-making relating to the number of primary waste packages to be emplaced in each monolith B, in order to ensure that there is no detrimental effect on the integrity of either the monolith or the surrounding Boom Clay. The anticipated impact of swelling on the Boom Clay surrounding a disposal gallery has already been characterised (Valcke *et al.*, 2013). However, the implications of swelling bituminised waste on the integrity of the monolith B itself have not yet been studied, and will need to be explored in order to better underpin arguments in support of long-term safety, as well as to determine the feasibility of retrievability. Once disposed in a geological repository, the presence of Eurobitum waste will also lead to a continuous production of gas by anaerobic corrosion, radiolysis and microbial activity. Research is going on to evaluate whether these gases may be evacuated by diffusion (see Section 4.2.2.5 for RD&D results).

Another area of planned RD&D concerns the approach to ensure operational safety through appropriate packaging of specific waste types that will generate gas during the operational period (such as radium-bearing wastes which will generate radon gas). Depending on the potential dose to workers during waste emplacement activities, it could be desirable to implement a gas-tight overpack within monoliths B containing specific waste types, to prevent gas from escaping during repository operation. However, such an overpack could be subject to pressurisation from the build-up of hydrogen gas inside. Although the associated open questions relate to the design of the monolith B, this is clearly a cross-cutting issue that is also relevant for worker safety, covered under FS 2.2. The preferred way forward is to manage the potential impacts of gas release through implementation of an appropriate repository ventilation system as discussed in Section 5.6.1. Only if this is shown not to be feasible will a gas-tight overpack within the monolith B be considered.

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### **Roadmap – Section 5.1.2 – Monolith B fabrication**

*For SFC1*, ONDRAF/NIRAS will assess the thermal and radiological conditions and stresses in the monolith B components (pre-cast caisson, mortar filler and lid) during fabrication, storage, transport and disposal and potential retrieval of monolith B.

An intensive RD&D programme is not envisaged for the monolith B as an input to SFC1 as it is considered that if the monolith A and the supercontainer are shown to be feasible to fabricate, then there will also be a high degree of confidence in the feasibility of fabricating the monolith B. Most issues regarding the monolith B fabrication are therefore deferred to later SFCs. ONDRAF/NIRAS will then do research on the design, composition, fabrication method and/or installation ways of several components: the pre-cast caisson (including the type of reinforcement, if required), the filler and the lid of this monolith B.

*For later SFCs*, ONDRAF/NIRAS will also address issues regarding specific waste types, assessing for instance the number of waste packages that can be included in a monolith B. It will also check how to include an internal gastight overpack in the monolith B design for specific waste types if needed (*e.g.*, to avoid release of gaseous radionuclides during the operational phase).

*For later SFCs*, ONDRAF/NIRAS will assess the time required to fabricate a monolith B (primary waste package emplacement and monolith closure included).

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### **5.1.3. Surface facilities for disposal package fabrication and storage**

Several studies have already been performed to consider the design of surface facilities for the fabrication, assembly and buffer storage of disposal waste packages, and to identify the associated equipment and human resources that will be required (Tractebel, 2007) (ONDRAF/NIRAS, 2009d). Similar studies on disposal package fabrication and storage facilities are also performed by other waste management organisations (*e.g.*, (Andra, 2005b) (Posiva, 2006)), and much of this experience is transferable, although the detailed design of surface facilities will be strongly linked to the design of the specific packages being fabricated. Other recent RD&D studies, including work on tilting and transferring the supercontainer (Jacquemin, 2011) are also relevant for identifying steps in the disposal waste package fabrication and transfer process (Section 5.3.2), and associated equipment required on the surface of the repository site.

Based on existing work performed to date, there is a high degree of confidence that it will be feasible to design, construct, operate and decommission the surface facilities required for disposal waste package fabrication and storage prior to transfer to the repository. This is reinforced by the widespread operation of complex waste package fabrication and storage facilities at nuclear power production and waste management sites worldwide, as discussed in Section 5.3.2. There are clear regulations in place for the construction, operation and decommissioning of such facilities in Belgium (Moniteur belge, 2001).

Some uncertainties relating to surface facilities for disposal waste package fabrication and storage remain, for example:

- Performance of equipment under hot cell conditions (if required).
- Identification of appropriate quality control measures during disposal waste package fabrication.

- Evaluation of the expected operating lifetime of surface facilities, and development of a methodology for their decommissioning.

However, these uncertainties mainly relate to optimisation, rather than demonstrating feasibility at the conceptual design level and are therefore more relevant for later SFCs. It is not considered necessary to carry out further, more detailed development of the design of these facilities until the disposal waste packages themselves have been more precisely specified.

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### **Roadmap – Section 5.1.3 – Surface facilities**

Based on existing work performed to date, there is a high degree of confidence that it will be feasible to design, construct, operate and decommission the surface facilities required for disposal waste package fabrication and storage prior to transfer to the repository. *For later SFCs*, ONDRAF/NIRAS will identify the specific issues regarding ageing and longevity of the surface buildings. (This is an optimisation issue.)

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## 5.2. Feasibility of repository construction

This section describes the RD&D programme to underpin the feasibility of excavating and constructing a repository for category B&C waste from an engineering perspective. The relevant FS that require substantiation are shown in Table 19.

**Table 19** – Excerpt of the FS hierarchy showing FS (Levels 1–4) relating to repository construction.

<b>FS 1 The engineering practicability of the disposal system is proven</b>	
Indeed,	FS 1.2 The repository for category B&C waste can be constructed
Indeed,	FS 1.2.1 The shafts can be constructed
and,	FS 1.2.2 The category B disposal area can be constructed
indeed	FS 1.2.2.1 The access gallery and the crossings with the disposal galleries of the category B disposal area can be constructed
and	FS 1.2.2.2 The disposal galleries for category B waste can be constructed
and,	FS 1.2.3 The category C disposal area can be constructed
indeed	FS 1.2.2.1 The access gallery and the crossings with the disposal galleries of the category C disposal area can be constructed
and	FS 1.2.2.2 The disposal galleries for category C waste can be constructed

Discussion in Section 5.2 covers the following areas:

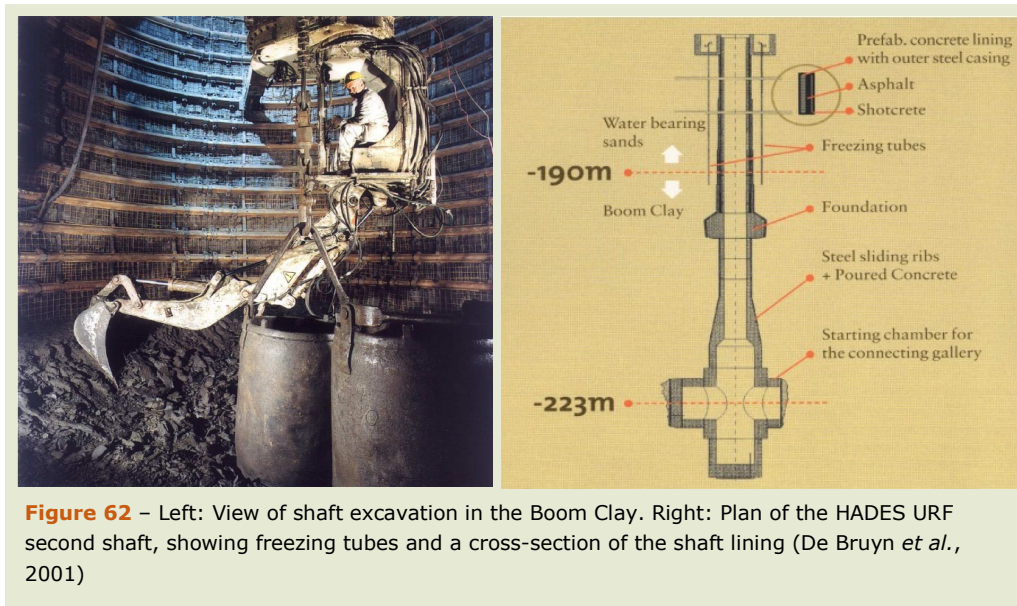
- The feasibility of constructing shafts to the proposed disposal depth in the reference geological environment, and particularly, the feasibility of constructing a large diameter waste shaft (Section 5.2.1). This discussion relates to FS 1.2.1.
- The feasibility of constructing access galleries and disposal galleries in the Boom Clay for the disposal of category B&C waste (Section 5.2.2). This discussion relates to FS 1.2.2 and FS 1.2.3 (and subsidiary FS).

### 5.2.1. Shaft construction

As mentioned in Section 3.2.3, the current reference design envisages construction of three shafts to allow transfer of disposal waste packages, personnel and equipment from the surface to the disposal depth (as well as removal of excavated spoil) (Van Cotthem *et al.*, 2012).

The two shafts dedicated to transport of personnel and equipment are likely to have a similar diameter to the shafts already excavated at the HADES underground research facility situated in the Boom Clay at Mol (Figure 62). Construction of shafts of diameter 2.5 – 3 metres to the reference disposal depth is clearly possible, given the safe construction and continued successful operation of HADES URF. A variety of techniques was employed to excavate and construct the two shafts at HADES URF (Galson, 2011). There is also extensive experience available from the construction of underground research facilities in host formations in other countries, such as the Meuse/Haute-Marne underground research facility in the Callovo-Oxfordian clay in France, and the Mont Terri project in the Opalinus Clay in Switzerland. However, this experience has somewhat

limited transferability to the Belgian concept, due to the different geological environments involved (host formations under consideration in France and Switzerland are more indurated than the Boom Clay).



**Figure 62** – Left: View of shaft excavation in the Boom Clay. Right: Plan of the HADES URF second shaft, showing freezing tubes and a cross-section of the shaft lining (De Bruyn *et al.*, 2001)

A particular challenge arises from the need to construct shafts passing through the permeable sandy aquifers overlying the Boom Clay. This makes it necessary to implement a waterproof lining to prevent water from entering the shafts while they are being used. Techniques used during construction of the HADES URF included (Galson, 2011):

- A polyethylene lining sandwiched between two concrete layers.
- A multi-layer lining, with the outer layer consisting of cast shotcrete, and the inner layer consisting of prefabricated concrete rings reinforced by a sheet of waterproof steel. The space between the two linings is filled with asphalt, which preserves the waterproofing of the shaft and distributes stresses on the shaft lining homogeneously.

In both cases, the water in the aquifer sands overlying the Boom Clay was frozen prior to the shaft excavation to stabilise the shaft walls, and to provide hydraulic isolation of the area until a waterproof lining was installed. Following construction, some asphalt leakage was observed from the lining of the second shaft of HADES URF, requiring regular asphalt refilling.

The main outstanding uncertainty relating to repository shaft construction concerns the feasibility of constructing a sufficiently large shaft, the waste shaft, to permit transfer of disposal waste packages from the surface to the disposal depth. The internal diameter of the waste shaft needs to be large enough to permit horizontal transfer of the longest supercontainer (6.25 metres in length), and must also accommodate the main hoisting system, emergency personnel hoist and potentially other infrastructure (*e.g.*, for ventilation). Initial studies suggested that an internal shaft diameter of 10 metres might be required (Belgatom, 2005). A more recent study carried out to optimise the waste shaft diameter concluded that an internal diameter of 8 metres would be sufficient to permit horizontal transfer of the largest supercontainer (DBE-TEC, 2010), and 8 metres

is now considered as the reference waste shaft internal diameter. This study is discussed further in Section 5.3.2.

Other areas of uncertainty relating to shaft design and construction include:

- The feasibility of constructing the intersection with the access gallery.
- How the later installation of a seal in the shaft will affect the shaft design and construction. The design of seals to be implemented in the galleries and shafts is being developed and is further explained in Section 5.4.2.
- The potential transferability of shaft construction techniques to other disposal depths.

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### **Roadmap – Section 5.2.1 – Shaft construction**

*For SFC1*, ONDRAF/NIRAS will assess the feasibility of constructing a sufficiently large shaft, the waste shaft, to permit transfer of disposal waste packages from the surface to the disposal depth and its intersection with the access gallery. ONDRAF/NIRAS will also address the issue of achieving waterproofing of the shaft lining in the aquifer sands.

*For later SFCs*, ONDRAF/NIRAS will evaluate the impact of the later installation of a seal in the shaft on the shaft design and construction.

*For SFC1*, ONDRAF/NIRAS will perform a preliminary analysis of the potential transferability of the shaft construction techniques considered for Boom Clay in the Mol-Dessel area to other disposal depths.

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### **5.2.2. Access gallery and disposal gallery construction**

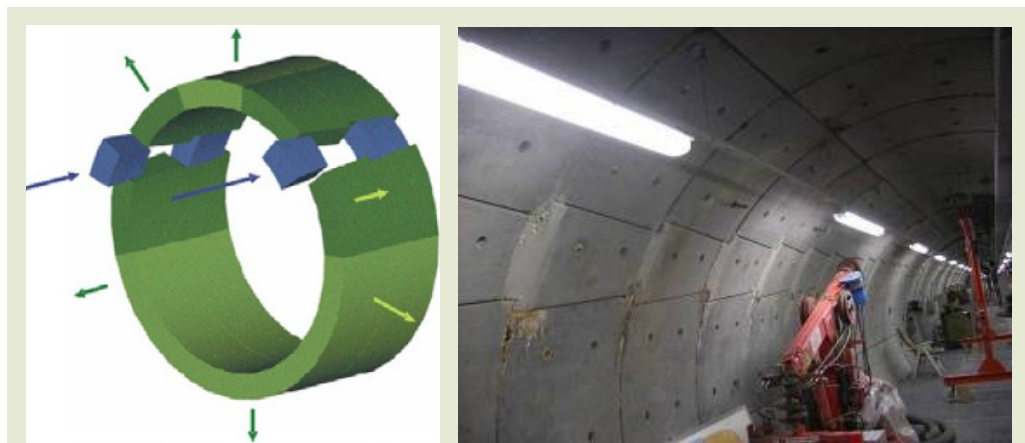
In the current reference design, all disposal galleries have an internal diameter of 3 metres while the internal diameter of the access gallery is 6 metres. It remains to be confirmed whether these dimensions allow the safe transport of the disposal waste packages in the underground repository (Section 5.3.2). The reference lining is made of concrete wedge blocks.

Feasibility Statements relating to access gallery and disposal gallery construction consider the category B and category C disposal areas separately because of the different thermal (and mechanical) load cases arising from waste emplacement. However, similar techniques are likely to be employed for the excavation and construction of all galleries, so the feasibility issues associated with both areas are discussed together in this section. There are therefore three main components to the discussion hereafter:

- The feasibility of excavating and constructing disposal galleries.
- The feasibility of excavating and constructing the larger diameter access gallery and the crossings with the disposal galleries.
- The performance of galleries under heat loading from category C waste.

Excavating and constructing disposal galleries with the required diameter (3 metres) at the reference depth in the Boom Clay has been demonstrated, based on experience constructing the HADES URF, where tunnels with internal diameter of up to 4 metres have been constructed. Because of the low strength of the Boom Clay, the excavated galleries require a lining. A variety of tunnel lining techniques have been successfully employed in HADES URF, including cast iron segments, concrete wedge blocks and sliding steel ribs.

The reference approach for the repository is to excavate by using a road header tunnel boring machine (TBM), as employed for excavation of the HADES URF Connecting gallery. The high excavation rates (3 metres per day for the Connecting gallery) and the application of an expanding lining type (wedge block system) (Figure 63) limit the development and extent of the damaged zone (Bastiaens *et al.*, 2003) (Section 4.2.2.1). Numerical simulations performed in the frame of the CLIPEX<sup>80</sup> project, gave reliable blind predictions in terms of displacement and pressure on the lining. This simulation allowed the optimisation of the tunnelling machine (CLIPEX, 2003).



**Figure 63** – Concrete wedge block system used to line the Connecting gallery of the HADES URF. The trapezoid “keystones” shown on the left in blue are inserted last, forcing the tunnel lining outwards, and limiting convergence of the surrounding Boom Clay.

The risk of the tunnelling machine getting stuck was tested by a stop-and-go test during the excavation of the PRACLAY gallery of the HADES URF. Restarting the tunnelling machine after a standstill could be difficult as the friction between the clay and the shield increases with time due to the convergence of the Boom Clay around the shield. Therefore, the excavation works were stopped for one week. No problems in restarting the works were encountered (Van Marcke and Bastiaens, 2012).

It is considered that the techniques used to excavate and construct the tunnels at the HADES URF could be scaled up to construct the larger (6 metres diameter) access gallery of the repository. This expectation will be fully evaluated through further RD&D.

A key outstanding uncertainty relates to the feasibility of constructing and reinforcing the large intersections required between the access gallery and the disposal galleries, which are set at right angles in the reference design. These intersections will have a

80 CLIPEX: Clay instrumentation programme for the extension of an underground research laboratory (EU project).

complex geometry, and will need to be large enough to allow a 90° rotation of the largest supercontainer (6.25 metres in length). The lining at the intersections will be subjected to high bending and torsion stresses. A concrete lining would not withstand these stresses without heavy reinforcement. The design and construction feasibility of the crossing points is therefore being further investigated. Two proposed solutions are:

- The installation of a rigid steel ring system as successfully employed at the intersection of the Connecting gallery and the PRACLAY gallery in the HADES URF. Scaling up the system used in the HADES URF to the size required in the repository is expected to be feasible. However, this system is expensive particularly since a reinforcing structure will be needed at every crossing point in the repository. Moreover, employing this system would introduce large amounts of steel into the repository, which over the long term could corrode, generating relatively large quantities of hydrogen gas. Such a significant source of gas could potentially affect repository performance. Gas generation and migration, and the associated impacts on repository evolution are discussed in greater detail in Section 4.2.2.5).
- The use of a cast iron lining in the access gallery instead of concrete wedge blocks. This approach was considered appealing because the distance between the disposal galleries for category B waste is small (50 metres), so changing the lining type for short sections was considered to be uneconomical and cast iron was maintained as lining material for the whole access gallery length (Belgatom, 2008). This system is also expensive and introduces large amounts of iron in the repository, a potential source of gas.

Given both proposed systems have their disadvantages, alternative solutions will be sought.

The design and layout of disposal galleries that will accommodate significant quantities of heat-generating wastes are highly dependent on the thermal output of these wastes. Heat transport calculations have been performed aiming at characterising the evolution of the near-field temperature in a backfilled repository (Weetjens, 2009). The effects of heating over a wider scale (*i.e.*, in the far field) have also been studied (Sillen and Marivoet, 2007). Further calculations will aim to confirm expected repository temperatures determined previously, and will then consider the potential impacts of these thermal loads on performance of the repository, which might require adaptation of the reference design, for example, relating to the spacing of adjacent disposal galleries.

Compressible materials are incorporated in the concrete wedge block lining of the PRACLAY gallery (Van Marcke and Bastiaens, 2012). These materials are polysiloxane sheets placed between the lining rings in the heated part of the gallery and steel foam panels inside the lining rings. Their purpose is allowing some thermal expansion of the lining and in that way limiting the thermally induced stresses in the concrete blocks. This limitation is especially important in case of retrievability. The behaviour and performance of these materials will be evaluated during the PRACLAY Heater Test (Annex A4). This test will also assess whether these blocks are required in real disposal galleries.

Other areas of uncertainty relating to gallery design and construction include:

- The impact of waste transfer and emplacement activities (particularly differential mechanical and thermal loading) on the gallery lining and the integrity of the gallery floor. Underground waste transfer activities are discussed in Section 5.3.2.



- The potential impact of gallery seals on gallery design and the choice of construction techniques.

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### **Roadmap – Section 5.2.2 – Gallery construction**

*For SFC1*, ONDRAF/NIRAS will study how to construct the crossings between the access gallery and the disposal galleries. It will also check the impact of heat generated by the waste on the design of the lining of the disposal gallery.

*For later SFCs*, ONDRAF/NIRAS will estimate the impact of subsequent installation of seals in the access and disposal galleries with regard to their respective design and construction. It will also assess the impact on the lining and floor structure of the progressive filling of a disposal gallery with disposal waste packages.

*For SFC1*, ONDRAF/NIRAS will perform a preliminary analysis of the potential transferability of the access and disposal galleries construction techniques considered for application at the reference site for RD&D in the Boom Clay to other disposal depths.

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### 5.3. Feasibility of repository operation

This section describes the RD&D programme to underpin the feasibility of operating a repository for category B&C waste from an engineering perspective, focusing in particular on the feasibility of the various waste package transfer activities that will be required. The relevant FS that require substantiation are shown in Table 20.

**Table 20** – Excerpt of the FS hierarchy showing FS relating to repository operation.

<b>FS 1 The engineering practicability of the disposal system is proven</b>	
Indeed,	FS 1.3 The repository for category B&C waste can be operated
Indeed,	FS 1.3.1 The primary waste packages can be removed, handled and transported from interim storage facilities to the post-conditioning facility
and,	FS 1.3.2 The disposal waste packages can be handled and transported from the post-conditioning facility to their final destination in the disposal galleries including reversibility of these operations

Discussion in Section 5.3 covers the following areas:

- The feasibility of handling and transferring primary waste packages from interim storage facilities to post-conditioning facilities, and the feasibility of storing primary waste packages appropriately on the disposal site, prior to post-conditioning (Section 5.3.1). This discussion relates to FS 1.3.1.
- The feasibility of handling and transferring disposal waste packages from the post-conditioning facility to their final destination in the disposal galleries including reversibility of these operations (Section 5.3.2). This discussion relates to FS 1.3.2.

#### 5.3.1. Handling and transport of primary waste packages

There is a high degree of confidence in the feasibility of handling and transporting primary waste packages because these activities are already routinely carried out in Belgium and worldwide across the wider nuclear industry. Examples of primary waste package storage and storage facility are shown in Figure 64. Further examples are presented elsewhere (Galson, 2011).

Various different primary waste packages containing components of the Belgian radioactive waste inventory are currently held in interim storage facilities on the surface. Further storage of primary waste packages at the disposal site, if this is required, is therefore considered to be feasible.



**Figure 64** – Examples of interim storage of category B waste in Belgium. Left: The B127 interim storage facility contains bituminised waste. Right: The B151 interim storage facility contains low activity long life wastes (ONDRAF/NIRAS, 2008).

Primary waste packages in interim storage have already been transferred from their place of origin/conditioning to interim storage facilities, and the existence of suitable equipment for the handling and transfer of these packages is an essential prerequisite for such activities. Moreover, storage facilities are, by definition, designed to facilitate removal of primary waste packages, to enable transfer to a permanent disposal site. Therefore, the feasibility of primary waste package removal, handling, transfer and transport is considered to be proven, provided that storage facilities are adequately maintained over their lifetime.

No further RD&D is required to support SFC1.

### 5.3.2. Handling and transport of disposal waste packages

There are several stages in the disposal process involving handling and transport of disposal waste packages. These include:

- Storage of disposal waste packages.
- Tilting of the disposal waste package at some stage.
- Surface transport of disposal waste packages from on-site storage to the waste shaft.
- Transfer of disposal waste packages down the waste shaft.
- Underground transport from the shaft to the disposal galleries and transfer to the emplacement position.
- All these transfer stages have to include reversibility. This means that it has to be possible to carry out the transfer in both the forward and backward directions, if desired. Each of these stages is discussed separately hereafter.

Storage of disposal waste packages is considered to be feasible. Many countries with a nuclear industry (including Belgium in Doel) employ dry storage facilities for storing irradiated fuel. The shielded storage containers employed are typically comparable in size and mass to the supercontainer and monolith B.

The specific design of a storage facility for disposal waste packages, and the associated handling equipment, will need to be tailored to the design of the packages. There has been some consideration of this as part of RD&D studies examining the design and construction of post-conditioning facilities, as discussed in Section 5.1.3. Further consideration of this topic relates to optimisation of the disposal design and therefore is not planned for SFC1.

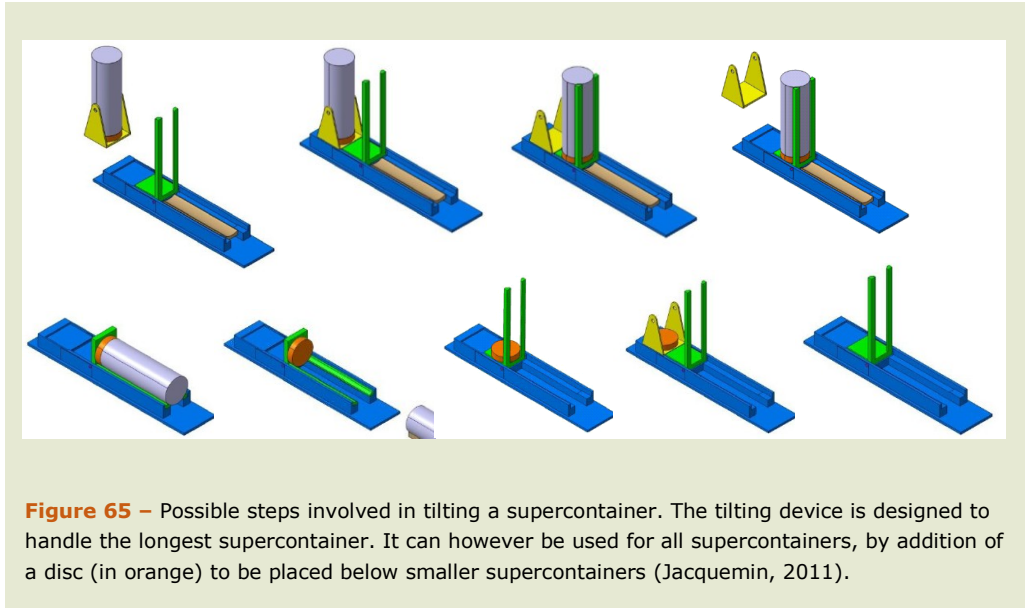
Surface transport of large waste packages is routinely carried out using a variety of techniques, including rail-bound transport, wheel-mounted transport and air-cushion transport. Various examples of surface transport of waste packages comparable in size and mass to the supercontainer are presented elsewhere (Galson, 2011). The feasibility of surface transport is therefore considered to be proven.

It is assumed that the same transport system will be applied for disposal waste package transfer steps on both the surface and underground. However, underground transport introduces various additional challenges, relating, for example, to spatial constraints and operational safety considerations. These issues may affect the feasibility of some package transport techniques, and therefore govern the selection of a particular approach for both surface and underground transport.

Tilting of disposal waste packages, particularly the supercontainer, is a key activity that will be required at some point between fabrication of the packages (the supercontainer buffer will be cast with its long axis vertical) and emplacement in disposal galleries (in a horizontal orientation). For reversibility reasons, the tilting has to be feasible in both directions: from a vertical position into a horizontal position and opposite. It is important to ensure that tilting will not unduly affect the integrity of the disposal waste package, for example, by creating cracks in cementitious components that could affect the level of radiological shielding provided, or the long-term evolution of the package.

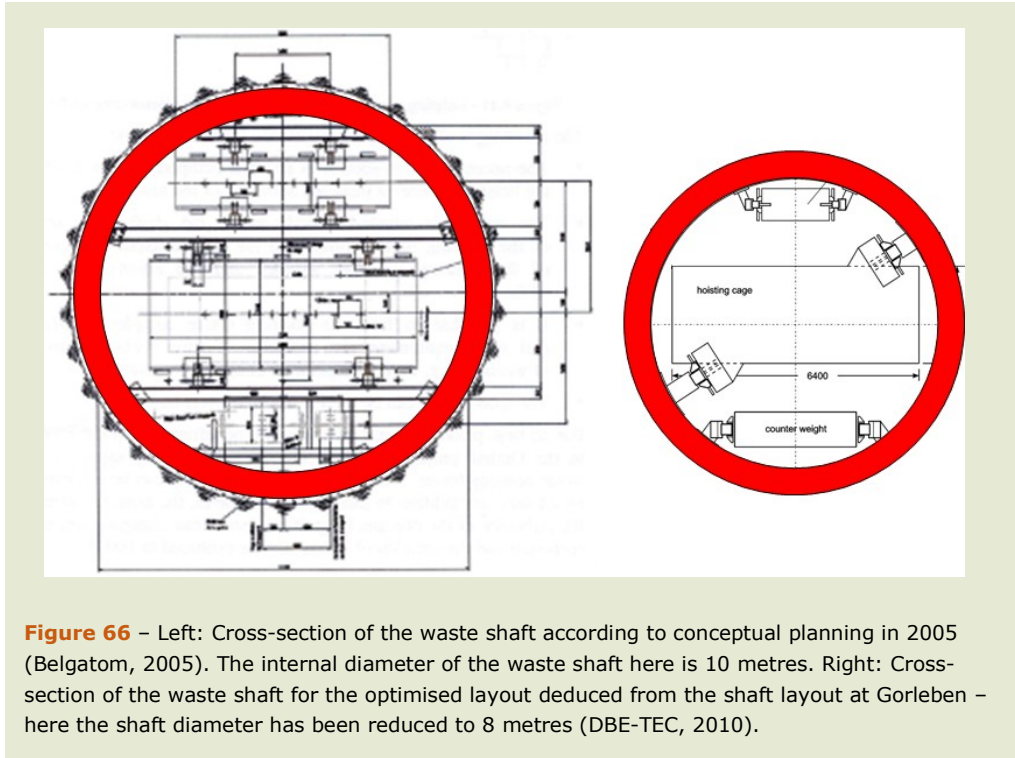
The current reference approach envisages tilting on the surface after fabrication and horizontal transfer thereafter. The orientation of packages during storage has not yet been decided, but the preferred orientation (and timing of tilting) will be influenced by any effects that package tilting and orientation might be expected to have on the curing of cementitious components. Tilting a supercontainer on the surface has been investigated in several studies (Figure 65) (Tractebel, 2010) (Jacquemin, 2011) and is considered to be feasible, although further work is planned to strengthen confidence, and to confirm the transferability of work to-date on the supercontainer to tilting the monolith B.

Based on the feasibility of tilting disposal waste packages at the surface, combined with the feasibility of constructing a large diameter waste shaft that permits horizontal transfer of the supercontainer and category B monolith to the disposal depth (as discussed in Section 5.3.2), it is assumed that there is no requirement to tilt disposal waste packages once they are transferred underground. This is an important assumption because underground tilting would require an additional underground operation and a large access chamber to be excavated at the bottom of the waste shaft, which could be difficult to construct without unduly affecting the integrity of the surrounding Boom Clay.



Shaft-based transport is generally considered to be feasible, being a widespread practice for the transfer of equipment and materials in mines and other underground facilities. Disposal waste packages are routinely transferred down a 650 metres shaft to the disposal horizon at the Waste Isolation Pilot Plant (WIPP) in the USA. However, the relatively large size and mass of the supercontainer and monolith B means that this step still requires careful evaluation.

As discussed in Section 5.2.1, a recent RD&D study concluded that an internal waste shaft diameter of 8 metres would be sufficient to accommodate the main hoist and counterweight, as well as an emergency personnel hoisting system, and would permit horizontal transfer of all disposal waste packages (DBE-TEC, 2010). As shown in Figure 66, the diameter was optimised by adapting the main hoisting system, from the original conceptual design using parallel rails, to a design based on the hoisting system used in shaft 2 of the Gorleben Exploration Mine in Germany, which uses guide rails mounted diagonally on the shaft wall (DBE-TEC, 2010) (Haverkamp *et al.*, 2012). Further studies in this area are focusing in greater detail on the design of the hoisting system and associated safety-relevant systems. The hoisting system has to allow both downward as upward transport to satisfy the requirement for reversibility. The various risks associated with handling packages in this environment will also be evaluated under a series of future studies on operational safety. Dropping a waste package down the shaft is not considered to be a key risk, since the likelihood of this occurring would be minimal by an adequate design of the hoisting system.



**Figure 66** – Left: Cross-section of the waste shaft according to conceptual planning in 2005 (Belgatom, 2005). The internal diameter of the waste shaft here is 10 metres. Right: Cross-section of the waste shaft for the optimised layout deduced from the shaft layout at Gorleben – here the shaft diameter has been reduced to 8 metres (DBE-TEC, 2010).

The requirement for reversible disposal waste package emplacement means that a hoisting system capable of transferring a payload of up to 70 tons (the mass of the largest supercontainer) both down and up the shaft is required.

As discussed above, the feasibility of underground transport of disposal waste packages is currently more uncertain than surface-based transport, because of the additional constraints associated with carrying out waste package transfer activities in a repository environment, particularly in a tunnel-based system, where space can be limited. Key uncertainties include:

- Whether the transport equipment will operate effectively in a repository environment, where some environmental conditions (for example the presence of dust) may be more difficult to control than in a surface facility.
- The minimum internal diameter for access and disposal galleries allowing safe transport of the disposal waste packages along these galleries. The feasibility of constructing these galleries is discussed in Section 5.2.2.
- How to transfer disposal waste packages from the access gallery to a disposal gallery, which will involve a 90° rotation of the package at the crossing point (intersection) between the two galleries. The feasibility of constructing these crossing points is discussed in Section 5.2.2.
- The potential impact of transporting heavy disposal waste packages on the integrity of the gallery floors and linings due to differential loading along the galleries. The impact these loads may have on the design and construction of the access galleries and disposal galleries is discussed in Section 5.2.2.

A rail-guided, wheel-based transport system has been selected as the current reference approach for both surface and underground transfer of disposal waste packages. An ongoing RD&D study aims to confirm the feasibility of implementing such a transport

system within the context of the Belgian disposal design. Originally, disposal waste package transport using an air cushion was considered by ONDRAF/NIRAS (Babcock Noell Nuclear, 2005) and it still remains an alternative option. However, air cushion transport places strict requirements on the smoothness and cleanliness of the transport surface (gallery floor), and this condition may be difficult to meet for transfer of heavy disposal waste packages in a repository environment. This might increase the possibility of air cushion transport equipment breaking down and a stranded package blocking the associated gallery. There are no known examples of air cushion transport technology being used in an underground facility, so it is not possible to see how this issue has been addressed elsewhere.

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### **Roadmap – Section 5.3.2 – Handling and transport of disposal waste packages**

*For SFC1*, ONDRAF/NIRAS will calculate the minimum internal diameters for access and disposal galleries, the shaft dimensions and hoisting system required for the transport of disposal waste packages.

*For SFC1*, ONDRAF/NIRAS will solve issues regarding the tilting of disposal waste packages (from a vertical into a horizontal position and, for reversibility purposes, from a horizontal into a vertical position), transport of the disposal waste packages along the shaft (both downwards as upwards) and transport of the disposal waste packages in the underground repository from the shaft until their final disposal position and back, for reversibility purposes.

*For SFC1*, ONDRAF/NIRAS will also list the requirements for the floors in the access gallery and disposal galleries to allow transport and installation of the disposal waste packages.

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## 5.4. Feasibility of repository closure

This section describes the RD&D programme to underpin the feasibility of closing a repository for category B&C waste from an engineering perspective, focusing in particular on the feasibility of backfilling and sealing the repository. The relevant FS that require substantiation are shown in Table 21.

**Table 21** – Excerpt of the FS hierarchy showing FS relating to repository closure.

<b>FS 1 The engineering practicability of the repository is proven</b>	
Indeed,	FS 1.4 The repository for category B&C waste can be closed
Indeed,	FS 1.4.1 The repository for category B&C waste can be backfilled
and,	FS 1.4.2 The repository for category B&C waste can be sealed

Discussion in Section 5.4 covers the following areas:

- The feasibility of progressively backfilling the disposal galleries, access gallery and shafts (Section 5.4.1). This discussion relates to FS 1.4.1.
- The feasibility of progressively sealing the disposal galleries, access gallery and shafts (Section 5.4.2). This discussion relates to FS 1.4.2.

### 5.4.1. Repository backfilling

Backfilling of mine openings is a widespread practice to reduce void space and to stabilise underground structures (Belem *et al.*, 2008). Backfilling is also envisaged for all radioactive waste repositories (using materials such as concrete, clay or crushed rock), but to date, repository backfilling has not been widely implemented because many repositories are still either being planned or are in operation. However, there are some examples where backfilling has been implemented, for example at the Morsleben repository for radioactive waste in Germany where several large cavities have been backfilled, mainly using crushed salt and salt concrete (Galson, 2011) and where it is foreseen to further backfill more than two million cubic metres of cavities with a cementitious material.

It is envisaged that a cementitious material would be used to progressively backfill each disposal gallery in a step-wise manner, following emplacement of about 30 metres of waste packages. The backfill would:

- Provide mechanical stability.
- Help to prevent the formation of advective transport pathways in the near field.
- Reduce voids in the repository where, in the long term, water, and thus also fissile material, could accumulate and lead to a criticality event.

The thermal conductivity of the backfill material must be high enough to allow sufficient dissipation of the heat from the category C waste into the surrounding clay. A high porous backfill material can provide a storage volume for gas generated in the repository and consequently it might help in limiting a gas pressure build-up.



Another important requirement for the backfill material follows from the potential requirement for waste retrievability. Retrieval of the waste some time after its emplacement and after the gallery has been backfilled implies the removal of the backfill material. Consequently, a backfill material would have to be selected which could be sufficiently easily removed. Also the implications of retrievability on backfilling and sealing will be evaluated.

A full-scale (and reduced-scale) demonstration of backfilling a disposal gallery was carried out as part of the European Union ESDRED<sup>81</sup> Project (ESDRED, 2009) (Van Humbeeck *et al.*, 2007) (Figure 67). The outcomes of this study provide key evidence underpinning the feasibility of preparing and injecting grout into a disposal gallery at a sufficient rate to prevent setting during emplacement – 85 m<sup>3</sup> of grout was injected over seven hours, using a single injection pipe. It also demonstrates the feasibility of adequately filling void spaces – more than 98% of the available void spaces were filled with cementitious grout. The grout has a low compressive strength (< 10 MPa), to facilitate retrievability. However, the water content of the cement used was found to be too high, leading to non-optimal maturing of the emplaced backfill. Future studies (for later SFCs) will therefore need to examine and optimise the backfill cement formulation.



**Figure 67**– Full-scale mock-up of a disposal gallery (with diameter 3 metres, length 30 metres and built-in simulation of heat-generating waste) developed, as part of the ESDRED Project, to demonstrate the feasibility of repository backfilling.

Ongoing RD&D in this area, in support of SFC1, is expected to focus on the methodology to backfill of an underground repository. There are two possible approaches to transfer backfilling materials to the emplacement depth:

- The various components of the backfill formulation can be transferred underground separately, before mixing with water to produce the backfilling material. This approach requires the provision of powerful water and electricity supplies in the repository, as well as sufficient space to carry out mixing operations. However, the mixed backfill only needs to be transported over quite short distances.
- Alternatively, the backfill formulation can be mixed above ground and transferred hydraulically to the disposal depth and emplacement position. This approach reduces the space and infrastructure required underground, but the fabricated backfill needs to be transported over longer distances, which can lead to problems arising from the backfill setting in the transfer equipment (if a continuous flow is not ensured).

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81 ESDRED: Engineering Studies and Demonstration of Repository Designs (EU project).

The second approach is currently preferred by ONDRAF/NIRAS because it reduces the requirement for large underground excavations (Galson, 2011). Experience at the Morsleben repository for radioactive waste in Germany suggests that this method is feasible, but further RD&D is needed to confirm the most suitable emplacement approach applicable to the Belgian disposal design, as well as the appropriate composition of the backfill.

Beside the selection of a backfill material and the development of a procedure to install the backfill material, an approach to verify the success of the backfill operations has to be developed. Furthermore the impact of backfilling on the disposal waste packages and on the disposal galleries, access gallery and shafts remains to be evaluated.

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#### **Roadmap – Section 5.4.1 – Repository backfilling**

*For SFC1*, ONDRAF/NIRAS will search for the most appropriate materials composition for the backfill material for the disposal galleries, access gallery and shafts, taking into account retrievability. It will study how to perform the backfill operations and how to check the success of the backfill operations.

*For later SFCs*, ONDRAF/NIRAS will evaluate the impact of backfilling on the disposal waste packages and on the disposal galleries, access gallery and shafts.

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#### **5.4.2. Repository sealing**

Once a decision to close the repository has been made, seals will be emplaced in the disposal galleries, access gallery and repository shafts (disposal galleries could be sealed before this time, depending on the approach to backfilling, and decisions about retrievability). Seals can contribute to operational safety and long-term safety by creating a physical barrier to the waste (and thus contribute to the isolation of the waste) and by compartmentalising the repository and thus limiting the impact of incidents if they would occur in one part to the other parts of the repository. Specific requirements are under development for the sealing of the different parts of the repository.

The design of the seals and their installation have to be feasible and consistent with the safety strategy that ONDRAF/NIRAS follows to develop its disposal system (ONDRAF/NIRAS, 2011e). This includes, among other considerations, the requirements that seals and their installation will not unduly perturb the safety functions of the host formation and that there are preferences for materials and implementation procedures for which broad experience and knowledge already exist.

As for the backfill material, the design of the seals has to take into account the potential requirement for waste retrievability.

There are numerous examples of tunnel and shaft sealing available from the mining industry, which show the feasibility of implementing seals in a variety of geological environments. However, the applicability of this experience to a repository is somewhat

limited because of the strict requirements placed on the long-term performance of repository seals, and as with repository backfilling, seals have not yet been implemented at most repositories. Nevertheless, various conceptual designs of tunnel and shaft sealing systems are available, for example for the salt formations, from the Morsleben radioactive waste repository in Germany, as well as from the WIPP in the USA (Galson, 2011). Conceptual seal designs typically employ a sequence of different load-bearing and impermeable materials, including crushed rock, concrete, asphalt and bentonite clay.

The RESEAL<sup>82 83</sup> project has demonstrated *in-situ* and on a large scale the feasibility of installing a seal in a shaft in Boom Clay and the effective sealing of this shaft (Van Geet *et al.*, 2005) (Van Geet *et al.*, 2008d) (RESEAL II, 2009). The goal was to demonstrate that it is feasible to build a seal with a hydraulic conductivity not higher than the Boom Clay one, in order to avoid any preferential transport pathway through the seal. This goal was achieved by imposing the following requirements to the sealing material and process:

- To remove the lining and the grout layer applied during the building of the shaft so that the sealing material is in contact with Boom Clay;
- To use a sealing material with a swelling capacity so that any cavities remaining after emplacement of the seal get filled as well;
- To use compacted bentonite with a high dry density as sealing material so to get a low hydraulic conductivity as it is inversely related to the dry density of the bentonite.

The seal was installed within the experimental shaft of HADES URF (Figure 68). To this end, the bottom part of that shaft was filled with grout. The lining and the grout (between the Boom Clay and the lining) were removed. The sealed section was about 2.2 metres in diameter (due to the removal of the grout layer, an irregular wall of Boom Clay is observed and an exact diameter cannot be given) and 2.24 metres in height (Figure 69). The seal consisted of a mixture of 50% of powder and 50% of highly compacted pellets of FoCa clay, a sedimentary clay (bentonite) from the Paris Basin. The powder/pellet mixture has been optimised to obtain the best balance between saturation time, swelling pressure, hydraulic conductivity and ability to be compacted. Laboratory tests have demonstrated that the 50/50 mixture becomes homogeneous after saturation. The first 60 centimetres of the seal were compacted. (The compaction was stopped just below the first instrumented level.) The seal was kept in place with a top concrete lid of about 1 metre thick. Many sensors measured the pore-water pressure, total pressure, displacement and relative humidity among others, following the hydro-mechanical evolution of the seal and of the surrounding host formation. In addition, several filters inside the sealed section enabled artificial hydration.

It took about six years to fully saturate the seal. The hydration time depends on the sealing materials: the hydration time is longer for high-density bentonites, chosen for their low hydraulic conductivities, than for low-density bentonites. After saturation, the hydraulic conductivity of the excavation disturbed zone around the seal and of the seal

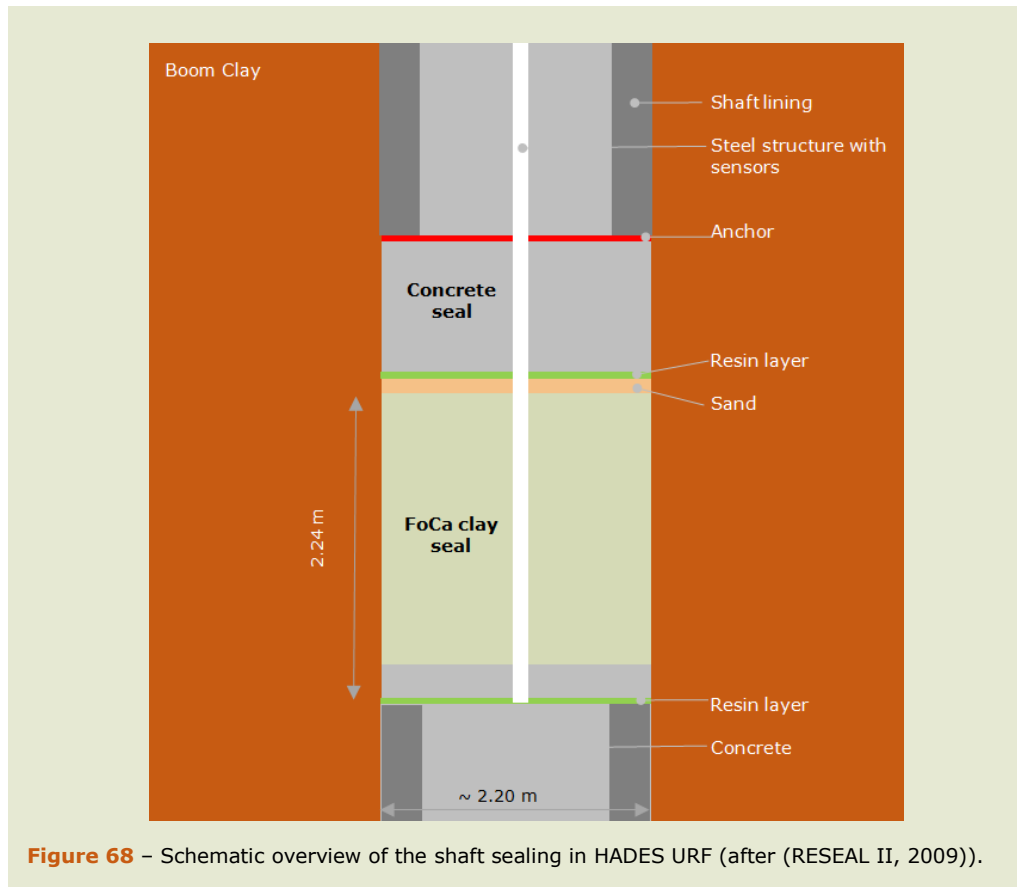
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82 RESEAL I: Large-scale *in-situ* demonstration test for repository sealing in an argillaceous host formation – Feasibility: borehole sealing and shaft sealing (EU project).

83 RESEAL II: A large-scale *in-situ* demonstration test for repository sealing in an argillaceous host formation – Phase II (EU project).

itself were in the range of the hydraulic conductivity of the undisturbed host formation. Two gas breakthrough tests were performed by injecting gas on a filter in the middle of the seal. After these two tests, the hydraulic conductivity at the injection filter came back to its original value, demonstrating the good self-sealing capacity of the FoCa clay.

It is thus possible to construct seals with features similar to Boom Clay. Table 22 summarises the outcomes of the RESEAL project, which have since been confirmed by results of the PRACLAY seal project (detailed hereafter).



**Figure 68** – Schematic overview of the shaft sealing in HADES URF (after (RESEAL II, 2009)).

Important lessons can be drawn from the installation of the PRACLAY seal in the HADES underground research facility for the sealing of horizontal galleries. This consists of an annular ring of compacted bentonite placed against the Boom Clay and a stainless steel structure enclosing the bentonite. However, the PRACLAY seal was necessary to create the desired boundary conditions for a large-scale heater test. Its design was oriented to this specific application and it was not intended as a prototype for a seal in a repository, where the requirements placed on the seal would be different.

Experience from the installation of the PRACLAY seal revealed the complexity of such an operation. Heavy components had to be assembled in a very limited workspace and the assembly tolerances were very high. Considering the large number of seals in a repository, the installation procedure will have to be very robust to ensure a correct installation of all seals. The PRACLAY seal showed that developing a seal design and installation in a very robust manner is a technological challenge.

**Table 22** – RESEAL outcomes ((after (RESEAL II, 2009)).

	<b>Requirements</b>	<b>RESEAL outcomes</b>
Design	Feasible	✓
	Safely installable	✓
Confidence building	Same hydraulic conductivity as host formation	✓
	Knowledge of hydration time and hydration mechanisms	Hydration time longer than expected and saturation mechanisms not yet fully understood
	No preferential gas flow through the seal	✓
	Self-sealing	✓
	No preferential migration of radionuclides at the interface seal/Boom Clay	✓
	Homogenised mixture after saturation	✓
	Stable THMC (thermo-hydro-mechanical and-chemical) during required lifetime	Not tested
	Good process understanding allowing modelling	Increased but not sufficient



**Figure 69** – RESEAL test: tube instrumented for total and pore pressure, relative humidity and temperature measurements (RESEAL II, 2009).

A major factor influencing the design of the seals will be a decision on whether these components should be gas permeable, to prevent gas build-up and pressurisation in the repository. As discussed in Section 4.2.2.5, there is a substantial programme of ongoing RD&D to characterise the mechanisms by which gas is produced and the volume of gas that may be generated (together with the gas generation rate), in order to improve understanding of the potential impact of gas generation on the long-term evolution of the disposal system.

Conceptual designs of gas permeable seals have been developed by Nagra and are being investigated further under the gas-permeable seal test (GAST) at the Grimsel Test Site<sup>84</sup> in Switzerland (Rueedi *et al.*, 2011).

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**Roadmap – Section 5.4.2 – Repository sealing**

*For SFC1*, ONDRAF/NIRAS will define which materials should be used as seals, taking into account retrievability and how to install seals in the disposal galleries, access gallery and shafts, taking into account retrievability.

*For later SFCs*, ONDRAF/NIRAS will check whether a large-scale seal (in the waste shaft) can be constructed with features similar to Boom Clay.

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84 Grimsel Test Site, 2011. Website at URL: <http://www.grimsel.com/gts-phase-vi/gast/gast-introduction> (Last visit: Augustus 2012)

**Monitoring** is defined as the continuous or periodic observations and measurements to help evaluate the behaviour of the components of the waste disposal system and the impacts of the waste disposal system and its operation on the public and the environment. Most specifically this covers radiological, environmental and engineering parameters (IAEA, 2012).

## 5.5. Feasibility of repository monitoring

This section describes ONDRAF/NIRAS perspective on the feasibility of monitoring a repository for category B&C waste from an engineering perspective, and highlights various ongoing studies to develop approaches to repository monitoring. The relevant FS that requires substantiation is shown in Table 23.

**Table 23** – Excerpt of the FS hierarchy showing FS relating to repository monitoring.

### FS 1 The engineering practicability of the disposal system is proven

Indeed, FS 1.5 The performance of the disposal system can be monitored

Discussion in this section covers the feasibility of monitoring the proposed disposal system in line with ONDRAF/NIRAS monitoring strategy (ONDRAF/NIRAS, 2009f).

Disposal waste packages could require monitoring during storage, transport, emplacement and after final emplacement in the repository. Changes in the characteristics of the repository environment could also require monitoring through all phases of repository activities, starting from before excavation commences (to determine the baseline conditions of the disposal site), through all operational activities, and possibly beyond repository closure, although post-closure monitoring would not be required to assure safety (IAEA, 2006).

Monitoring during storage is widely carried out in existing storage buildings, and there is considerable experience in this field. A range of techniques are available for monitoring waste packages and other components of storage facilities, such as the environmental conditions within the store, in order to confirm satisfactory performance of the waste packages prior to disposal (Galson, 2010) (National Nuclear Laboratory, 2010). Monitoring of waste packages during transport is also an established practice, and is captured as a requirement within regulations, European directives and laws for the safe transport of radioactive material (EU, 1993) (IAEA, 1997) (EU, 2006) (IAEA, 2009). Consequently, there is a high degree of confidence in the feasibility of monitoring radioactive waste during transport and storage.

Extensive work has been carried out internationally to develop the principles, objectives and strategies for monitoring a repository for radioactive waste and to develop technologies to enable monitoring to be conducted without compromising the long-term safety provided by a geological repository (IAEA, 2001) (NIREX, 2004) (Galson, 2004) (IAEA, 2012). Much of this work has involved collaborative partnerships across many waste management organisations, including ONDRAF/NIRAS and other Belgian organisations. In 2009, an integrated project known as MODERN<sup>85</sup> was established. This 4-year project involves 18 partner organisations, including EURIDICE, and aims to provide a reference framework for the development and possible implementation of monitoring activities and associated stakeholder engagement during relevant phases of radioactive waste disposal. Activities within the MODERN Project are split into six work packages, which consider the strategic, technical and social issues associated with

85 MODERN: Monitoring Developments for Safe Repository Operation and Staged Closure (EU project).

monitoring geological disposal. Also in 2009, a symposium involving participants from ONDRAF/NIRAS, URS Corporation and Sandia National Laboratories (USA) was held to define the strategy for the development of a testing and monitoring programme for the Belgian geological disposal programme (ONDRAF/NIRAS, 2009f).

The objectives of the Belgian monitoring programme of a geological repository are:

- To demonstrate adequate protection of man and the environment and compliance with the regulatory requirements;
- To confirm that the disposal system behaves and evolves as expected in the Safety and Feasibility Case;
- To identify any deviations from the expected behaviour of the disposal system;
- To confirm and refine the key assumptions in the Safety and Feasibility Case and enhance understanding of the environment and disposal system;
- To acquire data for supporting decision-making;
- To provide background information for any post-closure surveillance programme.

Based on existing experience in other international disposal programmes with monitoring and ongoing RD&D activities (*e.g.*, the MODERN project), there is a high degree of confidence that, from a feasibility perspective, monitoring can be carried out in line with ONDRAF/NIRAS general monitoring strategy (ONDRAF/NIRAS, 2009f).

Further development of the ONDRAF/NIRAS monitoring strategy will be required once the repository design progresses beyond the conceptual stage (*i.e.*, after SFC1), in order to enable a more focused evaluation of the feasibility of carrying out monitoring in accordance with this strategy. It is appropriate to defer such an evaluation until repository development has progressed, in order to take account of ongoing developments in the state-of-the-art of monitoring technologies. In the meantime, ONDRAF/NIRAS is via EURIDICE involved in the above-mentioned MODERN project and will maintain a watching brief on developments in monitoring strategies and technologies made elsewhere. Further development of ONDRAF/NIRAS monitoring strategy (including consideration of when/where measurements need to be conducted, how long for, and how monitoring will assist in decision-making), will require, among others, societal input to identify potential stakeholder requirements for monitoring and dialogue on the limits of monitoring (Chapter 11).

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### **Roadmap – Section 5.5 – Feasibility of repository monitoring**

*For confidence building*, ONDRAF/NIRAS will continue to follow up the development of monitoring techniques. It will further develop its monitoring strategy (including consideration of when/where measurements need to be conducted, for how long, and how monitoring will assist in decision-making), with societal input to identify potential stakeholder requirements for monitoring. It will also define the monitoring strategy to be followed (what will be measured at which stage in the disposal programme) and the way to implement it. Available results will be integrated in SFC1 and subsequent SFCs.

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## 5.6. Feasibility from a health, safety and environmental perspective

This section describes the RD&D programme to underpin the feasibility of implementing the geological repository from a health, safety and environmental perspective. The relevant FS that require substantiation are shown in Table 24.

**Table 24** – Excerpt of the FS hierarchy showing FS relating to health, safety and environmental issues during the operational phase.

<b>FS 2 The safety of workers, the public and the environment can be guaranteed during the operational phase</b>	
Indeed,	FS 2.1 The non-radiological risks associated with a normal operating scenario can be mastered
and,	FS 2.2 The radiological risks associated with a normal operating scenario can be mastered
and,	FS 2.3 The risks resulting from accident scenarios and external events can be mastered
and,	FS 2.4 Fissile materials can be handled appropriately from a security, safeguards and criticality perspective

Demonstrating the operational safety of the disposal system has to take account of normal operations and potential accidents or external events. In addition, the ability to handle fissile materials taking account of all relevant requirements for security, safeguards and criticality management during the operational phase of the repository needs to be demonstrated. The FS relating to operational safety and the discussion hereafter are therefore structured as follows:

- Non-radiological risks associated with a normal operating scenario are discussed in Section 5.6.1. This discussion relates to FS 2.1.
- Radiological risks associated with a normal operating scenario are discussed in Section 5.6.2. This discussion relates to FS 2.2.
- Risks resulting from accident scenarios and external events are discussed in Section 5.6.3. This discussion relates to FS 2.3.
- Appropriate handling of fissile materials from a security, safeguards and criticality perspective is discussed in Section 5.6.4. This discussion relates to FS 2.4.

The term “normal operating scenario” refers to normal operation conditions and activities. This excludes accidents and external events.

It should be noted that the discussion presented in this section relates to evaluation of safety and environmental impacts during construction and operation of the repository only. Consideration of the long-term evolution of a repository, and associated implications for safety and the environment is also a key focus of ONDRAF/NIRAS activities, but falls outside the scope of the feasibility programme, so is discussed elsewhere in this document (see Chapters 7 and 8).

Previous RD&D studies and the prevalence of underground operations and handling of radioactive waste worldwide suggest the feasibility of ensuring that the impacts of repository construction and operation on the public and the environment will be minimal.

There are no potential operational impacts on the public and the environment foreseen that would be unique to development of a geological repository in Belgium, so experiences and management approaches employed elsewhere are expected to be transferable.

A more detailed analysis of risks to the public and the environment during repository construction and operation will, of course, need to be conducted as the repository development programme progresses. Some potential issues and uncertainties have already been identified, such as how to manage the large volume of excavated spoil. However, the risks associated with disposal activities at a repository will depend significantly on the detailed repository design and its planned operation and it is difficult to specify and evaluate these risks in detail at present, since the repository design is still at a conceptual stage of development. The discussion in this section is therefore mainly focused on the risks for workers.

### **5.6.1. Non-radiological risks associated with a normal operating scenario**

Based on worldwide experience constructing and operating similar underground facilities in Belgium and further afield (including HADES URF, other underground research facilities, repositories such as the WIPP in the USA, and widespread mining practices), it is clearly feasible to protect workers, the public and the environment against the non-radiological risks during construction and operation of a geological repository provided that relevant safety regulations and instructions are followed and that the associated risks are thoroughly evaluated and effectively managed.

A conceptual operational safety analysis for the Belgian disposal design has already been performed (Belgatom, 2005), and further experience is transferable from the operational safety assessments of other radioactive waste disposal programmes in clay host formations (Andra, 2005b). It will be necessary to carry out more detailed operational safety analyses for a Belgian repository in future, but these will be dependent on the detailed repository design, so cannot be carried out at this conceptual stage. However, it is appropriate to consider, at a high level, aspects of the repository design that will be particularly important for the safety of workers, the public and the environment, including the risks associated with some specific activities during construction and operation, in order to provide additional confidence in the robustness of substantiating arguments underpinning feasibility for SFC1. Relevant considerations include:

- Risks associated with the construction of the shafts and galleries and the installation of the backfill material and seals and the measures required to mitigate against these risks.
- The approach to ventilate the repository, including identification of the minimum number of shafts needed to ensure adequate ventilation.
- Additional requirements on the repository design relating to operational safety, for example, requirements on the repository layout allowing evacuation of workers in case of an incident, the maximum length of the galleries permissible without the need to construct a rescue chamber, and the potential impact of blind galleries on worker safety.
- Management of the large volume of excavated spoil.

These issues will be considered further as part of several RD&D studies that will review and evaluate the risks associated with construction and operation of the repository. Specific RD&D on the repository ventilation system will also be carried out.

Based on the worldwide experience constructing and operating similar underground facilities, there is a high degree of confidence that workers, the public and the environment can be protected against the non-radiological risks of constructing and operating a geological repository in a normal operating scenario. However, there are some specific aspects of the disposal design that would benefit from further study for SFC1 (see roadmap hereafter).

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#### **Roadmap – Section 5.6.1 – Non-radiological risks associated with a normal operating scenario**

*For SFC1*, ONDRAF/NIRAS will evaluate the “general risks at work” and the risks associated with the repository construction, backfill and seal installation, as well as the measures required to mitigate against these risks. ONDRAF/NIRAS will evaluate in greater detail the impact of operational safety on the layout (number of access galleries and shafts, length of disposal galleries etc.).

*For later SFCs*, ONDRAF/NIRAS will check the safety guidelines to follow during repository construction, backfill and seal installation and the requirements for the air quality and ventilation system. It will also evaluate whether the number of shafts is sufficient and estimate the maximum allowable length of the blind (dead-end) disposal galleries. Another issue to solve concerns managing the large volume of excavated spoil.

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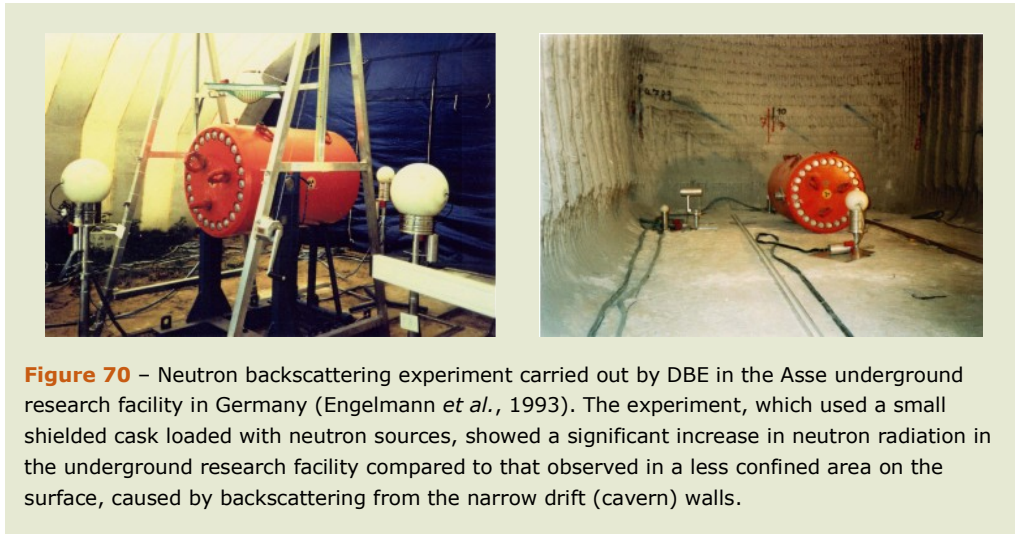
#### **5.6.2. Radiological risks associated with a normal operating scenario**

FS 2.2 considers the radiological risks to workers, the public and the environment during the operational phase. Long-term safety is considered under the safety assessment programme, which is discussed in Chapter 6. FS 2.2 includes the assessment of doses to workers and the public during the operational phase during normal operations. Possible doses resulting from accidents and external events are not considered within the scope of FS 2.2 and are taken into account in FS 2.3 (Section 5.6.3).

Relevant considerations include:

- The potential use of radiologically controlled and non-controlled areas to segregate activities in the post-conditioning facilities and the repository, and associated impacts on the repository design.
- Anticipated worker doses arising from contact handling of disposal waste packages during emplacement under normal conditions. Experiments carried out in Germany, illustrated in Figure 70, suggest that worker doses during waste emplacement could be affected by backscattering of neutron radiation from the walls of a repository (Engelmann *et al.*, 1993).

- The potential need for a gastight internal overpack in the monolith B to prevent the release of gaseous radionuclides during the operational phase.



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### Roadmap – Section 5.6.2 – Radiological risks associated with a normal operating scenario

For *SFC1*, ONDRAF/NIRAS will evaluate the risks associated with the handling and transport of disposal waste packages and the measures required to mitigate against these risks (radiological impact). It will also assess the risks during construction and operation of the category C disposal area arising from the existence of the (closed or open) category B disposal area. It will see how to define and manage the zones within the repository (*e.g.*, definition of “controlled nuclear zone”, limiting personnel access).

For *later SFCs*, ONDRAF/NIRAS will evaluate the impact of underground conditions on radiation backscattering and find ways to secure the surface and the underground facilities. It will estimate whether a gastight overpack is required in monolith B to ensure safety when handling gas-producing waste.

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### 5.6.3. Risks associated with accident scenarios and external events during the operational period

The scope of consideration of accident scenarios and external events within the feasibility programme focuses on the ability to design and build the repository in a way that reduces the risks and/or mitigates the impacts of accidents (such as dropping a disposal waste package) and external events (such as earthquakes and flooding). Scenarios which consider the impact of such events on long-term safety will be considered within safety assessments for *SFC1*, as discussed in Section 2.3.1. Unauthorised access to the disposal site during the operational phase (*i.e.*, deliberate human intrusion) will be prevented through active security measures such as entry/exit checks and other on-site security, as also required under FS 2.2 and FS 2.4. Inadvertent

human intrusion is also not considered plausible during the period of institutional control of the repository.

For a geological repository situated in Belgium, the external event that is considered to have the greatest potential to affect the repository during the operational phase is an aeroplane crash followed by a kerosene fire in the vicinity of the repository surface facilities. This could affect the integrity of waste packages held on the surface, and could also damage shaft-hoisting towers and associated hoisting systems. Therefore, the surface facilities have to be able to resist an aeroplane crash. Nuclear facilities resistant to an aeroplane crash have already been built and this is therefore considered feasible.

Earthquakes are considered unlikely to occur at a magnitude sufficient to significantly affect performance of the disposal system, particularly for sub-surface components, since the impacts of seismic waves tend to be reduced at depth (Section 4.2.1.1). Flooding events can be envisaged, but it is considered possible to implement engineered solutions such as surface flood defences to prevent any significant associated impacts on the disposal system. It would also be possible to “compartmentalise” the repository by backfilling portions of the disposal galleries and emplacing seals periodically along their length, so that only a portion of the inventory would be susceptible to flooding. However, such an approach would need to be balanced against the increased difficulty of implementing waste retrieval, if this were required.

Relevant considerations associated with this FS include:

- The risk of a fire occurring in the repository and associated impacts on the strategy for processing and packaging waste, the repository design and repository ventilation.
- The potential for accidents or breakdown of equipment during waste emplacement activities, and associated implications for worker doses.

The potential impacts of accident and external events and approaches to mitigate against the associated risks will be evaluated as part of various planned and ongoing RD&D studies focusing on the design and engineering construction of the EBS (such as the shaft hoisting system).

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### **Roadmap – Section 5.6.3 – Risks associated with accidents scenarios and external events during the operational period**

*For SFC1*, ONDRAF/NIRAS will define the accident scenarios to be taken into account and the measures required to mitigate against the risks associated with these scenarios.

*For later SFC1*, ONDRAF/NIRAS will list the external events that can pose a risk to the repository and provide design answers for the system to be resistant to such an event.

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#### 5.6.4. Managing fissile materials

The scope of FS 2.4 covers the ability to handle fissile materials appropriately, from receipt, through storage, processing (packaging), transfer and emplacement in the repository, taking account of all relevant requirements for security, safeguards and criticality management during the operational phase of the repository. The long-term potential for formation of a critical mass as the repository evolves will also need to be evaluated, but such phenomenological studies fall outside the scope of this FS, and are captured in Section 4.2.3.5.

FS 2.4 is mainly applicable to the management of irradiated fuel disposed of in a repository, although there may also be smaller quantities of fissile materials in some category B waste streams. For category B waste, acceptance criteria limit the inventory of fissile materials in the individual waste packages to be managed by ONDRAF/NIRAS (e.g., see (ONDRAF/NIRAS, 2008c)). In the current reference design, it is considered that irradiated fuel assemblies from commercial reactors are conditioned into metallic boxes; the interstices being filled up with an inert material before closure. This conditioning route must still be confirmed (Section 3.1.3). The boxes are placed in the overpack in a massive cast iron internal structure. This internal structure assures that the distance between the assemblies is kept large enough to prevent criticality accidents during the operational phase. A French RD&D experimental programme demonstrated this option with a full-scale prototype (Andra, 2005b).

Since the safeguards approach applied to a geological repository will have implications on its construction and operation, the RD&D programme includes studies on possible implications of safeguards approaches on the design and operation of the geological repository since 2006 (van der Meer and Verstricht, 2008) (van der Meer and Turcanu, 2012).

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#### Roadmap – Section 5.6.4 – Managing fissile materials

For *SFC1*, ONDRAF/NIRAS will define the safeguard requirements for the disposal of fissile materials. It will perform a global evaluation as to how the appropriate security, safeguards and criticality management measures can be implemented, based on the waste inventory and the design of the disposal waste packages. International guidance for safeguards application is under development. National and international approaches and requirements for managing fissile materials will be reviewed and their applicability to the Belgian disposal design will be considered.

Securing the surface and underground facilities of the repository is already covered in the roadmap of Section 5.6.2.

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## 5.7. Feasibility from a financial perspective

This section describes how feasibility will be evaluated for SFC1 from a financial perspective, based on the costs of constructing, operating, closing and monitoring the repository. The discussion focuses on FS 3 and associated Level 2 FS, which are shown in Table 25. There are no associated Level 3 FS at present.

**Table 25** – Excerpt of the FS hierarchy showing FS relating to repository costs.

<b>FS 3 The costs for the construction, operation and closure of the repository can be covered</b>	
Indeed,	FS 3.1 The costs for construction, operation and closure of the disposal facility for category B&C waste, including decommissioning of the site surface installations, have been evaluated
and,	FS 3.2 Waste tariffs and current funding mechanisms are adequate to cover the required costs taking into account escalation

An evaluation of repository costs and consideration of available funding mechanisms to meet these costs need to be carried out, and updated periodically, as a repository implementation programme progresses. Costs and funding mechanisms should be analysed and iteratively developed in a manner that is proportionate to the current stage of the programme. At this conceptual design stage, it is not considered necessary to develop detailed financial breakdowns for the purpose of demonstrating feasibility.

The costs associated with the Belgian geological disposal design were estimated in 2007 (Tractebel, 2007), and were most recently evaluated in the context of waste tariffs and the long-term waste fund in 2009 (ONDRAF/NIRAS, 2009d). Ongoing RD&D studies are providing indicative cost estimates for implementing specific components of the disposal design such as shaft construction (Antea-BG, 2010). Such information will be incorporated into the next cost assessment for the whole disposal design.

The funding mechanism for the long-term fund is such that it guarantees in principle that ONDRAF/NIRAS will be able to cover its fixed costs eventually and will enable it to cover its variable costs as they arise. It applies to the producers who have signed agreements with ONDRAF/NIRAS for the collection of their waste and is based on the following three fundamental elements (ONDRAF/NIRAS, 2011c):

- Contractual quantities: each of the main radioactive waste producers notifies ONDRAF/NIRAS of its total waste production programme, enabling ONDRAF/NIRAS to share its fixed costs between them;
- Tariff payment: each producer pays a contribution into the long-term fund (volume of waste × tariff applicable to this waste), based on the total cost (fixed and variable costs, including margins for technological and project risks) for medium-term and long-term management of the waste taken charge of by ONDRAF/NIRAS;
- Contractual guarantee: each of the main producers agrees to pay into the long-term fund at least the amount of the fixed costs relative to the capacity reservation that it has made.

# 4

## **Part 4**

**The long-term safety of geological disposal in Boom Clay can be assessed**





## **6. The long-term safety of the disposal system can be assessed**

During the current preparatory safety assessment phase, the consequences of new RD&D results are regularly evaluated by means of safety calculations whose results are expressed in terms of safety and performance indicators, providing guidance and prioritisation for future studies. This is a period of sustained interactions between the three poles of expertise (phenomenology, feasibility and safety assessment) (Chapter 2).

On the way to SFC1, this period will be followed by the formal assessment phase, which aims, through a wise selection of calculation cases and scenarios, at demonstrating that the Safety and Feasibility Case complies with the requirements. Formal safety calculations are performed every decade on average when notable progress in the geological programme has been achieved so that a Safety and Feasibility Case supporting a decision to go forward can be compiled. Being an integral part of the Safety and Feasibility Case, the comprehensive description of the safety assessments is obviously out of scope of this RD&D Plan. Therefore, the present chapter only presents a selection of examples illustrating how the interactions between the safety calculations and the RD&D during the preparatory phase act as a driver of the geological programme. Section 6.1 describes the reference scenario and how the RD&D results guide the iterative development of the reference case. Section 6.2 exposes the strategy deployed to assess and potentially mitigate the impact of gas in the disposal system. Section 6.3 describes how the disturbed zone at the interface between the repository and the geological host rock is treated in the current reference case, as example of abstraction process of the phenomenological knowledge in safety assessment. Section 6.4 presents some lessons learned during this preparatory phase.

### **6.1. Reference scenario and working versions of the reference case**

In the ONDRAF/NIRAS methodology, the reference scenario is a high-level, abstract description of the system evolution, with a time-deployment of the safety functions according to the safety concept. The reference scenario takes thus account of processes and events likely to occur. The reference scenario is represented by the so-called reference case, based on a reference set of models and parameter values, and by multiple alternative cases that adopt different assumptions or examine the impact of different uncertainties and design options. Impacts of the uncertainties and design options are assessed by comparing the results of the alternative cases with those of the reference case.

The current reference scenario originates from SAFIR2 with adaptations to the supercontainer concept. The reference scenario for category C waste is described as follows. The repository is constructed at depth in Boom Clay. The geological formation is stable and no human or natural events will alter the isolation provided to the disposal system. The containment of radionuclides and other contaminants within the overpack lasts until at least the end of the thermal phase (a few thousands years after waste disposal in the underground repository). The Boom Clay pore water will diffuse slowly

into the EBS. Eventually, it will start to corrode the envelope (if present), then the overpack and finally the primary waste packages. The containment safety function is assigned to the overpack only, although it is recognised that the envelope (if present) and the primary waste packages can extend the containment phase. After perforation of the overpack, the waste will be exposed to the pore water, begin to dissolve and release the contaminants that will diffuse through the near field into the Boom Clay host formation. The Boom Clay around the repository will be disturbed by the excavation, construction, operation and post-closure evolution of the repository. It is considered in the reference scenario that the spatial extent of these perturbations remains limited and is bounded. Transport is diffusion-dominated and migration is further delayed by retention processes. After the slow diffusive transport through the Boom Clay formation, during which a large fraction of the radionuclides will have decayed, only a minor fraction will reach the biosphere.

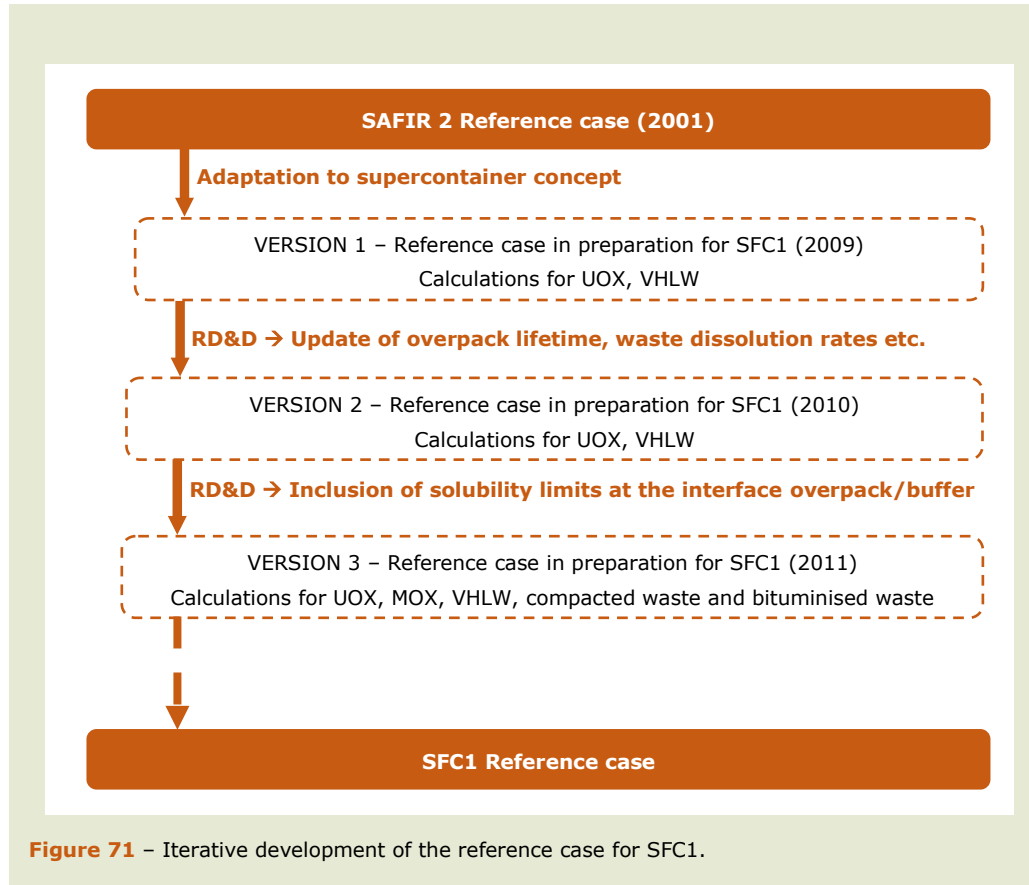
The safety concept and its related reference scenario are defined early in the programme stage and set the scope of the RD&D programme of the Safety and Feasibility Case at hand. The reference scenario is not expected to change over time due to its abstract nature, describing a “broad-brush” evolution of the system. The reference case is a particular realisation of the reference scenario with specific choices regarding the models assumptions and the parameter values. It is an abstraction of the detailed knowledge of the assessment basis and integrates the RD&D results. It will thus be refined over the RD&D programme. In order to evaluate the consequences of the RD&D progress from the safety viewpoint, several versions of the reference case, called the “working versions”, are developed during the current preparatory phase. These successive iterations include updated RD&D results in safety assessments and give quantified indications of their impacts in terms of safety. These iterations can be seen as a yardstick guiding the RD&D towards the fulfilment of the objectives of the Safety and Feasibility Case at hand.

Iterating the reference case during the preparatory phase gives the opportunity to the safety assessors to check stepwise with the experts whether the scientific and technical knowledge has been correctly abstracted. Whereas the reference scenario sets the frame of the RD&D, the different versions of the reference case guide it.

Three versions of the reference case have been developed since the beginning of the SFC1 preparatory assessment phase (Figure 71). The knowledge from the previous formal safety assessments (reported in SAFIR2), combined to the supercontainer design, were the basis for developing the first working version of the reference case in 2009 (ONDRAF/NIRAS, 2001b). The safety assessment results based on this first working version highlighted the need to focus research on the processes occurring in the EBS, such as carbon steel corrosion and waste dissolution. The phenomenological knowledge associated with the new EBS concept was indeed still limited at that time and the hypotheses behind the reference case were consequently over-conservative. The first version also included over-conservative assumptions about the migration of some radionuclides in Boom Clay, considering that all actinides migrate as complexes with mobile dissolved organic matter that are not retarded. This assumption strongly underestimates the retention capacities of the clay host rock. The need for a better understanding of the chemical interactions between the radionuclides and the organic matter was thus also necessary. Additional RD&D results lifted many over-conservative assumptions in the second (and subsequent) version(s) of the reference case, mainly regarding the waste matrix and overpack lifetimes and the retardation processes in

Boom Clay. A better understanding of the disturbed zone resulting from the research performed in the national programme and in the SELFRAC and TIMODAZ projects led also to a less conservative abstraction of this zone in the model used for safety calculations (Section 4.2.2.1).

Version 3 of the reference case is a prospective case dedicated to the assessment of potential retention processes in a concrete environment. At the time of SAFIR2, the EBS was backfilled with a bentonite-based material. Upon dissolution, the contaminants would be thus in contact with bentonite, whose properties are similar to those of Boom Clay. Knowledge of retention properties in the host rock was thus transferable to some extent to the near-field environment. This is not the case with the supercontainer design: contaminants must migrate through successive layers of concrete before being in contact with Boom Clay, as the buffer, backfill and gallery lining are made of this material. The total thickness of the concrete layers is larger than 1 metre for category C waste. It is realistic to think that interactions between radionuclides and the concrete will happen. The chemistry in this concrete near field is dynamic and complex. Many interactions are known to occur in cement such as complexations, co-precipitations and sorption processes, whose importance depends on the cement initial composition and structure and its evolution. Abstracting this plethora of processes into a simple and conservative conceptual representation captured in safety analysis is under discussion between experts from the poles "phenomenology" and "safety assessment". In order to estimate the impact of retention processes occurring in the concrete, it was decided to include them in the safety calculations via an approach based on "solubility limits". Solubility limits of radionuclides (considered as amorphous pure phases without consideration of co-precipitation) were imposed at the interface overpack/buffer in the third version of the reference case. The selection of solubility limits was based on the available knowledge from the category A disposal programme. (In this programme, minima, best estimates and maxima of the solubility for relevant radionuclides were derived in oxidising conditions for the four concrete degradation states.) These solubilities are assumed to be conservative for the reducing conditions expected in the geological system. Future studies on the consistency of this transferability should confirm or refine this abstraction. Results of these prospecting calculations give indications of the potential benefits that could result from accounting for such retention processes.



**Figure 71** – Iterative development of the reference case for SFC1.

## 6.2. Is gas an issue for geological disposal in Boom Clay?

Generation of gas is inevitable after closure of the disposal gallery, mainly due to anaerobic metal corrosion, radiolysis, (bio-)chemical microbial degradation of wastes and radioactive decay. Preliminary assessments performed for SAFIR2 indicated that gas transport is a potential safety issue, if the rate of gas generation within the system is higher than what can be evacuated by diffusion of the dissolved gas through the host rock, as detailed in Section 4.2.2.5. ONDRAF/NIRAS has developed a multi-step, iterative cross-disciplinary approach to identify problematic waste families in terms of gas production and removal. Implementing this approach required collaboration between safety assessors and many research groups:

- Group “inventory”: to provide the source terms characteristics in terms of gas production (e.g., quantity of metals) (Section 3.1.3) and select the potentially impacting families.
- Group “feasibility”: to evaluate the quantity and types of metals used in the EBS components, for potentially impacting families.
- Group “corrosion”: to provide corrosion rates for the different types of metals identified by the inventory and feasibility groups.
- Group “migration”: to provide the effective diffusion coefficient of dissolved hydrogen through Boom Clay.

An exploratory calculation (comparison of the time-dependent gas source term with the time-dependent diffusive removal capacity) was performed on the selected waste families in their EBS in order to evaluate the relevance of this issue in the geological programme. The results of this calculation indicated the importance of pursuing RD&D studies in order to reduce the uncertainties linked to parameters used in the calculations, such as the corrosion rate of carbon steel in a concrete environment and the diffusion rate of dissolved hydrogen in Boom Clay. These studies, whose results are summarised in Chapter 4, led to a substantial reduction (at least by one order of magnitude) of the uncertainty associated with the above-mentioned parameters.

Based on these RD&D outcomes, a second round of calculations was performed. Their results allowed screening out category C waste as a problematic waste type for gas generation and transport: in the case of disposal of this waste, diffusive transport would be sufficient to evacuate all generated hydrogen as dissolved gas. There is now confidence that gas generation and transport is not a safety issue for category C waste, a conclusion considered as reliable since the hypotheses err on conservative/pessimistic assumptions (for instance, higher limit of the uncertainty range associated with the corrosion rates were used in the calculations).

Category B waste shows a different picture: Some waste families of this category did not successfully pass the screening and a further reduction of the uncertainty of the source term seems difficult. Indeed, the large and complex specific surface of the CSD-C waste, radiolysis of organics and their possible microbial degradation are difficult to characterise and compels to bounding assumptions. In accordance with the safety strategy, which involves the three poles of expertise, the pole “feasibility” is studying a design variant that would limit the quantity of metallic components in the EBS (Section 5.1.2). Should the gas generation remains critical for specific waste families, feasibility studies might be initiated to investigate the design of an engineered barrier system in which the storage

and the non-disruptive transport of gas would be organised, for instance by the choice of a high-porosity, non-compacting backfilling material. This kind of design solution is already under consideration in other countries. Although gas production for category B waste remains an open issue requiring more RD&D, ONDRAF/NIRAS is gaining confidence that gas perturbation can be sufficiently understood and controlled, and does not represent a “show-stopper” to the geological programme.

### **6.3. What is the extent of the damaged zone to be considered in the reference case for category C waste?**

The Boom Clay around the repository will be disturbed by the excavation, construction, operation and post-closure evolution of the repository. As discussed in Section 4.2.2, different types of perturbations will disturb the host formation at various spatial and temporal scales. The disturbed zone of a specific perturbation originating from the repository is the zone of the host formation and its surrounding sediments where the values of any property are modified by this perturbation to such an extent that they evolved beyond their nominal range. Several processes affect the properties of the disturbed zone in time, causing its extent also to change in time. For some perturbations, the disturbed zone is possibly open-ended. The RD&D in this field aims to describe all perturbations and evaluate their extent, as detailed in Section 4.2.2.1 and is summarised hereafter for category C waste. During the excavation of the disposal gallery and shaft, an open fracture zone is inevitably formed in the first metre of Boom Clay around the gallery because of the mechanical failure caused by stress redistribution. Beyond this fracture zone, an eye-shaped disturbed zone with enhanced hydraulic conductivity (by a factor 2 – 3 at most) extending to a few metres around the gallery is observed. However self-sealing of the fractures occurs in a relatively short time and the permeability evolves towards that of undisturbed clay within a few years. Next to this hydro-mechanical perturbation, oxidation is also unavoidable during excavation and operation of the repository structures. This perturbation is limited to the surfaces of open fractures in the EDZ and the extent of the oxidised zone of the Boom Clay remains limited to about 1 metre around the galleries. The emplacement of heat-emitting waste in a repository will induce thermal perturbations in the host formation during the so-called thermal phase. The thermally disturbed zone will extend over the whole thickness of Boom Clay although the temperature change decreases rapidly with distance. Complete containment will be guaranteed until nominal ranges have been restored in the host rock so that radionuclide transport should not be influenced by this perturbation, provided that it does not lead to irreversible changes of radionuclide migration parameters. The most important chemical perturbation extending in the long term is the formation of an alkaline plume due to the chemical interactions between the host formation and the high-pH EBS materials. Geochemical reactive transport simulations showed a perturbation up to 2 – 2.5 metres after 100 000 years consistent with exploratory calculations based on mass balance calculations suggesting a maximum of 3 metres of perturbed Boom Clay. In case of disposal of category C waste, the produced gas will most likely be entirely evacuated by dissolution within the pore water and diffusion. The space restriction is expected to limit microbial development in a closed repository.

Based on the current phenomenological knowledge, conclusions for the post-containment period for category C waste are summarised as follows: There are no lasting effects expected for thermo-hydro-mechanical (THM)-related perturbations on

the Boom Clay matrix structure. At the expected time of overpack failure, the porosity, density, permeability, pore diffusion coefficients as well as temperature are assumed to have recovered to their nominal ranges. The chemical perturbations of the alkaline plume might however affect the retention properties of the host rock in the long term.

Of sole importance for safety assessments is the impact of perturbations on the safety relevant properties. The impacted zone is called the “damaged zone”, defined as the part of the disturbed zone where properties are modified by the repository to such an extent that the safety functions of the disposal system are significantly and negatively affected. As several processes affect the state and host formation properties of the disturbed zone in time, the extent of the damaged zone might also change in time (Van Geet *et al.*, 2008b). Safety assessments of the disposal system need to take into account the damaged zone and its evolution.

The modelling of the damaged zone in the second and third versions of the reference case rests on the following assumptions: its extent is limited conservatively to 3 metres based on exploratory calculation results (maximal extent of the alkaline plume from mass balance calculations); the R2-safety function (limitation of the water flow through the disposal system) is efficient in this damaged zone while the R3-safety function (retardation of contaminant migration) is non effective. Consequently, permeability and effective diffusion coefficients of radionuclides in the damaged zone are comparable to those in undisturbed Boom Clay while, because of the remaining uncertainties regarding the geochemical conditions, sorption and precipitation are assumed not to occur.

#### **6.4. Lessons learned**

The previous examples illustrate some typical aspects of the “safety assessments” during the preparatory assessment phase. The principles of robustness and simplicity lead the exploratory calculations. The example on gas outlines how the safety assessment tackles specific issues by delineating the scope of future RD&D studies, while triggering at the same time the development of design-out solutions (link with the feasibility aspects). The safety assessment rests on robust hypotheses that constitute a reliable line of argumentation next to more realistic modelling and observations.

The successive versions of the reference case relax progressively some conservatism to account of new results from ongoing research but also the need for the safety assessment to keep the description of the overall evolution of the system simple in order to comply with the objective of demonstration.

Therefore, for the sake of simplicity and robustness, the safety assessment requires an *ad-hoc* use of abstraction such as illustrated by the example of the damaged zone, and thus to rely on simple and conservative hypotheses.



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**Roadmap – Chapter 6 – The long-term safety of the disposal system can be assessed**

ONDRAF/NIRAS will first pursue the preparatory phase of the SFC1 (including for instance the development of performance-assessment models and further iterations of the reference case accounting for the evolving conditions and transferability issues, the alternative cases and altered scenarios and sensitivity analyses). It will then perform the formal assessment phase. This phase will include the full range of scenarios and performance-assessment calculation cases necessary to demonstrate the safety and feasibility of geological disposal in poorly indurated clay.

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# 5

## **Part 5**

**The requirements can be met**



## 7. The long-term radiological impact can be assessed

The International Commission on Radiological Protection (ICRP) specifies the dose limits to any individual from regulated sources in planned exposure situations other than medical exposure of patients that should not be exceeded (ICRP, 2007) (ICRP, 2013). In Belgium, the Belgian nuclear safety authority transposes the appropriate limits specified by the ICRP into the specific legal and regulatory framework for geological disposal of B&C waste (Moniteur Belge, 2001) (FANC, 2010) (FANC, 2010b) (FANC, 2012) (FANC, 2012b). The appropriate limits depend on the considered scenario.

The overall safety of a geological repository is assessed by means of simulations of the radionuclide release and transport. The outcomes of these simulations are often called safety indicators and are compared with the appropriate limits specified by the authorities or with reference values. The most commonly used safety indicator is the effective dose rate. However, the uncertainty in dose rate calculations increases with time, especially in the aquifer system surrounding the host formation and the biosphere. Therefore, additional indicators are developed that can improve the reliability of the results of the safety assessment. For increasing the confidence of various stakeholders in the results of the safety evaluations, it is essential to develop also indicators that explain the functioning of the disposal system by quantifying the contribution of its main barriers or safety functions; such indicators are called performance indicators (Marivoet *et al.*, 2010). The safety and performance indicators to be used for formal assessments will be chosen in line with the Belgian nuclear safety authority, based, among others, on results from European projects SPIN<sup>86</sup> and PAMINA<sup>87</sup> (SPIN, 2002) (Becker *et al.*, 2009) (Marivoet *et al.*, 2010).

The results of the assessments presented in SAFIR2 showed doses below the envisaged constraint for all waste streams considered and for most analysed cases. These assessments highlighted that the Boom Clay is the dominant contributor to the overall safety in the reference scenario and other plausible evolution scenarios (ONDRAF/NIRAS, 2001). Preparatory safety assessments performed in the frame of the current RD&D programme confirm these results.

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### Roadmap – Chapter7 – The long-term radiological impact can be assessed

For SFC1, ONDRAF/NIRAS continues to follow the evolution of ICRP recommendations and analyses how these may affect its assessments. It will take into account the regulator's recommendations on safety and performance indicators.

ONDRAF/NIRAS will develop the SFC1, with safety calculations for the impacting families (roadmap Section 3.1), for disposal in Boom Clay and Ypresian clays, with different scenarios.

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86 SPIN: Testing of safety and performance indicators (EU project).

87 PAMINA: Performance Assessment Methodologies in Application to Guide the Development of the Safety Case (EU project).

Part 5 – The requirements can be met

## 8. The environmental impact can be assessed

Besides the aspects of radiological protection developed in Section 2.1, radioactive waste is managed taking into account environmental aspects. In Belgium, the Regions are the main actors in environmental matters. They are indeed responsible for the transposition of directives and the various international treaties. The municipalities also have a role to play as a relay of the regional policy of the protection of the environment and urbanism. Nuclear safety is however under the responsibility of the Federal Government. The distribution of responsibilities between different governance levels can sometimes lead to conflicts.

ONDRAF/NIRAS has checked regulations and laws applicable to the protection of the environment surrounding a disposal system in Boom Clay or Ypresian clays (Moniteur belge, 1983) (EU, 1992) (VLAREM, 1995) (Moniteur belge, 2003b) (EU, 2006b) (EU, 2008) (EU, 2010) and has identified three main issues to be treated, summarised hereafter.

### Temperature increase of the upper aquifer

The thermal output generated by high-level waste induces an increase of temperature of the disposal system and of the surrounding geological layers, which include aquifers. This temperature increase must be limited in order to meet environmental regulations. On behalf of ONDRAF/NIRAS, Ecorem analysed the current Flemish, Belgian and European legislations with respect to the possible thermal increase of groundwater also used for drinking water. Flanders imposes a maximum admissible temperature for groundwater 25°C with a standard value of 12°C. The limit of 25°C originates from the fact that Legionella microbes do not show important growth below this temperature. This is the most stringent regulation among those studied by Ecorem (European Community legislation, Belgium (Flanders and Wallonia), Germany, the Netherlands, France, and the United Kingdom) (Ecorem, 2008). In the case of Boom Clay, the temperature of its upper aquifer – the Neogene aquifer – may thus not exceed 25°C. As the temperature at the interface between the Boom Clay and the Neogene sands is between 14 and 15°C at the reference site for RD&D in the Boom Clay, the maximum admissible repository-induced temperature increase should not exceed 10°C in that area. This value is site-specific and will be re-evaluated during the siting process. This leads to constraints on the design of the repository for heat-emitting waste, in particular on the spacing between disposal galleries and on the thermal load per unit length of gallery. (The detailed design of the EBS has only a marginal impact on the temperatures in the surrounding clay.)

Sillen and Marivoet performed exploratory calculations in order to determine the minimum distance required between disposal galleries in order to meet this requirement of limited temperature increase (Sillen and Marivoet, 2007). Their results suggest that the temperature criterion could be met with the current design:

- The temperature increase can be kept below the required value in case of disposal of supercontainers with vitrified high-level waste cooled for 60 years before disposal, in galleries 50 metres apart.

- The temperature increase is slightly above the required value in case of disposal of supercontainers with UOX irradiated fuel cooled for 60 years before disposal, in galleries 120 metres apart. This is due to an over-conservative source-term: it is assumed that *all* assemblies have been irradiated to the maximised authorised burnup<sup>88</sup> (55 GWd tHM<sup>-1</sup>) although the burnup – and thus the thermal output – of a large part of the Belgian inventory is lower than this value.

### **Increase of the soil surface level**

The disposal of heat-emitting waste will lead to the thermal expansion of the Boom Clay and of the surrounding geological layers. Although there are currently no regulatory limits for uplift – increase of the elevation of the ground –, Sillen and Marivoet performed an assessment of this thermal expansion, considering the disposal of irradiated fuel or of vitrified high-level waste after 50 years of cooling in the current repository design (Sillen and Marivoet, 2007). Results indicate that the maximum uplift of the ground level above the geological repository is about 10 centimetres in case of irradiated fuel disposal, occurring about 125 years after disposal. The maximum uplift is about 15 centimetres in case of vitrified high-level waste and occurs about 60 years after disposal. This uplift is uniform over the repository area (no localised differential uplift). The uncertainty in the uplift calculations is considerable and more information on this field is expected from the PRACLAY Heater Test (Annex A4).

### **Chemical contaminants**

The chemical contaminants contained into the waste may pose a risk to the man and the environment and are thus part of the RD&D programme, in particular in the field of solutes transport (Section 3.3.9).

Regulations limit the concentration of chemical contaminants in the environment (VLAREM, 1995). Results of a preliminary study in which the maximum levels of toxic elements in the aquifers were compared with the standards that apply to drinking water indicate that the concentration of chemical contaminants always remains below standards (Harju-Autti and Volckaert, 1995). This study examined mainly the migration of metals (pure chemical elements) through Boom Clay. Its conclusion is not surprising given most of the metals are present in solution in a cationic form and that positively charged species are strongly sorbed on the Boom Clay (Section 3.3.9.3) (ONDRAF/NIRAS, 2001b). A new study is under way to reassess the impact of chemical contaminants, including organics, with a new methodology, based, among others, on updated waste inventories (Section 3.1).

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88 As of January 2012.

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### Roadmap – Chapter 8 – Environmental impact

For *SFC1*, ONDRAF/NIRAS will continue to monitor the evolution of regulations and laws applicable to the protection of the environment surrounding a disposal system in Boom Clay or Ypresian clays. It will evaluate their impact on the disposal system as needed. In line with the law and regulations mentioned above, ONDRAF/NIRAS will continue its investigations on the protection of the aquifer resources, among others, and will develop them as needed:

- For *SFC1*, studies confirm that the impact of chemical contaminants released by the disposal system is low, so as to ensure, in particular, that this impact does not endanger the quality of the water resources and, more generally, does not unacceptably affect the disposal system's environment, including the surface environment, and man.
- For *SFC1*, ONDRAF/NIRAS will update calculations of thermal output of category C waste with realistic values. It will then revise the description of the thermal evolution of the disposal system and its potential environmental consequences (particularly within the aquifers). It will also re-evaluate the uplift above a repository for heat-emitting wastes using a more realistic model and results from laboratory experiments. For *later SFCs*, the model will be further adapted to include knowledge gained from the PRACLAY Heater Test (Annex A4) and from the thermal properties of layers surrounding the Boom Clay (see roadmap Section 3.4.1).





## 9. Other external requirements can be met

As stated in the Waste Plan, ONDRAF/NIRAS considers that the development and implementation of the technical solution it recommends will have to meet conditions arising from the consultations, in addition to the applicable standards and regulations (ONDRAF/NIRAS, 2011c). These conditions result from concerns that are largely shared by the public and from concerns expressed by the official institutions consulted.

Some of these conditions pertain to the development and implementation of a solution for the long-term management of radioactive waste and have been transposed by ONDRAF/NIRAS to the specific case of geological disposal. Other societal concerns, in particular the need for independent monitoring of the decision-making process, have been included in the technical solution and/or the decision-making process outlined by ONDRAF/NIRAS (ONDRAF/NIRAS, 2011c).

In general, the public, whether or not it is in favour of a geological disposal solution, considers that it must be possible to retrieve the radioactive waste from the facility in which it has been placed, that it must be possible to control that the facility is functioning properly and is safe, and that knowledge of both the waste and the facility must be transferred from one generation to the next. ONDRAF/NIRAS intends to take account of these requests in developing and implementing the geological disposal solution it recommends and has included them in its strategic choices (Section 2.1). The scope of these requests will have to be further specified in dialogue with all stakeholders, taking into account the need to meet the requirements regarding safety and technical and financial feasibility (see also Chapter 11).

In this context, ONDRAF/NIRAS undertakes to

- ensure the reversibility of disposal during operation and examine the measures that could facilitate the possible retrieval of the waste after partial or complete closure of the repository for a period that is yet to be defined. These aspects are mainly integrated in Chapter 5. However, enhancing retrievability in the design and implementation of a repository cannot occur at the expense of radiological safety, physical security and non-proliferation measures for nuclear materials (safeguards); enhancing retrievability could have an impact on the cost of the repository;
- monitor the proper functioning of the repository, which will be performed in addition to regulatory controls. This will require societal input to identify potential stakeholder requirements for monitoring (Chapter 11), which will then be integrated in the ONDRAF/NIRAS monitoring strategy (Section 5.5). However, these controls cannot be performed at the expense of perturbing the system and thus its proper functioning;
- prepare in the most appropriate way the transfer of knowledge of the repository and the waste it contains to future generations. This transfer can be organised at both national and international level, in particular by means of the reports to be provided under international requirements. However, it is up to each generation to determine what knowledge and resources it wishes to transfer to the next generation.

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### **Roadmap – Chapter 9 – Meeting other external requirements**

*For SFC1*, ONDRAF/NIRAS examines the measures that could facilitate the possible retrieval of the waste after partial or complete closure of the repository for a period that is yet to be defined by stakeholders (see roadmaps of Chapter 5.) ONDRAF/NIRAS also examines the measures to monitor the proper functioning of the repository (see roadmap of Section 5.5). ONDRAF/NIRAS prepares the transfer of knowledge of the repository and the waste it contains to future generations. ONDRAF/NIRAS currently takes part in the international project of the NEA Radioactive Waste Management Committee called Preservation of Records, Knowledge and Memory across generations<sup>89</sup>. The project aims to compare approaches, test potential solutions and build common references in this field (Chapter 11).

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89 Website: <http://www.oecd-nea.org/rwm/rkm/> (Last visit: 2 February 2013).

# 6

## **Part 6**

### **Extending the knowledge basis**



## 10 The Ypresian clays are a potential host rock

### 10.1 Introduction

Since the first Safety Assessment and Feasibility Interim Report (ONDRAF/NIRAS, 1990), the Ypresian clays, another non-indurated clay unit in Belgium, have been proposed as an alternative host rock to Boom Clay (Secretary of State for Energy, 1990) (ONDRAF/NIRAS, 2001). Present in the northwest part of the country, the Ypresian clays have geological characteristics close to those of Boom Clay. It is therefore likely that the development of a disposal system in Ypresian clays may benefit from the knowledge acquired so far for Boom Clay.

ONDRAF/NIRAS has carried out several studies and exploratory boreholes in the Doel-Kallo area, the reference zone for RD&D in the Ypresian clays. The first drilling campaign took place in Doel in 1998 and the second one in Kallo in 2009, both followed by a programme of laboratory experiments on core samples. In this text, the boreholes in the areas are called respectively "ON-Doel" and "ON-Kallo". A full interpretation of the results is still in progress. Data from other boreholes are also available (*e.g.*, Knokke borehole). For the Ypresian clays, the degree of knowledge is still at the level of parameter characterisation, while for Boom Clay a level of knowledge has been achieved at which high-level conclusions and decisions can be taken.

Insofar as Ypresian clays present characteristics similar to those of Boom Clay, it is reasonable to assume that the safety strategy developed for geological disposal in Boom Clay can be applied to geological disposal in Ypresian clays, that the same type of underground facility design can be used, and that most of the knowledge relating to Boom Clay is valid for Ypresian clays. The safety strategy takes an iterative approach, which allows stepwise adjustments if necessary. Owing to the similarity of both potential host rocks, but in the absence of an underground research facility in Ypresian clays and of an extensive research programme, research in the Ypresian clays is driven by a transposability approach. The approach aims to assess the extent to which the knowledge obtained in Boom Clay (parameter, technique, process understanding, conceptual model or high-level conclusion) can be used as proxy in Ypresian clays. It is based on the comparison of basic properties and prevailing conditions and can lead to the conclusion that they do not have, at first sight, to be studied again, or, on the contrary, cannot be applied as equivalent and need additional investigation (Section 2.3.1).

This chapter is structured in parallel to the parts of this document devoted to Boom Clay (Parts 2, 3 and 4). Section 10.2 reviews the knowledge of a disposal system in Ypresian clays and of its environment. Section 10.3 explains the evolution of the disposal system and its environment while Section 10.4 treats the feasibility issues. Section 10.5 summarises the way leading to assessing the long-term safety of geological disposal in Ypresian clays.

## **10.2 The system components can be characterised**

### **10.2.1 The conditioned wastes can be characterised**

Knowing the wastes to be disposed of is crucial for safety assessments. Section 3.1 details knowledge of the technical inventory, the identification of families that either require the highest system performances or are liable to impair these performances, the remaining uncertainties and their consequences on the RD&D programme.

Most knowledge of the conditioned wastes is transposable to disposal in Ypresian clays. Indeed, the waste classification (in categories, families and “generic types”) is valid for disposal in Ypresian clays as in Boom Clay.

### **10.2.2 The other parts of the engineered barrier system can be characterised**

The current design of the engineered barrier system (including the supercontainer and the monolith B) and the repository layout for the disposal of category B&C waste in Boom Clay are detailed in Section 3.2. The complete characterisation of the engineered barrier system (EBS) will be performed during the next stages of the programme. At this stage of research, no separate design or layout has been developed for a potential disposal system in the Ypresian clays. It has therefore been decided to transpose, the current design of the EBS (including the supercontainer and the monolith B design) and the repository layout of the disposal system developed for Boom Clay.

Some points of these design and layout could differ between Boom Clay and Ypresian clays, such as the spacing between disposal galleries or the number of primary waste packages in disposal packages (due for instance to potential different thermal properties of the host rocks).

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#### **Roadmap – Section 10.2.2 – Characterisation of the EBS (YC)**

*For SFC1*, ONDRAF/NIRAS will evaluate the thermal properties of Ypresian clays and surrounding layers as they may affect the design and layout of a repository.

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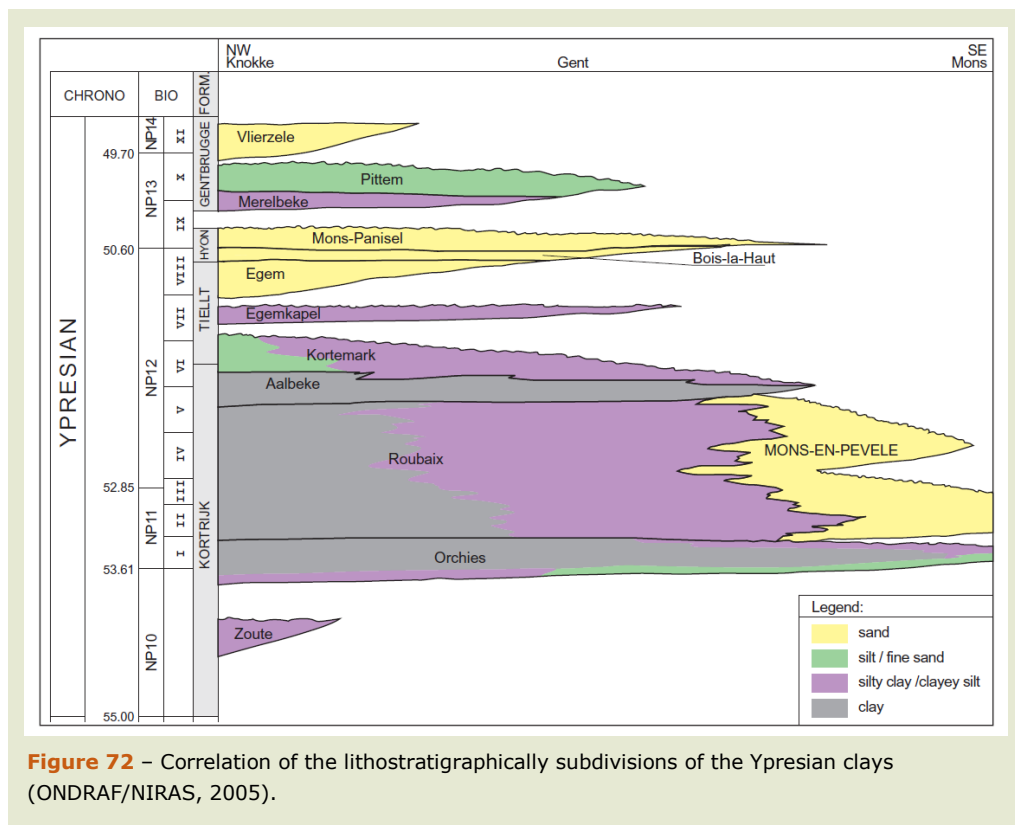
### 10.2.3 The Ypresian clays can be characterised

#### 10.2.3.1 The Ypresian clays and their occurrence area

##### Stratigraphic definition of the Ypresian clays

The term “Ypresian clays” is an informal name for a relatively thick sequence of dominantly fine-grained sediments deposited early in the Eocene (about 54 to 51 million years ago). The considered clayey units belong to the Kortrijk Formation and to the Kortemark Member, which is the lower part of the Tielt Formation (ONDRAF/NIRAS, 2001).

The Kortrijk Formation is, from base to top, further subdivided into four Members (Table 29) (Figure 72): Mont-Héribu Member, Orchies Member, Roubaix Member and Aalbeke Member (Steurbaut, 1998) (Laga *et al.*, 2001) (Steurbaut, 2006). In the Knokke borehole, an additional 4 metres thick basal member, the Zoute Member, has been defined, but it is probably restricted to the northwesternmost extremity of Belgium (*e.g.*, (Steurbaut, 2006)). Laterally (east-south-easterly), the Roubaix Member passes into the Mons-en-Pévèle Member, which is, because of its coarse-grained nature, not included in the Ypresian clays (Steurbaut and Nolf, 1986). The Tielt Formation is subdivided from base to top into the Kortemark Member and the Egem Member. An additional Egemkapel clay unit is sometimes recognised as a separate member in-between or is, in contrast, interpreted as bed at the top of the Kortemark Member or the base of the Egem Member (De Ceukelaire *et al.*, 2012).



**Figure 72** – Correlation of the lithostratigraphically subdivisions of the Ypresian clays (ONDRAF/NIRAS, 2005).



### Sequence stratigraphic interpretations

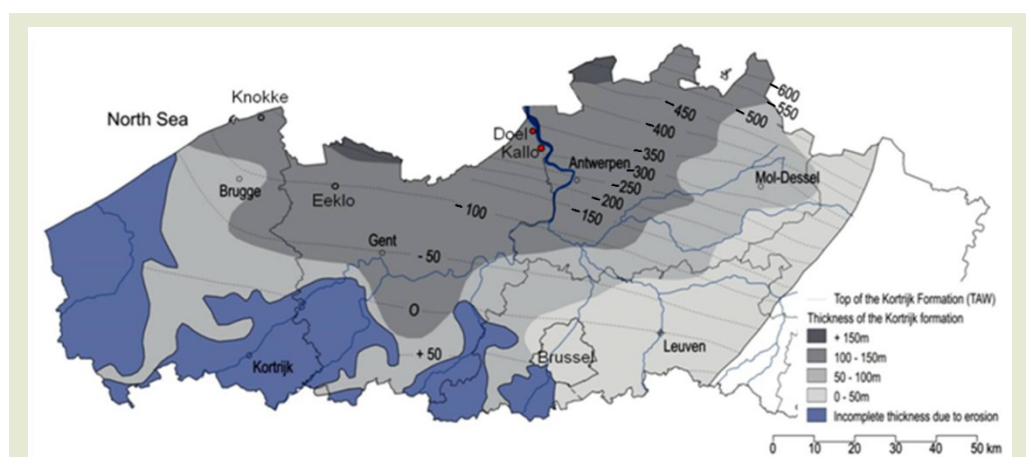
During the past decades, a number of proposals have been made to subdivide the Palaeogene and thus the Ypresian deposits into sedimentary sequences based on changes in grain-size distribution and mineralogical composition as observed in samples or derived from classical well logging (gamma ray and resistivity) (e.g., (Vandenberghe *et al.*, 1988) (Steurbaut, 1998) (Vandenberghe *et al.*, 1998) (Jacobs *et al.*, 2001) (Vandenberghe *et al.*, 2004) (Welkenhuysen and De Ceukelaire, 2009)). These sequences have been correlated over large distances (e.g., (Vandenberghe *et al.*, 1998) (Welkenhuysen and De Ceukelaire, 2009)). Cautious attempts have been made to correlate these sequences or sequence boundaries to known lithostratigraphic units.

### Stratigraphic interpretations of the available ONDRAF/NIRAS boreholes

In the framework of potential radioactive waste disposal in the Ypresian clays, ONDRAF/NIRAS performed two drilling campaigns, one in Doel (in 1998) and one in Kallo (in 2009). The ON-Doel borehole has been interpreted stratigraphically by different authors (written communication of Etienne Steurbaut in a letter to Laurent Wouters on 29 May 1998) (ONDRAF/NIRAS, 2001) (ONDRAF/NIRAS, 2005)) and the ON-Kallo borehole has been interpreted by Mohammad *et al.* (Mohammad *et al.*, 2009). The different interpretations give similar limits for the Kortrijk Formation (top of Aalbeke Member and top of Tienen Formation). They however (especially the interpretation of the ON-Kallo borehole compared to the interpretation of the ON-Doel borehole) show important differences in thickness of the Ypresian clays Members. The classical geophysical logs of both boreholes, on the contrary, display similar trends with depth.

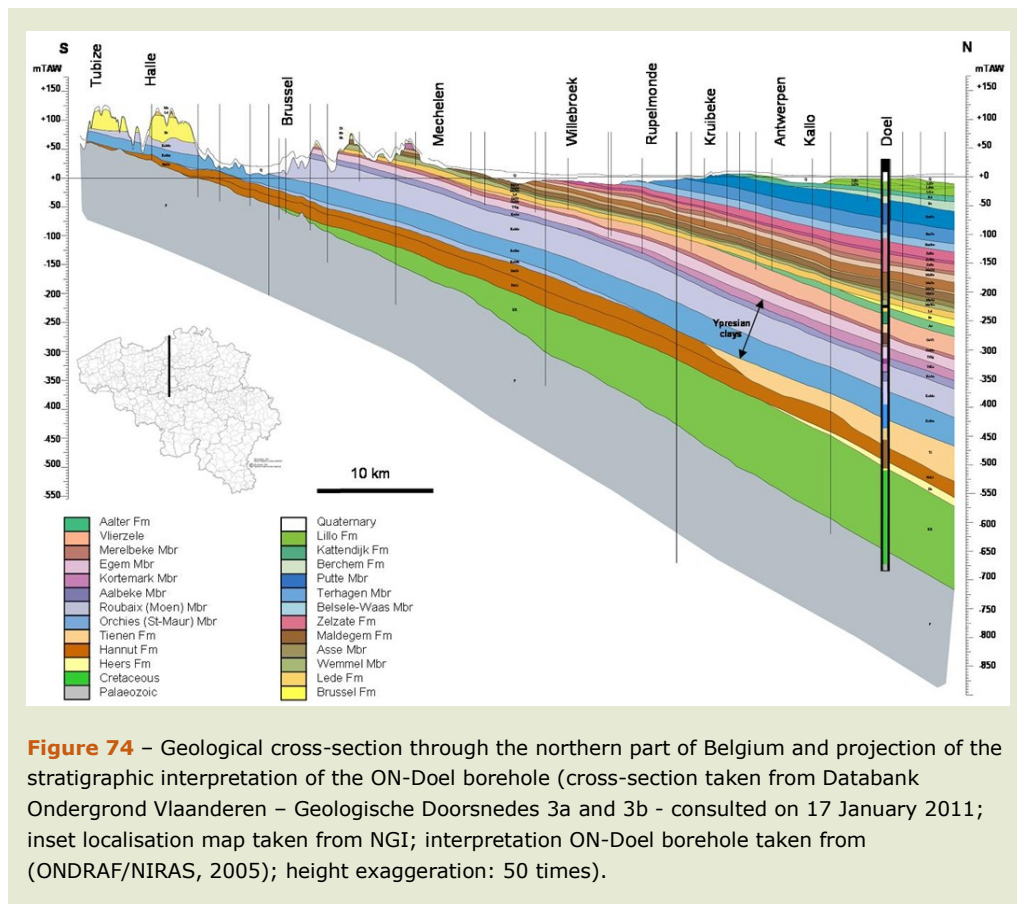
### Occurrence area of the Ypresian clays

The occurrence area of the Ypresian clays and their lateral equivalents (e.g., Mons-en-Pévèle Member) corresponds to the shaded area (blue and grey) in Figure 73.



**Figure 73** – Map of northern Belgium showing the depth below sea level of the top of the Kortrijk Formation (base Tielt Formation) and thickness of the Kortrijk Formation. Red dots indicate the approximate locations of the ON-Doel and ON-Kallo boreholes (slightly modified after (ONDRAF/NIRAS, 2001).

The occurrence area is bordered in the southeast by a straight line grossly retracing the original palaeocoastline (e.g., (Steurbaut and Nolf, 1986) (Steurbaut, 2006)). The lateral equivalents were deposited directly northwest of this line, in the broad area around Mol-Leuven-Brussels, where the thickness of the deposits is inferior to 100 metres (lightest and light grey on Figure 73). The considered sedimentary deposits are situated north-westerly of this rim of shallow-marine sediments, at larger distance from the palaeocoastline, in the deeper parts of the sedimentary basin. On the Belgian territory, the Ypresian clays crop out in the southern and western part of West-Flanders, the south of East-Flanders, the western part of Hainaut, Brussels, Walloon and Flemish Brabant. In these areas, the Ypresian clays were subjected to erosion, so that the sequence is only partly preserved (blue shade in Figure 73).



As can be observed on the cross-section in Figure 74 and derived from the lines of equal depth (isohypses) of the top of the Kortrijk Formation in Figure 73, the Ypresian clays dip towards the north so that in northern Belgium, the Ypresian clays are not affected by erosion but are covered by younger sediments. This northerly dip angle slightly increases from west to east and towards the north. Between the ON-Doel and ON-Kallo boreholes, an apparent dip of  $0.4^\circ$  can be calculated, corresponding to a true dip of about  $0.5^\circ - 0.6^\circ$  to the north-northeast. De Ceukelaire *et al.* recently extrapolated similar isohypse maps from borehole data for base and/or top of the individual members as defined by these authors (De Ceukelaire *et al.*, 2012). The depth distribution of the different members, and as a consequence their thickness, is thus fairly well known, although one has to consider the scarcity of borehole data in the northern part of the occurrence area. No important thickness variation or sudden depth variation have been

reported, to date. The thickness of the Kortrijk Formation is usually about 100 metres and more than 100 metres when the entire sequence of Ypresian clays is considered (see also (Welkenhuysen and De Ceukelaire, 2009)).

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### Roadmap – Section 10.2.3.1 – Occurrence area (YC)

For *SFC1*, ONDRAF/NIRAS will clarify the characteristics of the Mont-Héribu Member. If the Mont-Héribu Member is restricted to the lower-most, coarse-grained or heterogeneous deposits as described in the literature, ruling it out of the definition the Ypresian clays should be considered.

Stratigraphic knowledge is of prime importance for transferability. ONDRAF/NIRAS will thus continue stratigraphic studies to increase knowledge of the depth and the thickness distribution of the Ypresian clays and of separate members. It intends to clarify (at a national or international level) whether the Egemkapel Member/bed is a separate, formal member and whether it is part of the Ypresian clays. Other points of concern are the correlation of geophysical logs and the correlation of local stratigraphic subdivision in neighbouring countries, in order to demonstrate the lateral continuity and possibly transfer information.

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### 10.2.3.2 Discontinuities in the Ypresian clays

#### Tectonic faults

There are currently no geomorphologic indications of active faults in the northwest of Belgium and no faults affecting the base of the Cretaceous (or younger strata) have been indicated on the sub-Quaternary geological map of Flanders<sup>90</sup>. In the past, a few large-scale faults have been drawn on old pre-Cretaceous subcrop maps of the Brabant Massif (see maps after (Legrand, 1968) (De Vos *et al.*, 1993)), but these do not figure on the most recent version of the subcrop map, by lack of clear evidence (see (Piessens *et al.*, 2005)). Additionally, no major anomalies can be noticed on the aeromagnetic and gravity anomaly map (*e.g.*, (Williamson *et al.*, 2004) (Chacksfield *et al.*, 2004)). Smaller-scale faults might be visible on offshore<sup>91</sup> seismic profiles: in the southern North Sea, detailed seismic campaigns have indicated the presence of some possibly Paleozoic or Mesozoic faults with throws of tens of metres, which might have been reactivated during the Cenozoic (Henriet and De Batist, 1989) (Henriet *et al.*, 1989). In the geological record, the erosive bases in sediments of latest Ypresian - earliest Lutetian age and the presence of paleoseisms indicators in *e.g.*, the Egem sands (Ampe Quarry, Tielt) indicate tectonic activity at that time, which is related to the uplift and separation of the Paris and North Sea Basins (Vandenberghe *et al.*, 2003). Potential faults related to this tectonic activity are, however, unknown in the northwest of Belgium.

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90 Website <https://dov.vlaanderen.be/dovweb/html/index.html> (Last visit: 21 March 2012).

91 There are no known onshore seismic sections.

There is not much evidence of important tectonic faults crosscutting the Ypresian clays in the northwest of Belgium. The presence of faults with large throws can therefore probably be excluded. However, based on the present knowledge, which is of too low resolution, the presence of smaller-scale faults cannot be ruled out.

### Erosion surfaces

It is well known from the geological record that, after deposition of the Ypresian clays, relative sea-level changes have given rise to three important erosion events, which might have incised or removed the sediments deposited before (*e.g.*, (Vandenberghe *et al.*, 1998) (De Batist and Henriët, 1995) (Vandenberghe *et al.*, 2004)):

- Erosive base of the Egem sands,
- Erosive base of the shell-rich sandstone and laminated Pittem clay,
- Erosive base of the Brussels sands (in NE Belgium and Brussels area) and erosive base of the Vlierzele sands (in the northwest of Belgium and North Sea Basin).

The exact stratigraphic relationship between erosive bases of the Brussels sands and of the Vlierzele sands is not really clear (Vandenberghe *et al.*, 1998) (Vandenberghe *et al.*, 2004). They might represent lateral equivalents. Gullies of up to 20–25 metres deep have been described in the case of the Vlierzele sands (De Batist and Henriët, 1995) and channels of at least 30 metres deep in the case of Brussels sands. The base map of the Ledo-Paniselian-Brusselian aquifer system and the thickness map compiled by Cools *et al.* do not show important anomalies in the northwest of Belgium (Cools *et al.*, 2006).

It is unknown whether the erosion surfaces described above might have eroded parts of the Ypresian clays. It is suggested that more recent periods of erosion will probably not have affected the Ypresian clays (*e.g.*, base of the Diest Formation), since they were already at depth at these later stages.

### Mass movements

Relatively sudden stress and/or fluid pressure changes might cause mass movements in poorly indurated clay, as there have been described vertical upraise structures of Boom Clay underneath the Scheldt River and Scheldt Estuary (Section 3.3.2) and likewise, and of the Ypresian clays in the valley bottom of the Senne Valley in Brussels (Treve Christian, personal communication, 22 February 2013). In a recent study, Hobbs *et al.* concluded that the process of valley bulging is probably the most appropriate term to describe the mechanism that produced these features (Hobbs *et al.*, 2011). It is not clear whether the Ypresian clays buried at large depth might also have been affected by such mass movements on the one hand, as a response to the incision of the Scheldt or erosion in the North Sea or, on the other hand, by other gully erosions, earlier in the geological history (*e.g.*, erosive base of the Brussels Formation). A number of intraformational features observed (on seismics) in the Ypresian clays of the North Sea and Scheldt Estuary have been indicated as diapirs (*e.g.*, (Henriët *et al.*, 1982) (Henriët *et al.*, 1988) (Henriët *et al.*, 1991)) and onshore, in quarries, sedimentary dikes have been described by Verschuren (Verschuren, 2001). The nature of these structures, neither their origin is, however, clear.

### Intraformational faults

The literature over intraformational or polygonal faults is abundant in Belgium and abroad (Henriet *et al.*, 1982) (Henriet *et al.*, 1988) (Henriet *et al.*, 1991) (Verschuren, 2001) (Dehandschutter, 2004) (Dehandschutter *et al.*, 2005) (Dehandschutter *et al.*, 2005b) (Cartwright, 1994) (Cartwright and Dewhurst, 1998) (Lonergan *et al.*, 1998) (Lonergan *et al.*, 1998b) (Clausen *et al.*, 1999) (Goult, 2001) (Cartwright *et al.*, 2003) (Goult and Swarbrick, 2005) (Goult, 2008) (Ireland *et al.*, 2010) (Cartwright, 2011) (Davies and Ireland, 2011).

The structures of these faults are a typical feature of very fine-grained clays and oozes (Cartwright and Dewhurst, 1998). These faults have been detected in, among others, the Ypresian clays in the North Sea (on seismics *e.g.*, (Henriet *et al.* 1988)). These structures might possibly correspond to onshore examples of intraformational features in clay pits (Figure 75) (*e.g.*, (Henriet *et al.* 1988) (Verschuren, 2001)). Different models have been proposed to explain the development of intraformational faults, but there is no consensus to date (Henriet *et al.*, 1988) (Cartwright and Dewhurst, 1994) (Goult, 2001) (Dehandschutter *et al.*, 2005) (Ireland *et al.*, 2010). In the northwest of Belgium, there is a lack of knowledge whether they are present or not and since there exists many controversies about the (chemo-hydromechanical) mechanism of development, their presence cannot be predicted. Better understanding the genesis of these structures and the conditions at which they might form is, moreover, crucial for predicting whether they might or might not form in the future as a response to evolving conditions. It might be interesting to characterise the properties of such faults, namely their density, their vertical and horizontal extent, their linkage, their throw and the hydromechanical properties inside the fault zone.



**Figure 75** – Overview of a clay quarry (Marke) in the Ypresian clays, with potential onshore intraformational features as suggested by (Verschuren, 2001) (taken from ONDRAF/NIRAS, 2001).

### Ductile shear bands

Well-oriented or omni-directionally, high- to low-angle dipping shear bands (slickensides) might develop in poorly indurated clay that underwent burial and uplift (and erosion) (Dehandschutter, 2004) (Dehandschutter *et al.*, 2005b). Dehandschutter (2004) does not describe these structures for the Ypresian clays, but suggests that the omnidirectional intraformational faults with variable dip in the Ypresian clays – not observed yet at depth – might result from such a mechanism. Studies on analogous structures in Boom Clay outcrops indicate that the shear bands are compacted and form no potential preferential path for gas or fluids (Dehandschutter, 2004), an element that can be transposed to the Ypresian clays at this stage of research but which should be compared to the views of (Henriet and De Batist, 1996), (Walraevens *et al.*, 1996) and (Walraevens *et al.*, 2001b) and who postulate that intraformational faults might have been pathways for fluid migration.

### Sub-vertical joints

In outcrop areas, an orthogonal system of two sets of vertical joints has been observed, which presents the same orientation than the sub-vertical joint system observed in the outcrop areas of Boom Clay (Dehandschutter, 2004) and fracture patterns recognised in northern France, among others in the London Clay, the lateral equivalent of the Ypresian clays (*e.g.*, (Bevan and Hancock, 1986)). No observations or estimations are, however, available for the Ypresian clays that might shed a light on the penetration depth of these joints and whether they are present or not in the Ypresian clays at depth. In the present situation, it is probably reasonable to transpose the (order of magnitude of the) formation depth obtained for Boom Clay (see (Mertens *et al.*, 2003) (Dehandschutter, 2004) (Dehandschutter *et al.*, 2005b)) towards the Ypresian clays and assume that the northwest of Belgium is presently not at conditions of extensional failure. However, the evolutions through time of burial depth, fluid pressure, horizontal stress and geomechanical parameters are unsatisfactorily known to evaluate whether the Ypresian clays in the northwest of Belgium were ever subjected to conditions at which joints might have formed.

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### Roadmap – Section 10.2.3.2 – Discontinuities (YC)

It is important *for SFC1* to check the continuity of Ypresian clays, in order to check for the potential presence of discontinuities. (Discontinuities have been observed in outcrops.). ONDRAF/NIRAS will therefore start a literature review to collect information about the presence of features that might disturb the continuity of the Ypresian clays. Based on this literature review, ONDRAF/NIRAS will then focus on understanding the formation mechanisms of the features, *e.g.*, intraformational faults, in collaboration with neighbouring countries.

ONDRAF/NIRAS will meanwhile start studies to increase its knowledge of the geomechanical properties of Ypresian clays; properties that can be used as an approximation for the past in order to check whether the Ypresian clays in the northwest of Belgium have ever been at unstable conditions necessary for forming deformation structures. ONDRAF/NIRAS will also compile information about the tectonic, burial and denudation

history of the northwest of Belgium and surroundings, necessary to reconstruct the evolution of the stress state (see Section 10.2.4.1).

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### **10.2.3.3 Lithology of the Ypresian clays**

Because of the earliest Eocene basin configuration and possibly tectonic activity, the Ypresian clays progressively grade into more near-coastal, coarser-grained deposits towards the southeast, like the Mons-en-Pévèle sands (*e.g.*, (Steurbaut and Nolf, 1986)). Five zones, sub-parallel to the palaeocoastline and isobaths of the earliest Eocene basin have been identified representing this gradual coarsening towards the southeast (figures in (De Smet and Olivier, 1996) and (ONDRAF/NIRAS, 2005)). The lateral continuity of such coarser-grained layers is unknown, and any systematics in this layering has not been reported to date. Coarsening- and fining-upwards trends at the scale of the members appear, however, to be relatively continuous, even across the borders of the different zones, suggesting a good lateral continuity of the Ypresian clays (based on geophysical log correlation in *e.g.*, (Welkenhuysen and De Ceukelaire, 2009)). Differentiation of layers visible in the field or on cores might also arise from the admixture of other minerals (glauconite, carbonates) or organic matter, but knowledge of these variables is only fragmental.

Localised cementation by carbonates (nodules, septaria) is rare in the Ypresian clays; pyrite and phosphate concretions are more common in certain members than in others (Steurbaut and Nolf, 1986).

Literature reports the presence of volcanic ash layers for the very earliest Eocene Tienen Formation and for the Zoute Member (Kortrijk Formation, Knokke borehole) and mineralogic evidence exists for (reworked) volcanic material in the Ypresian clays sequence (Mohammad *et al.*, 2009) (Zeelmaekers, 2011) (Zeelmaekers *et al.*, 2012), but there are no indications that volcanic deposits have particularly contributed to the layering of the Ypresian clays.

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#### **Roadmap – Section 10.2.3.3 – Lithology (YC)**

*For SFC1*, ONDRAF/NIRAS will document the vertical variability – and lateral correlation – of the admixture of certain minerals and organic material in order to check the continuity of Ypresian clays. Their presence should be understood.

*During the siting process*, the lateral continuity at the small scale (layers that can be differentiated) should be better documented, among others by comparing available core information and geophysical logs.

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#### 10.2.3.4 Mineralogy

The bulk mineralogy and clay mineralogy (*i.e.*, the mineralogy of the separated < 2 micrometre fraction) have been determined for the ON-Kallo borehole site (Mohammad *et al.*, 2009). For the ON-Doel borehole a semi-quantitative mineralogy of the clay, silt and sand fractions is available, but no bulk mineralogy (Walraevens and Mahauden, 1999). The grain size distribution and clay, sand and silt fractions are only known for the ON-Kallo samples. Minimum and maximum measured values of the bulk mineralogy are given in Table 26. Comparison of both boreholes is difficult due to the fragmental knowledge of the ON-Doel borehole, the use of different analysis techniques for interpreting the XRD-data and the differentiation into different mineral phases in both analyses.

The bulk mineralogy (as a percentage of dry weight) of the Ypresian clays at the Kallo site is composed of minimum 25% to up to 65% of clay minerals and 35% to maximum 75% of non-clay minerals (Mohammad *et al.*, 2009). The fraction of non-clay minerals is dominantly composed of quartz and significant amounts of feldspar. The carbonate content is generally low and varies with depth. As accessory minerals, framboidal pyrite (0.3 – 1%) has been observed in the ON-Kallo borehole. Opal-CT (cristobalite-trimydite) (occasionally) and zeolite (in a few samples) have also been observed (Mohammad *et al.*, 2009). The presence of zeolites of the clinoptilolite-heulandite group as well as the presence of opal-CT in some members of the Ypresian clays is confirmed by literature (Mercier-Castiaux and Dupuis, 1988) (Zeelmaekers, 2011).

The clay minerals within the bulk mineralogy are dominantly composed of smectite equivalent minerals and illite equivalent minerals (distinction based on cation exchange capacity) and to lesser extent of chlorite and kaolinite (Mohammad *et al.*, 2009). This is also reflected in the extracted clay fraction (whose size is lower than 2 micrometres). In the lowermost 15 to 20 metres, the proportion of smectite relative to other clay minerals decreases and is compensated by an increase in kaolinite and illite and, to a lesser extent, chlorite. These trends in the Ypresian clays are well known in the literature (*e.g.*, (Mercier-Castiaux and Dupuis, 1988) (Zeelmaekers, 2011)). The high clay content, and in particular the high smectite content, is also evidenced by the high values for the cation exchange capacity and the total specific surface (see Table 26). The contribution of organic matter to the cation exchange capacity is probably minor given its low concentration in the Ypresian clays. The organic matter content (as a percentage of dry weight) has been quantified in the ON-Doel borehole and ranges between 0.37 – 1.11%. Its chemical composition (functional groups, length of chains, maturity etc.) has not been characterised and it is, moreover, not clear which types of organic matter (*e.g.*, kerogen, dissolved organic matter) have been considered in this analysis.

In scanning electron microscopy images, some of the smectite grains appear to have a flaky texture sometimes overgrowing detrital quartz grains and are closely associated with opal-CT suggesting they are authigenic. Zeelmaekers suggests linking this feature to the rather weak development of the bedding-parallel fabric in the Ypresian clays (Zeelmaekers, 2011).

From a diagenetic point of view, it can be expected that the framboidal pyrite and possibly the smectite with authigenic appearance developed *in-situ*, probably early after deposition. Apart from these few mineral (trans-)formations, most rock constituents are believed to be detrital in origin (*e.g.*, no smectite-to-illite transformation) (Mercier-



Castiaux and Dupuis, 1998). A continuous, but very slow interaction between host rock particles (dissolution/precipitation of some mineral phases and/or organic matter) and the pore water can, however, not be excluded.

**Table 26** – Bulk composition of the Ypresian clays of ON-Doel and ON-Kallo borehole samples (raw data).

Mineralogical composition (% weight) (min-max)	ON-Doel			ON-Kallo		
Non-clays (total)				35	–	75
Quartz				24	–	72
Opal-CT				0	–	6
Feldspar				3	–	15
Carbonates	0.5	–	9 *(a)	0	–	4
Pyrite				0.3	–	1
Clay minerals (total)				25	–	65
Kaolinite				1	–	9
Chlorite				0	–	6
2:1-clays				19	–	57
“Smectite Equivalent”				13.1	–	34.8
(smectite)				(10)	–	(36)
“Illite Equivalent”				5.9	–	25.6
(Interstratified Illite/Smectite)				(6)	–	(14)
(Illite)				(2)	–	(16)
Organic matter	0.37	–	1.11 *(a)		–	
<b>Cation exchange capacity (CEC) (meq·100g<sup>-1</sup>)</b>	17.5	–	35.6 *(b)	13.1	–	34.8
<b>Total specific surface (m<sup>2</sup>·g<sup>-1</sup>)</b>	23	–	85 **(b)			

Reference for ON-Kallo: (Mohammad *et al.*, 2009). Number of samples for ON-Kallo: 15 (except for Cation exchange capacity: 17 samples).

References for ON-Doel: (\*) (Walraevens and Mahauden, 1999), (\*\*) (I.N.I.S.Ma, 1998)

Number of samples for ON-Doel: (a) 49; (b) 25.

Data between brackets refer the percentage of weight of smectite, randomly interstratified illite/smectite and illite, calculated from their relative proportion in the extracted < 2 µm fraction and the total percentage of weight of 2:1 clay minerals detected in the bulk.

#### Roadmap – Section 10.2.3.4 – Mineralogy (YC)

For SFC1, ONDRAF/NIRAS will pay attention to the mineralogy of Ypresian clays, as this may affect the retention and transport processes of contaminants. ONDRAF/NIRAS will integrate data from ON-Doel and ON-Kallo boreholes and/or perform re-measurements of samples, with more precise and standardised techniques. ONDRAF/NIRAS will document the spatial (vertical and lateral) variability of the grain size, the mineralogic composition and the organic matter content. ONDRAF/NIRAS will initiate a study to document the nature (authigenic or detrital) of smectite.

For later SFCs, it could be interesting to further characterise the organic matter of Ypresian clays, to better document the link between mineralogic clay content and grain-size distribution and/or geophysical properties, and, for the understanding of geomechanical processes, to document the fabric of the host rock and the potential occurrence of diagenetic products.

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### 10.2.3.5 Density and water content

The density of the solid particles composing the Ypresian clays has been determined on ON-Doel samples, by pycnometry in different types of fluids and gas (LGC, 1998) (I.N.I.S.Ma, 1998). The derived densities (*i.e.*, about 2.6-2.9 kg·dm<sup>-3</sup>) meet the expectation for a siliciclastic rock.

The dry and wet bulk density measurements of Ypresian clays have been performed on ON-Doel samples and on ON-Kallo samples (LGC, 1998) (I.N.I.S.Ma, 1998) (Piña, 2011). Values range between 1.3 and 1.8 kg·dm<sup>-3</sup> for the dry density and 1.8 to 2.1 kg·dm<sup>-3</sup> for the wet bulk density. An increase in density with depth (both wet and dry) can be observed, especially in the uppermost and lowermost part of the Ypresian clays. This density change can probably be related to changes in porosity (Section 10.2.3.6) rather than to limited changes in density of the solid phases. An increase in (wet) density can also be observed on the logs of the ON-Kallo borehole, which passes at 380 metres depth from less than 2 kg·dm<sup>-3</sup> to more than 2 kg·dm<sup>-3</sup> (Cammaer *et al.*, 2009).

The gravimetric water content (mass water/mass solids) has been derived for the Ypresian clays and varies between 19 and 35% by weight (LGC, 1998) (I.N.I.S.Ma, 1998) (Piña, 2011). The water content decreases with depth, as does the porosity (Section 10.2.3.6).

The plastic and liquid limit and the calculated plastic index are available for the ON-Doel (LGC, 1998) and ON-Kallo boreholes ((Piña, 2011) and preliminary results of on-going research)). A correlation seems to exist with other parameters as porosity, wet and dry density and clay or silt fraction, but these correlations should be subject to further investigation.

**Table 27** –Properties of Ypresian clays (Doel and Kallo) (LGC, 1998) (Piña, 2011).

Property	Range of values
Plastic limit	24.1 to 47%
Liquid limit	91.5 to 221%
Plasticity index	63.6 to 175%

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**Roadmap – Section 10.2.3.5 – Density and water content (YC)**

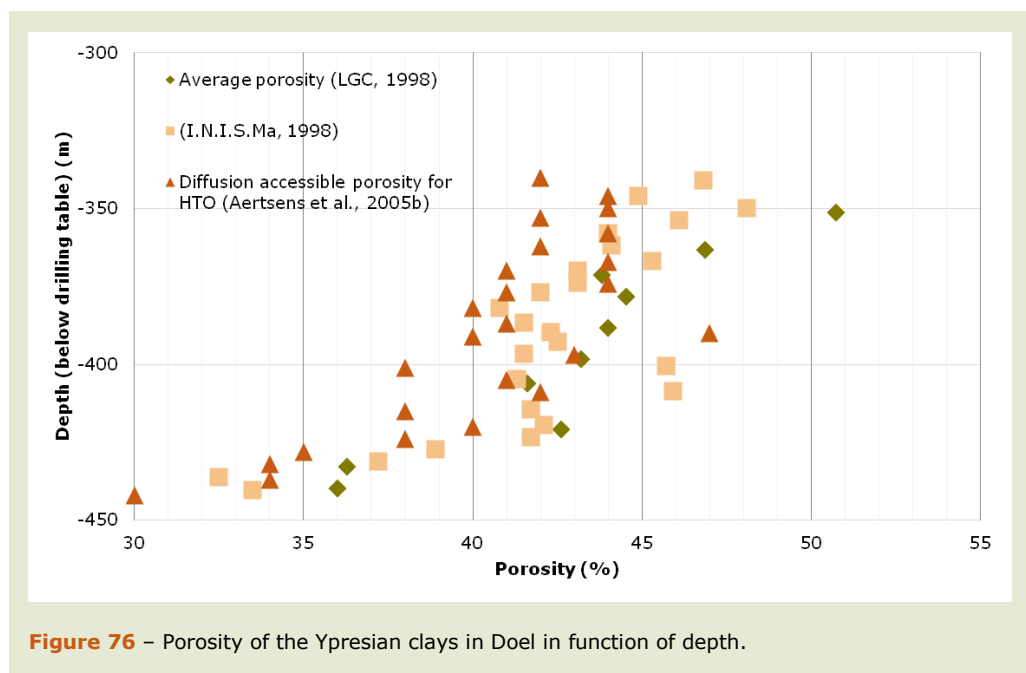
For SFC1, ONDRAF/NIRAS will pursue the current research on the plastic and liquid limit and the calculated plasticity index.

During the siting process, ONDRAF/NIRAS will further characterise the vertical and horizontal variability of density and water content.

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**10.2.3.6 Porosity**

The porosity in the Ypresian clays has been determined for the Doel site, indirectly by calculation out of other measured parameters (LGC, 1998) (I.N.I.S.Ma, 1998) and by migration experiments (Aertsens *et al.*, 2005b). The results obtained by these different techniques and authors fairly well correspond (see Figure 76). The porosity is high, relatively constant or slightly decreases with depth in about the upper 80 metres of the Ypresian clays sequence and decreases more drastically in about the lower 20 metres.



The pore size distribution in the Ypresian clays has been studied by mercury intrusion porosimetry for 25 samples from the ON-Doel borehole (I.N.I.S.Ma, 1998) and 2 samples from the ON-Kallo borehole (Piña, 2011). Although the results are difficult to compare due to the different ways of representation, most of the graphical representations of the data displays a bimodal distribution with a first peak at pore sizes below 100 nanometres and a second peak at a few hundreds of nanometres. Additional mercury intrusion porosimetry measurements on samples that underwent different stress paths in oedometers, indicated that the larger pores close first when the sample is loaded (even at burial stress level), but that this population of larger pores reappears when unloaded (Piña, 2011).

### 10.2.3.7 Hydraulic conductivity

The vertical hydraulic conductivity has been measured by pulse injection experiments on core samples taken in Doel (Aertsens *et al.*, 2005b) and Kallo (experiments in progress). A few vertical hydraulic conductivity data are also available from geomechanical tests on ON-Kallo samples (Piña, 2011). Hydraulic conductivity data derived from pumping tests in piezometers installed in the Ypresian clays in Kallo are also available (Ecorem, 2010). Integration and interpretation of these data is necessary. The pulse injections tests performed on ON-Doel samples are, at this stage, the only systematic data depicting the variability present in the Ypresian clays. The vertical hydraulic conductivities derived from these pulse injections experiments range between  $8.2 \text{ E}^{-13}$  and  $5.7 \text{ E}^{-11} \text{ m}\cdot\text{s}^{-1}$ , with the highest values in the middle part of the Ypresian clays and the lowest values in top and base. The vertical variability appears to be relatively high. This variability and covariance with other parameters have been studied in detail by Huysmans and Dassargues (Huysmans, 2006) (Huysmans and Dassargues, 2006). There is a relatively good correlation between the vertical hydraulic conductivity and the apparent diffusion coefficient, the diffusion-accessible porosity and the grain size. Although the core samples have been selected based on gamma ray and resistivity logs in order to cover the entire range of possible hydraulic conductivity data (Aertsens *et al.*, 2005b), the correlation with these geophysical parameters appears to be limited (Huysmans and Dassargues, 2006).

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#### Roadmap – Section 10.2.3.7 – Hydraulic conductivity (YC)

*For SFC1*, ONDRAF/NIRAS will integrate available data on the hydraulic conductivity of Ypresian clays and surrounding rocks. It will start additional analyses to specify, among others, its vertical variability and anisotropy. The first results might be integrated in SFC1.

*After site selection*, ONDRAF/NIRAS will check the vertical variability of the hydraulic conductivity at the chosen site.

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### 10.2.3.8 Pore-water composition

The composition is an important parameter for many processes involving chemical reactions. The pore-water composition in the Ypresian clays has been measured in pore waters obtained by squeezing of core samples of the ON-Doel and ON-Kallo boreholes and in pore waters collected from piezometers installed in one of the ON-Kallo boreholes (Walraevens and Mahauden, 1999) (Aertsens *et al.*, 2005b) (Eurofins, 2009) (Eurofins, 2009b) (Eurofins, 2009c). There are also data available from the over- and underlying strata at these localities, both on squeezed pore water as well as on pore water collected in piezometers. Table 28 presents the concentrations of the main cations and anions in the pore water of the Ypresian clays obtained from squeezing. Data obtained for the ON-Doel borehole usually have an equilibrated charge balance, but show evidence for pyrite oxidation for half of the samples. In contrast, there is usually a charge imbalance in the case of ON-Kallo samples and all squeezed pore waters have been affected by pyrite oxidation of the cores.

Despite these analytical problems treated in the ongoing research programme, one might, in general, conclude that the ionic strength or the total mineralisation of the pore water in the Ypresian clays in Doel and in Kallo is relatively high, but differ at both locations (see Table 28). Chloride, as a relatively conservative tracer (*e.g.*, not influenced by pyrite oxidation) has, *e.g.*, measured concentrations about 1/10 to 1/2 or more the concentration of seawater (about 19 400 mg·L<sup>-1</sup>). At both locations one might suspect a gradual increase of chloride with depth (*e.g.*, (Colenco, 2010)), although this trend is largely obscured by high vertical variations, which might represent the natural variability and/or results from analytical problems. This trend with depth can also be recognised for a number of other cations and anions, but is often obscured by the effects of pyrite oxidation and consequential re-equilibration processes (dissolution of minerals, destabilisation of organic matter and ion exchange on minerals and organic matter).

The carbonate and bicarbonate concentrations as well as the partial pressure of CO<sub>2</sub> have been measured in the Ypresian clays of ON-Doel. By chemical equilibrium, the relative concentrations of the different species of dissolved CO<sub>2</sub> are, however, strongly pH-dependent. The pH measured in Doel ranges between 6.56 and 8.84, but an influence of pyrite oxidation can be expected. This might explain the increase in HCO<sub>3</sub><sup>-</sup> concentration with increasing sulphate concentration, as observed in ON-Doel. In Kallo, the pH measured on squeezed samples ranges between 2.8 and 7.4. This range is unreasonably low for a pore water in equilibrium with carbonate minerals. The redox potential E<sub>h</sub> measured on squeezed pore waters displays positive values, but these values should be negative *in-situ* owing to the presence of pyrite and organic matter. Exploratory geochemical calculations assuming equilibrium between the pore water and solid phases confirm the inconsistencies of measured pH, pCO<sub>2</sub> and E<sub>h</sub> (Colenco, 2011).

Although some doubts can be formulated on the representativity of the data, the ionic strength can be expected to be high in the northwest of Belgium. The results on ON-Doel and ON-Kallo are in agreement with the general trends with depth and location already described by De Smet and Olivier (De Smet and Olivier, 1996). The most probable source of elevated concentration of chloride and other ions in the present setting is seawater, which might dominate the chemistry in the pore waters because of salty/brackish sea/estuary water intrusion, fossil intruded seawater or connate seawater (for details on these processes, see (Post *et al.*, 2003) (Post, 2004)). There exists evidence in the literature for the presence of brackish water in the Scheldt Estuary (*e.g.*,

(Soetaert and Herman, 1995) (Verlaan *et al.*, 1998)) as well as for successive periods of salinisation/freshening along the Belgian and Dutch coastal areas and the Scheldt Estuary (Walraevens *et al.*, 2001) (Post *et al.*, 2003) (Post, 2004) (Vandenbohede and Lebbe, 2006) (Blaser, 2007) (Blaser *et al.*, 2010) (Vandenbohede *et al.*, 2010b) (Hermans *et al.*, 2012). Research has also been performed on the ageing and freshening of the groundwater in the case of the Ledo-Paniselian aquifer and Neogene aquifer (van der Kemp *et al.*, 2000) (Walraevens *et al.*, 2007) (Blaser, 2007) (Coetsiers and Walraevens, 2009) (Blaser *et al.*, 2010). There is a need to integrate these data and possibly perform additional research for better understanding of the distribution and evolution of the salinity with time.

**Table 28** – Pore-water chemistry of the Ypresian clays obtained by chemical analysis of squeezed pore water from ON-Doel and ON-Kallo borehole samples (raw data). Precision and accuracy of the measurements are unknown. These data are the unfiltered measured data and include laboratory artefacts (*e.g.*, disequilibrium of cation/anion charge balance, unrealistic pH values) and the effects of pyrite oxidation (*e.g.*, elevated sulphate concentration) (as reported by (Colenco, 2010b) and (Colenco, 2010)). Data between brackets are questionable.

Borehole	ON-Doel				ON-Kallo	
Concentrations	Min. – Max. (mg·L <sup>-1</sup> )				Min. – Max. (mg·L <sup>-1</sup> )	
	with [Number of samples] and [references]				17 samples	
Ca <sup>2+</sup>	132	–	808	[30]	[1] [2]	2.5 – 210
Mg <sup>2+</sup>	83	–	418	[30]	[1] [2]	33.8 – 105
K <sup>+</sup>	67.5	–	919	[30]	[1] [2]	37.5 – 124
Na <sup>+</sup>	4 060	–	7 459	[30]	[1] [2]	2 230 – 3 490
Cl <sup>-</sup>	6 069	–	13 540	[30]	[1] [2]	328 – 4 990
Br <sup>-</sup>	(66)	–	(368)	[25]	[1]	
	23.7	–	33	[ 5]	[2]	1.29 – 17.1
SO <sub>4</sub> <sup>2-</sup>	226	–	7 265	[30]	[1] [2]	707 – 4 430
HCO <sub>3</sub> <sup>-</sup>	24.4	–	275	[25]	[1]	
<b>Other parameters</b>	<b>Min.</b>	<b>Max.</b>				<b>Min.</b> <b>Max.</b>
pH	6.56	–	8.84	[25]	[1]	2.8 – 7.2
Dissolved organic carbon (mg C·L <sup>-1</sup> )	11	–	70.3	[30]	[1] [2]	< 5 (DL) – 16.89

References ON-Doel borehole: [1] (Walraevens and Mahauden, 1999); [2] Annex 14 in (Aertsens *et al.*, 2005b). References ON-Kallo borehole: (Eurofins, 2009), (Eurofins, 2009b), (Eurofins, 2009c). DL: detection limit

The pore water also contains dissolved organic matter. The measured concentrations range from 11 to 70.3 mg C per litre in Doel and from below detection limit to 16.89 mg C per litre in Kallo. In both cases, the concentrations are inversely proportional to the pH (high-carbon content at low pH). A relationship with increasing ionic strength and/or pH of those pore waters, decreasing the stability of colloids, might be suggested. A detailed characterisation of *e.g.*, functional groups has not yet been performed. The concentration of organic matter should also be measured in water collected from piezometers or obtained by leaching (*cf.* (De Craen *et al.*, 2004)).

Synthetic pore waters have been derived for the Doel and the Kallo sites and applied in geomechanical tests, among others. The pore-water composition for the Doel site is

approximated by a ( $\text{Na}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ) ( $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ )-solution, as reported by Aertsens *et al.* ((Aertsens *et al.*, 2005b) Appendix 14). It corresponds fairly well to the average pore-water composition of samples showing no evidence for pyrite oxidation (except for  $\text{Mg}^{2+}$ ). The synthetic pore-water composition proposed for the Kallo site is a ( $\text{Na}^+$ ) ( $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ )-solution (communicated in an email of Norbert Maes on 9 November 2009). It considers the effect of pyrite oxidation for sulphate, but is not corrected for cations and other anions.

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#### **Roadmap – Section 10.2.3.8 – Pore-water composition (YC)**

*For SFC1*, ONDRAF/NIRAS will further investigate the composition and chemistry of the pore water from Ypresian clays. It will in particular focus on solving analytical problems encountered (large discrepancy of results between samples, between laboratories). It will improve documentation of the regional trends and the vertical variability (among others by resampling of piezometers).

*For later SFCs*, ONDRAF/NIRAS will study the evolution through time and space of the pore water (salinisation/freshening/residence time), integrating transport properties and models.

Other research areas concern the characterisation of organic matter (size, functional groups, stability as colloid) and the evaluation of the proposed synthetic pore waters.

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#### **10.2.3.9 Transport of solutes**

As in the case of Boom Clay, the identification of processes affecting solutes migration through the Ypresian clays is of major importance.

Research in the framework of Ypresian clays as potential host rock for radioactive waste disposal has, to date, concentrated on the characterisation of the pore network and to lesser extent on processes of interaction with the solid phase or on the chemical speciation. The (vertical) hydraulic conductivity has been systematically studied for the ON-Doel borehole (Section 10.2.3.7), as well as the diffusion-accessible porosity and (vertical) apparent dispersion coefficient. Migration experiments on ON-Kallo samples are in progress. Both the diffusion-accessible porosity and apparent dispersion coefficient slightly decrease with depth. An analysis of the relative importance of both advection and diffusion for non-retarded species has been carried out by Huysmans and Dassargues for the hydrogeological situation in Doel (Huysmans, 2006) (Huysmans and Dassargues, 2006). It appears from this analysis, that diffusion is the dominant transport mode. The contribution of advection in Ypresian clays at Doel is more significant than for Boom Clay at Mol (mainly due to the higher hydraulic gradient at Doel).

The porosity in the Ypresian clays is high (Section 10.2.3.6) and, as evidenced by migration experiments with tritiated water, nearly entirely interconnected and available for transport by diffusion of solutes.

Concerning the behaviour of species that interact with the solid phase, only results for iodide are available. Due to anion exclusion, the porosity accessible for diffusion of iodide represents about 60% of the total porosity. This relatively high fraction can be related to the relatively high ionic strength of the pore water in Doel (Aertsens *et al.*, 2005b) (see also (Moors, 2005)).

The processes occurring in Boom Clay and similar rocks are expected to occur in Ypresian clays:

- Reduction of the pore space accessible for anions by the presence of clay minerals;
- Filtration of elements sorbed on organic matter, by the fine pore structure;
- Cation-exchange as major sink for metal cations on clay minerals, especially smectite and illite;
- Surface complexation on clay minerals.

Therefore, as in the case of Boom Clay, one can expect that, based on chemical analogies, several groups of species displaying coherent geochemical behaviour to be delineated for the Ypresian clays geochemical conditions. These groups will probably be similar to the ones determined for Boom Clay geochemical conditions, but additional research is required to check this assumption.

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#### **Roadmap – Section 10.2.3.9 – Solutes transport (YC)**

ONDRAF/NIRAS will start studies before SFC1 on the effective diffusion coefficient and the speciation of relevant radionuclides in Ypresian clays. In particular, ONDRAF/NIRAS will focus on the anisotropy and vertical variability of the effective diffusion coefficient. ONDRAF/NIRAS will also investigate whether the speciation of relevant radionuclides in Ypresian clays differs from the one in Boom Clay. It will check whether knowledge from the literature and other argillaceous rocks (Opalinus clay, Callovo-Oxfordian clay, bentonites) is transposable to Ypresian clays. The first results might be available for SFC1.

*For later SFCs*, ONDRAF/NIRAS will perform a few speciation analyses of radionuclides in Ypresian clays conditions if necessary. *For confidence building*, ONDRAF/NIRAS will start migration experiments on a few radionuclides not yet studied to confirm their expected migration behaviour and their sorting in groups of elements with similar migration and retention behaviour.

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### 10.2.3.10 *In-situ* stress state and hydro-mechanical behaviour

#### *In-situ* stress state

The present-day stress state can currently only be approximated. The vertical stress, corresponding to the load of the overlying rock column, can be calculated from the rock density of the overlying rocks and the depth at which a potential disposal system would be constructed. Until now, the research programme of the Ypresian clays has concentrated on the depth range of about –290 metres depth (top of Kortemark Member at Kallo) to about –440 metres depth (base of Mont-Héribu Member at Doel). With an approximate rock density of  $2 \text{ kg}\cdot\text{dm}^{-3}$ , the overlying rocks exert a vertical stress between 5.8 MPa and 8.8 MPa, respectively.

The horizontal stresses have not been measured *in-situ* in the framework of the research programme on Ypresian clays. In a deformable rock, however, the horizontal stresses are proportional to the vertical stress. The ratio horizontal-vertical stresses is often referred to as the earth pressure coefficient  $K$  ( $\sigma_h = K \cdot \sigma_v$ ; with  $\sigma_h$  and  $\sigma_v$  the horizontal and vertical stresses, respectively) or the coefficient of lateral earth pressure at rest  $K_0$  when relating to the effective stresses ( $\sigma_h' = K_0 \cdot \sigma_v'$ , with  $\sigma_i' = \sigma_i - P_f$  with  $P_f$  as fluid pressure). Lima *et al.* estimated the earth pressure coefficient at rest  $K_0$  at about 0.85 ((Lima *et al.*, 2011) or see Appendix A in (Piña, 2011)). They calculated this value via an empirical relationship relating the coefficient of lateral earth pressure at rest to the friction angle (in undrained conditions) and over-consolidation ratio. Other empirical relationships exist in the literature but calculations with these relationships have not yet been carried out (*e.g.*, (Keskin *et al.*, 2004) (Federico *et al.*, 2009)). Based on the current knowledge of  $K_0$ , however, it can reasonably be assumed that the horizontal stresses are of the same order of magnitude as the vertical stress. The burial curves reconstructed for Doel ((Mertens, 2005) Figure 77) or Kruibeke (at about 10 kilometres of Kallo and 15 kilometres of Doel (Mertens, 2005)) suggest that the Ypresian clays in that area underwent a progressive burial with only minor erosion events and that the Ypresian clays are now approximately at their maximum burial depth. This suggests that no horizontal stresses exceeding the vertical load, inherited from the past, have to be expected, so that the largest principal stress is indeed probably the vertical one. This might be different more to the west. Moreover, since there are no evidences (neither at the surface, nor in the subsurface) for aligned structures like faults that are active deformation structures, it is even acceptable to assume a high degree of stress isotropy within the horizontal plane.

At Doel and Kallo, the hydraulic heads have been measured in the aquifers over- and underlying the Ypresian clays. The results indicate that the aquifers below the Ypresian clays are artesian, as already mentioned in (ONDRAF/NIRAS, 2001), and that fluid pressures in the Ypresian clays might thus be slightly suprahydrostatic. Despite these small overpressures, the fluid pressures can be approximated by the pressure exerted by the weight of the overlying water column. In the depth range studied until now in the research programme for the Ypresian clays (Doel and Kallo drilling programmes), fluid pressures of 2.9 MPa to 4.4 MPa can be expected. The vertical and approximated horizontal effective stresses ( $\sigma_i' = \sigma_i - P_f$ ) for this range of conditions corresponds then with 2.9 MPa to 4.4 MPa.

### Basic geotechnical properties

The values for the basic geotechnical properties are derived from the sole laboratory experiments on ON-Doel and ON-Kallo samples as there is no large scale experiment in Ypresian clays. These values are summarised in Table 29 (Piña, 2011). Additional laboratory tests on samples from the ON-Kallo borehole are still in progress, and given the uncertainty of most of these parameters (see hereafter), additional research is suggested. It is noteworthy here to mention the large drill hole diameter anomalies that were experienced during drilling of the ON-Doel and ON-Kallo boreholes (De Ceukelaire *et al.*, 2012), which might point to geomechanical instability, but remains unexplained.

**Table 29** – Values of basic geotechnical properties of the Ypresian clays derived from ON-Doel samples (LGC, 1998) and ON-Kallo samples (Piña, 2011) (raw data) (these values are subject to large uncertainties). It is not clear whether the tests on samples from ON-Doel were performed under drained or undrained conditions.

Property	ON-Doel		ON-Kallo	
	Min. – Max.	n (m)	Min. – Max.	n (m)
Young's modulus (E or E') (drained) (E')	11.2 – 91.27 MPa	10 (21)	146 – 287 MPa	1 (4)
Poisson's ratio ( $\nu$ or $\nu'$ )	0.02 – 0.5	10 (20)	-	-
Angle of friction ( $\phi'$ ) (drained)	7.8° – 20.5°	10 (20)	-	-
Cohesion (c') (drained)	0.21 – 0.60 MPa	10 (20)	-	-
Undrained shear modulus ( $G_u$ )	-	-	~ 90 – 220 MPa	1 (10)
Undrained shear strength ( $c_u$ )	-	-	-	-

n: number of analysed samples; m: number of individual measurements. Min. and Max. respectively refer to the minimum and maximum measured values in individual experiments.

### Stiffness of the Ypresian clays

The elastic response of the Ypresian clays to loading has been studied on uniaxial compression tests on ON-Doel samples (LGC, 1998). It is not clear whether these tests were performed under drained or undrained conditions. In general, the stress-strain paths display a concave section at the beginning of the experiment (artefact), followed by a nearly linear relationship, evolving into a convex segment, representing the onset towards plastic deformation. The Young's moduli values reported in Table 29 have been calculated as the secant slope of the stress-strain path at 33% of peak stress, and thus also integrates the low-angle, artificial part of the stress-strain curve. This might partly explain the relatively low Young's moduli, but low values are in accordance with the unconfined conditions of these uniaxial experiments. The stress-strain paths of triaxial experiments performed on ON-Doel samples (LGC, 1998), at different confining pressures, indeed confirm this increase in stiffness at increasing confining stress, but the low quality of the curves do not allow to effectively derive the Young's moduli and the experiments were, moreover, performed under undrained conditions. Experiments on ON-Kallo samples at more relevant conditions are in progress and suggest values of the Young's moduli of up to a few hundreds of MPa.

Poisson's ratios have also been derived from the uniaxial, unconfined compression experiments by LGC (LGC, 1998). The values vary significantly (Table 29), which might be related to the ambiguous drainage level of the samples.

### **Strength of the Ypresian clays**

As recognised in the uniaxial and triaxial experiments on ON-Doel samples (LGC, 1998), the strictly elastic domain is relatively limited and plastic deformation already starts before reaching the peak strength. Beyond the peak strength, most stress-strain paths reach a steady state, or display a limited strain softening. The values of peak strength and residual strength are clearly function of the confining pressure and series of (undrained) triaxial experiments on the same sample at different confining pressure has allowed defining an angle of internal friction at undrained conditions and a cohesion value. An angle of internal friction and a cohesion value at drained conditions have been recalculated from these experiments on ON-Doel samples (LGC, 1998) and are reported in Table 29. The results show a relatively high variability, but in general a weak resistance against failure in shear mode exists. Experiments on ON-Kallo samples are in progress.

### **Change of volume and pre-consolidation**

Piña performed drained oedometers tests on one ON-Kallo core (Piña, 2011). Tests are still in progress on a few additional samples. Drained oedometer tests aim at characterising the mechanical response of the rock skeleton to isotropic or following a  $K_0$ -path loading and unloading. Since pore water is able to enter and leave the system, the rock response is expressed as a change in void ratio in function of the applied effective load. Piña's experiments show that the void ratio decreases nearly linearly during loading, also at stresses inferior to the burial load ("elastic reloading") (Piña, 2011). At a certain loading stress (the "pre-consolidation pressure"), a slight increase towards higher strain/stress ratios can be observed in some experiments, indicating a transition towards a "virgin compression" of the rock. Although this change in slope is not very apparent, it allowed Lima and co-authors to calculate an over-consolidation ratio (the ratio between the pre-consolidation pressure and the *in-situ* effective vertical stress) of about 1.4 for a sample retrieved at a depth of 370 metres (Lima *et al.*, 2011). It appears from this result that the Ypresian clays can be considered as a normally to very slightly over-consolidated clay conform the idea that the Ypresian clays at Kallo are, at this moment, more or less at their maximum burial depth and no pronounced cementation or diagenesis has occurred since deposition. During unloading (in contact with water), a similar double-slope curve can be observed, characterised by first a weak volume increase in the high-pressure range, followed by a larger volume expansion in the low-pressure range. Mercury intrusion porosimetry on interrupted experiments (*i.e.*, sudden unloading without contact of water) indicates that a population of larger pores closes first when the sample is loaded (even at burial stress level), but that this population of larger pores reappears when unloaded (Piña, 2011). Research is going on to interpret the differentiated volume change during unloading and subsequent reloading.

### Unsaturated hydro-mechanical properties

The adhesion of water, as a wetting fluid, relative to the solid phase of the Ypresian clays, will, as a consequence of the very small pore sizes, result in significant capillary forces, which might, in the case of a partial saturation of the rock, result in matrix suction and increase the cohesion of the rock. This matrix suction is a major contributor to the total suction, which in experiments is measured in function of the water content during a drying and a wetting path; a relationship known as the water retention curve. Water retention curves have been determined for an ON-Kallo sample (Piña, 2011). It suggests that at initial desaturation, the total suction in the Ypresian clays is relatively limited (1.9 MPa according to (Lima *et al.*, 2011)). The authors relate this relatively low value to the low intimately related air-entry value, which is the threshold pressure needed to overcome the capillary forces of a wetting fluid in a pore when replacing it by a gas. Piña (2011) and Lima *et al.* (2011) report a value of about 0.4 MPa for the air entry value and they relate the low value to the bimodal pore-size distribution that they consider as characteristic for the Ypresian clays. According to Lima *et al.* (2011) the low air entry value might explain an early dilation and desaturation of the Ypresian clays when retrieved from depth. A modelling exercise starting from the pore size distribution obtained by mercury intrusion porosimetry data and aiming at predicting the suction in function of the water content confirms the low air entry value. However, one should be aware of circle reasoning, when using data of potentially dilated samples.

### Swelling capacity and creep

There are numerous indications that Ypresian clays exhibit strong swelling behaviour but this behaviour has not yet been fully characterised. The swelling pressure and swelling strain have been measured on ON-Doel samples in an experiment in which Ypresian clays samples were first allowed to swell by absorption of (pure?) water at a very low loading stress (0.015 MPa) before being progressively reloaded in a stepwise manner until a few MPa (LGC, 1998). In these experiments, the swelling strain is defined as the longitudinal strain experienced by the sample during the initial contact with water. The swelling pressure is defined as the loading stress at which the original length of the sample is restored. In more recent studies on Boom Clay as well as on the Ypresian clays, the procedure is, however, to first load samples to a total mean stress equivalent to the burial stress conditions and subsequently put them into contact with water, in order to avoid exuberant expansion by suction during which the rock fabric might be affected (*e.g.*, Lima *et al.*, 2011). There are numerous indications that Ypresian clays exhibit strong swelling capacity. However, this has not been parameterised.

As described earlier, plastic deformation already occurs before reaching the peak strength of the Ypresian clays in triaxial and uniaxial experiments. One should, however, realise, that even before this plastic deformation, the strain accumulated during the (nearly) elastic part of the stress-strain path, might become irreversible if the stress conditions are maintained during longer time periods, owing to very slow deformation processes. This time-dependent deformation is indicated as creep, but has not yet been documented for the Ypresian clays.

### Constitutive models

The knowledge of Ypresian clays is insufficient to construct constitutive models valid for the Ypresian clays in general. Results collected to date are usually sufficiently consistent to construct simplistic Mohr–Coulomb diagrams, applicable on a particular sample. As research is ongoing, and results of different types of tests, performed at different conditions, become available, more sophisticated models including more variables will become possible, in the future.

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#### Roadmap – Section 10.2.3.10 – In-situ stress state and hydro-mechanical behaviour (YC)

For *SFC1*, ONDRAF/NIRAS will gather information on basic geotechnical parameters (to document, among others, their (an)isotropy and their lateral and vertical variabilities) and better characterise the mechanical properties of the Ypresian clays in order to predict the elasto-plastic response of the rock to an underground excavation.

Data on the *in-situ* stress state and hydro-mechanical behaviour of Ypresian clays is still scarce. For *SFC1*, ONDRAF/NIRAS will check under which conditions the quantified parameters are valid. It will also perform an integration exercise and a critical interpretation of available data.

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#### 10.2.3.11 Thermal properties

A characterisation of the thermal properties of the host and surrounding formations is required to determine the evolution of the temperature field in the clay around disposal galleries for heat-emitting waste and, in turn, to assess the perturbations to the system resulting from the temperature changes. Limiting the near field and far field temperature increases to acceptable values is one of the major constraints on the design of a repository for heat-emitting waste (NEA, 2005). Near field temperature criteria result from EBS and host formation performance – or demonstrability of performance – considerations. In the far field, the maximum temperature criterion is usually derived from environmental guidelines (Chapter 8). As thermal criteria are usually set in terms of absolute temperature, the allowable temperature increase also depends on the *in-situ* temperature at the depth of the repository. There is no known report of the temperature distribution in the Ypresian clays.

Laboratory measurements of the thermal conductivity (unknown orientation) on ON-Doel samples suggest relatively low values, ranging from  $0.34 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  to  $1.17 \text{ m}^{-1}\cdot\text{K}^{-1}$  (I.N.I.S.Ma, 1998). Experimental and modelling results carried out on one ON-Kallo sample (preliminary result of on-going research) resulted, however, in a much higher thermal conductivity value,  $1.9 \text{ m}^{-1}\cdot\text{K}^{-1}$ . This large discrepancy does not offer much confidence in the data. Given the anisotropy of the thermal conductivity of clay minerals and the development of a bedding fabric in sedimentary clays, bulk anisotropy can, moreover, be expected.

The specific heat for dry Ypresian clays, measured on ON-Doel samples, ranges between 927 and 1017 J·kg<sup>-1</sup>·K<sup>-1</sup> (I.N.I.S.Ma, 1998). The specific heat for wet Ypresian clays and the volumetric heat capacity for wet and dry Ypresian clays have been derived from it. As can be expected from the decreasing porosity with depth, these derived parameters also vary with depth.

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#### **Roadmap – Section 10.2.3.11 – Thermal properties (YC)**

*For SFC1*, ONDRAF/NIRAS will evaluate the thermal properties of Ypresian clays and surrounding layers as they may affect the design and layout of a repository.

*For later SFCs*, ONDRAF/NIRAS could perform calorimetric studies, for measuring volumetric heat capacities and their variability according to depth, collect data about the present-day temperature distribution, and increase its knowledge of the drained and undrained thermal expansion coefficients of the Ypresian clays and their sensitivity to temperature.

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#### **10.2.3.12 Microbes**

It can at this stage of research not really be excluded or confirmed that microbes (or their endospores) (*e.g.*, sulphate-reducing microbes, nitrate-reducing microbes or methanogenic microbes) have been preserved in the Ypresian clays since sedimentation.

The presence of framboidal pyrite, likely formed soon after deposition, is a sign of early microbial activity. But the sulphate/chloride ratio of unoxidised samples is only slightly inferior to the one of seawater, suggesting that the influence of sulphate-reducing microbes is limited.

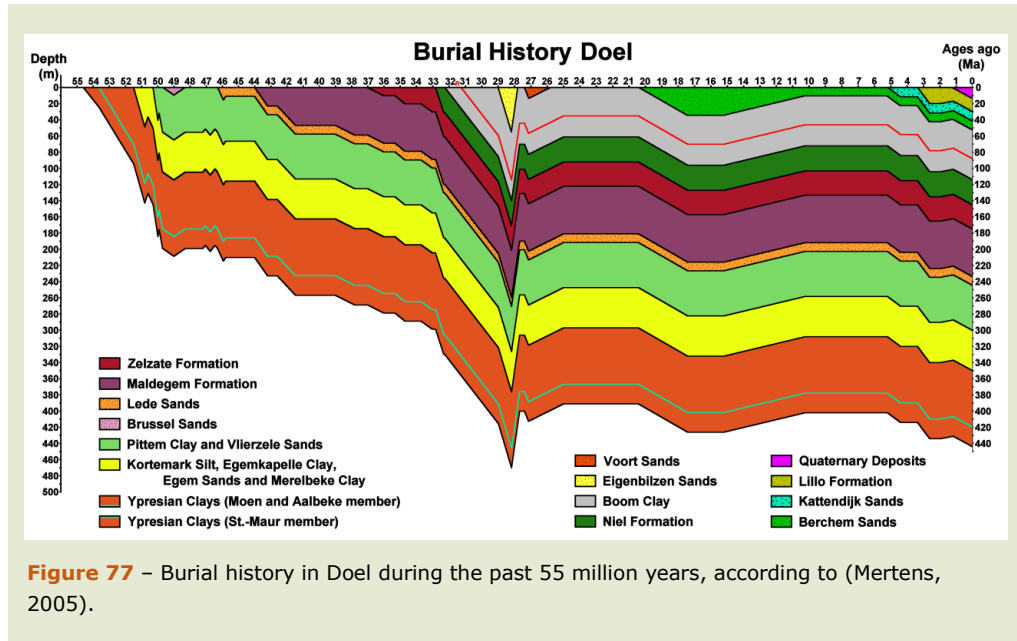
The microbial activity in undisturbed Ypresian clays is expected to be low as the small pore throats in the Ypresian clays, relative to the size of the microbes, limit the ability of microbes to colonise the sediment matrix so that the activity of sulphate reduction (and analogous processes) by microbes, remains low (Frederickson *et al.*, 1997) (Bottrell *et al.*, 2000). This argument should, however, be better documented in the case of the Ypresian clays.

ONDRAF/NIRAS pursues its research on microbial activity in a Boom Clay environment. It will first wait for the results of ongoing studies and then analyse their transferability to Ypresian clays before undertaking any action in this field in an Ypresian clays environment.

## 10.2.4 The environment can be characterised

### 10.2.4.1 Geological setting

The geological setting must be considered as a dynamic system with different actors playing at different time periods (*e.g.*, the Palaeozoic London-Brabant Massif, the Campine Basin, the North Sea Basin). During the Mesozoic, the North Sea Basin was initiated as a rift system. By the end of the Cretaceous, rifting ceased as a response to the opening of the North Atlantic Ocean that resulted in subsidence of the North Sea Basin and concomitant Cenozoic sedimentation. During the latest Eocene – earliest Oligocene, the Pyrenean and Alpine collisions renewed the subsidence in the basin, particularly in NE-Belgium (especially the Roer Valley Graben). Indeed, the Roer Valley Graben and its northwestern extension form part of the European Cenozoic Rift System (ECRIS) (Section 3.4.1), which is still to date the main actor in the tectonic stress field in Western Europe, possibly in combination with ridge pushes of the Atlantic Ocean (*e.g.*, (Ziegler and Dèzes, 2007)). The Southern Bight of the North Sea Basin is generally an undep sedimentary basin, sensitive to tectonic and eustatic sea-level evolutions. Vandenberghe and co-authors have fairly well identified the tectonic and eustatic components for the Late Cretaceous and Cenozoic sediments (Vandenberghe *et al.*, 2004). Mertens has reconstructed a burial/erosion curve for the Doel area and nearby Kruikeke area (Figure 77) (Mertens, 2005). This curve shows that the Ypresian clays in Doel underwent a progressive burial with only minor erosion events and that these clays are at this moment approximately at their maximum burial depth. As can be derived from the N-S section in Figure 74, an important component of the progressive subsidence in Doel can be attributed to a northward tilting. Palaeogeographical reconstructions are also available in international literature for the Cenozoic and for older periods, illustrating the alternation of regressions and transgressions of the coastline. The London-Brabant axis often acted as a barrier between the North Sea Basin to the north and the Paris Basin to the south. The connection between the two basins at the location of the Strait of Dover was created and lost regularly through the geological history (van Vliet-Lanoë *et al.*, 2002). During the two most recent glaciations, deep incision by catastrophic flooding occurred throughout the Strait of Dover which at that moment dammed the pro-glacial lake situated in the Southern Bight of the North Sea Basin (*e.g.*, (Smith, 1985) (Gupta *et al.*, 2007) (Gibbard, 2007)). The alternating warm-cold conditions have severely influence the geomorphology of northwest of Belgium during the Quaternary and even Holocene, with as main feature the Flemish Valley (*e.g.*, (Mathys, 2009)). The northwestern part of Belgium is free of active igneous activity although some occurrences were identified in the Eifel and Ardenne areas.



#### Roadmap – Section 10.2.4.1 – Geological setting (YC)

ONDRAF/NIRAS will follow up current studies on the geological setting and integrate them in the SFCs.

Later SFCs will include more information about the geological history and geological setting (actual stress state, displacement rates, tilting etc.).

#### 10.2.4.2 Hydrogeological setting

##### Hydrogeological system

The hydrogeological configuration in northern Belgium consists of an alternation of slightly north-dipping sedimentary layers of higher and lower hydraulic conductivities, deposited on top of a generally low permeable, possible fissured solid rock, the Brabant massif. On behalf of the Ministry of the Flemish Government, these hydrogeologically distinct units have been regrouped and coded into base units, sub-units and main units, which grossly correspond to the existing lithostratigraphic subdivision, called the HCOV-coding<sup>92</sup> (e.g., (VMM, 2008) (Meyus *et al.*, 2000) (Meyus *et al.*, 2004)). The main units form an alternation of aquifers and aquitards and are indicated in light and darker grey in Table 30. At a regional scale, this subdivision is even further condensed into 6 major groundwater systems, distributed over northern Belgium (Table 30). It is clear from this table that, especially in the western part, the Ypresian aquitard system, corresponding to the Ypresian clays, is supposed to act as an important hydrogeological barrier,

92 HCOV-coding: Hydrogeologische Codering van de Ondergrond van Vlaanderen.



separating the groundwater system below (“Basement system”) and above it (“Central Flemish system”, topped or replaced by the “Coast and Polder system” in the estuarine and coastal areas). In the eastern part of northern Belgium, a similar role can be attributed to the Boom Clay, while the Ypresian clays wedge out and become coarser-grained, so that its character as aquitard disappears in that direction. The hydrogeological framework in Doel and Kallo is somehow transitional, since the Ypresian clays can still be considered as an important aquitard, while the overlying groundwater system is also further compartmentalised, among others by Boom Clay, separating different aquifer systems. All these strata dip to the north. The water-conducting layers are mostly recharged in their outcrop area in the south (e.g., (De Smet and Olivier, 1996)). The direction and sense of groundwater flow at natural conditions and present-day conditions with groundwater extraction is fairly well known (e.g., (De Smet and Olivier, 1996)).

### Hydraulic gradient

Since the infiltration area of the different aquifers are situated in the outcrop area, usually at a higher topographic elevation, water pressure in the aquifers are in principle artesian more towards the north, where they are overlain by aquitards. Maps with modelled and measured hydraulic heads for natural and real conditions (respectively excluding and including groundwater extraction) are available for the different aquifer systems (e.g., (De Smet and Olivier, 1996) (VMM, 2008) (Vandenbohede *et al.*, 2010) (Labat, 2011)). It is clear from these maps that the present-day hydraulic heads are drastically influenced by groundwater extraction. Groundwater flow, which is upwards in natural conditions in the north-northwest of Belgium, is locally downwards due to over-exploitation (De Smet and Olivier, 1996) (ONDRAF/NIRAS, 2005) (Vandenbohede *et al.*, 2010). The hydraulic gradients calculated from modelled hydraulic heads in a broad zone around Doel and Kallo illustrate this change and local inversion of the hydraulic gradient, although the modelled gradients do not correspond to the measured ones (Vandenbohede *et al.*, 2010). The results of the follow-up of water levels in the piezometers in ON-Doel and ON-Kallo confirm the lowering in water level in the aquifers overlying the Ypresian clays, but also demonstrate that the water pressures in the underlying aquifers are still artesian and result in a significant, upward hydraulic gradient (Labat, 2011). Tidal fluctuations have been observed in all aquifers in Doel and Kallo (Ecorem, 2010).

### Hydrogeological modelling

The above-mentioned hydrogeological coding has been developed in the framework of the development of a regional-scale hydrogeological model, the “Vlaams Grondwater Model” or VGM (e.g., (Meyus *et al.*, 2004)). Precursory to this overall model, data have been collected in nine, partly overlapping sub-areas with clear hydrogeological boundaries and combined into an overall, seamless “atlas”. This “atlas” together with a groundwater supply model (Meyus *et al.*, 2004b) form the base for, on the one hand, 6 regional models corresponding to the identified groundwater systems (Table 30) and, on the other hand, local, transient, axisymmetric models evaluating the effect of pumping.

The approach followed by Vandenbohede *et al.* (2010) for the development of a hydrogeological model in a large area around Doel and Kallo is comparable to the one used to develop the VGM model. In the first instance, the regional basement model has been applied to establish the boundary conditions in the deep aquifers, and subsequently a local model has been developed using the HCOV-coding in order to simulate the natural hydraulic heads in different aquifers. This simulation was run for two sets of (discussable) hydraulic conductivities for Boom Clay and Ypresian clays. Thirdly, an axisymmetric model has been developed, investigating the influence of pumping and this, again, for both sets of hydraulic conductivities. Finally, particle tracking calculations (advective transport) in Ypresian clays and surrounding rocks have been performed for long times. This first attempt does not allow predicting *e.g.*, the high hydraulic gradient observed in the Doel and Kallo.

Smaller-scale modelling, including diffusive transport of non-retarded radionuclides, has been carried out by Huysmans and Dassargues, taking into account the high upwards hydraulic gradient (Huysmans, 2006) (Huysmans and Dassargues, 2006). In these conditions, the contribution of advection to the radionuclide fluxes has to be taken into account, in addition to diffusion.

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#### **Roadmap – Section 10.2.4.2 – Hydrogeological setting (YC)**

*For SFC1*, ONDRAF/NIRAS will develop a simplified hydrogeological model of the environment of Ypresian clays to estimate a dilution factor.

*For later SFCs*, ONDRAF/NIRAS will integrate available data on hydrogeological setting, from all sources. It will also further refine the hydrogeological models, as these do not fit measured parameters such as hydraulic conductivities. This will require better documentation of the hydrogeological complexity of the area around Doel and Kallo (proximity of Scheldt River, transition between different groundwater systems). Furthermore, diffusive-advective transport modelling should be matched up with the observed marine and estuarine influx of marine salts, in order to better understand the freshening and salinisation history.

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**Table 30** – Hydrogeological data and subdivision in the area Doel–Kallo, correlated to the stratigraphic subdivision (in Doel) and the broader hydrogeological context. Hydraulic conductivities are approximate values and their evaluation is in progress.

Doel–Kallo					Regional scale							
Chrono-stratigraphy	Formation	Member	Thickness (m) *	K (m·s <sup>-1</sup> ) (meas.)	K (m·s <sup>-1</sup> ) (used for modelling)	Interpretation	Groundwater systems West → East					
QUATERNARY			13		$10^{-8}$ - $10^{-4}$	Quaternary and Campine aquifer system (0100) (0200)	Coast and Polder system	Central Campine system	Meuse system			
PLIOCENE	Lillo (0233) (0241) (0251) Kattendijk (0241) (0251)		40	$5 \cdot 10^{-5}$	$10^{-7}$ - $10^{-4}$							
MIOCENE	Berchem (0254)											
OLIGOCENE	Boom	Putte (0302) Terhagen (0303) Belsele-Waas (0304)	98		$10^{-11}$ - $5 \cdot 10^{-8}$	Boom aquitard (0300)	Hiatus	Boom aquitard (0300)				
	Zelzate	Ruisbroek (0435) Watervliet (0442) Bassevelde (0453)			$5 \cdot 10^{-6}$	$10^{-6}$ - $10^{-5}$				Oligocene aquifer system (0400)		
EOCENE		Maldegem	47 45		$5 \cdot 10^{-9}$ - $5 \cdot 10^{-7}$	Bartoon aquitard system (0500)	Central Flemish system	Brussels Landen Cretaceous system				
		Lede (0612) Brussels (0620)	57 54	$10^{-6}$ $10^{-6}$		Ledo Paniselian Brusselian aquifer system (0600)						
		Aalter										
		Gentbrugge	24 14		$10^{-5}$ - $10^{-4}$	Paniselian aquitard system (0700)						
		Tielt	22 26	$10^{-7}$ $5 \cdot 10^{-6}$		Ypresian aquifer (0800)						
		Kortemark	20	$10^{-7}$	$5 \cdot 10^{-12}$ - $10^{-7}$							
		Kortrijk (0920)	67 23	$5 \cdot 10^{-9}$	$10^{-9}$ - $10^{-6}$ $10^{-10}$ - $5 \cdot 10^{-8}$	Ypresian aquitard system (0900)				Ypresian aquitard system (0900)		
		Mont-Héribu (0925)	10 11	$5 \cdot 10^{-7}$	$10^{-7}$ - $10^{-5}$							
PALAEOCENE	Tienen	Knokke (1011)								Basement system		
	Hannut	Halen (1021)	62.5		$5 \cdot 10^{-9}$ - $10^{-4}$	Paleocene aquifer system (1000)						
		Heers (1020)										
CRETACEOUS		Maastricht (1112) Gulpen (1113) Vaals (1120)	144.5 18.5	$10^{-7}$	$10^{-7}$ - $10^{-8}$	Cretaceous (1100)						
Palaeozoic (1300)					$10^{-6}$ - $10^{-5}$	Palaeozoic (1300)						

\* Thicknesses derived from hydrogeological data. They often differ from lithostratigraphic data.

Data in blue and green are rounded values taken from Possemiers and Meyus (2010) and originate respectively from pumping tests in Doel and Kallo. Data in red are the approximate ranges in vertical and horizontal hydraulic conductivities used for modelling by (Vandenbohede *et al.*, 2010). The codes (black numbers) and interpretation as aquifer, aquitard and groundwater system correspond to the HCOV-coding (VMM, 2008).

## 10.3 The evolution of the disposal system and of its environment can be bounded

### 10.3.1 Siting and design favour stability

Poorly indurated clay displays favourable properties to ensure the functions expected of a natural barrier, *i.e.*, long-term isolation, confinement and retention of radionuclides and chemical contaminants present in a geological repository. Section 4.1 details these properties for a geological disposal in Boom Clay. This section focuses on the transposability of them from Boom Clay to Ypresian clays.

#### 10.3.1.1 Limited number of drivers

In order to limit the number of perturbations to consider in the evolution of the disposal system, the design and siting processes will integrate all available knowledge. The knowledge about external perturbations can be transposed from Boom Clay to Ypresian clays:

- The main driver in the geodynamic evolution (tectonic activities) that could affect a disposal system in Ypresian clays and their consequences (such as faults) are identified. There are large zones in the northwest of Belgium where the impact of these drivers should be limited.
- Climate changes are not avoidable. However, their impacts decrease with depth. The siting process will consider this.
- Zones within the northwest of Belgium with significant resources and uses are identified and should be avoided. Groundwater is present in the northwest of Belgium. Possible conflict of uses will be investigated during the siting process.

The repository is designed in order to limit internal perturbations (perturbations due to the repository and the waste). Its main features are supposed to be transposable to a disposal in Ypresian clays (Section 10.4).

#### 10.3.1.2 Robust features

In addition to its favourable properties such as low permeability, poorly indurated clay is characterised by robust features that limit the impact of perturbations. This is demonstrated for Boom Clay in Section 4.1.2.1 (self-sealing capacity) and Section 4.1.2.2 (chemical buffering capacity), but not for Ypresian clays yet.

#### Self-sealing

Although self-sealing has never been studied for the Ypresian clays in particular, there is indirect evidence that these clays present a good self-sealing capacity:

- They have a relatively low strength, so that rock creep, at the stress state of a disposal system, is expected to be a relatively fast process.
- They generally have a high smectite content, promoting swelling, once saturated.

- Their high swelling potential is also expressed by the pronounced swelling stress and swelling strain observed in the tests of LGC (LGC, 1998).

One should, however, be aware that, although the fractures will probably close ("sealing"), they will probably not gain cohesion, and thus remain planes of weakness (no "healing").

### **Chemical buffering capacity**

Poorly indurated clay presents a significant buffer capacity with regard to chemical perturbations. This must still be confirmed for Ypresian clays.

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### **Roadmap – Section 10.3.1.2 – Robust features (YC)**

*For SFC1*, ONDRAF/NIRAS will continue analysing the transposability of knowledge from Boom Clay to Ypresian clays.

*For later SFCs*, ONDRAF/NIRAS will perform experiments in order to confirm the significant self-sealing and chemical buffering capacities of the Ypresian clays.

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## **10.3.2 For those drivers that cannot be avoided, the changes in properties and conditions can be bounded**

### **10.3.2.1 The evolution of the disposal system due to changes in its environment can be bounded**

#### **Natural external events and processes**

##### **Geodynamic evolution**

In the earth's interior, the conditions might be or become as such that they drive processes which can roughly be categorised as tectonic processes or igneous processes. These endogenic geodynamic processes might change the properties and conditions in the crust and thus in the disposal system and its environment and further give rise to a sequence of processes in which driving forces from outside the earth's interior (mainly hydrosphere and atmosphere) might play a role as well (exogenic geodynamic processes).

Tectonic processes basically result from the response of the rock with respect to the stress state subjected to that rock. The present-day stress state has not been measured in Doel or Kalo but is probably governed by the NW–SE compression and NE–SW extension, characteristic for Western Europe, which can be related to the European Cenozoic Rift System (ECRIS) (*e.g.*, (Tesauro *et al.*, 2006) (Ziegler and Dèzes, 2007)). Since such driving forces do not evolve rapidly, it can be supposed that the stress state,

at least the portion originating from the regional stress field, will not drastically change with time.

This stress state has given rise to the development of the European Cenozoic Rift System with the Roer Valley Graben as segment of interest in Belgium. This rift system is an active system representing a NE–SW elongation of the crust and lithosphere, accommodated by thinning of both, and by normal faulting in the upper, brittle part of the crust. The deformation in Belgium has mostly concentrated on the Roer Valley Graben, presumably because the crust and lithosphere were already thinned and weakened due to rifting during the Mesozoic and possibly the presence of older structures (Schenck-Wenderoth and Lamarche, 2005) (Cloetingh *et al.*, 2010). In northern Belgium, no important faults have been observed affecting the Cenozoic, so that it can reasonably be supposed that, through time, the stress state could always be sustained by the crust. Crustal processes were limited to tilting of the area and vertical movements, dominantly subsidence. If, as supposed above, the stress state is maintained during the next million years, future deformation will, given the inherited weaknesses, probably remain concentrated in the Roer Valley Graben, although an isolated fault can never be excluded. The rates of uplift, subsidence and tilting can reasonably be approximated by those during the Cenozoic. The effect of these processes on the properties and conditions in the disposal system must be further characterised. As long as the formation processes of structures like intraformational faults and joints are not understood, while these features might be present in the northwest of Belgium and, if so, developed during the Cenozoic, possibly as a response to the geodynamic evolution, their reoccurrence cannot be excluded for the future. Next to the geological record, informing about the potential perturbations that might occur in the future, also the effect on the engineered barrier system should be studied. For certain crustal processes with important far field effects (*e.g.*, earthquakes in case of fault activity), the geodynamic evolution outside northwest of Belgium should, moreover, be considered.

Concerning igneous processes, the actual working hypothesis is that igneous activity in proximity of the disposal system cannot be excluded, although it is not expected, since important elements promoting igneous activity, like a thinned crust and lithosphere, an increased heat supply and an active extension regime can be recognised along the segments on the European Cenozoic Rift System (see maps in *e.g.*, (Tesauro *et al.*, 2007) (Tesauro *et al.*, 2009) (Cloetingh *et al.*, 2010)). These criteria are certainly fulfilled in the Eifel area, where the probability of intrusion during the next million years is realistic, but also, to some extent, in the Roer Valley Graben. Following the same reasoning, the probability should decrease towards the Brabant Massif, characterised by a thicker and colder crust and lithosphere (see maps in *e.g.*, (Tesauro *et al.*, 2007) (Tesauro *et al.*, 2009) (Cloetingh *et al.*, 2010)).

When considering the effects of igneous activity on the properties and conditions in the disposal system, a distinction should probably be made between far field effects (*e.g.*, uplift and tilting related to doming) for which the geodynamic evolution outside northwest of Belgium has also to be considered and the near field effects (*e.g.*, disruption by intrusion), related to igneous activity in direct proximity of the disposal system. In the former case, the uplift of the Ardennes, related to the Eifel volcanism, might be considered as analogue study (Garcia-Castellanos *et al.*, 2000). In the latter case, the presence of deeply rooted, optimally oriented faults in the solid basement might be a preferential path for intrusion, but these faults have not been identified yet in the northwest of Belgium. In the overlying Meso- and Cenozoic cover, explosive,

phreato-magmatism, with the typical development of diatremes and maars, might be more expectable given the high water content of the sediments.

### Climate changes

Most results achieved in the frame of the research programme on Boom Clay transposable to disposal in Ypresian clays. However, the exact conditions exerted on the disposal system will be site specific, since land surface is also an important component of the climate system and require additional research efforts (*e.g.*, high sensitivity to sea level changes due to the low topographic elevation). These specific conditions might give rise to particular processes, possibly affecting the properties and conditions in the disposal system. Apart from these near-field effects for which one focuses on the local climatologic conditions, it is clear that one also have to take into account far field effects arising from more severe climatologic scenarios in neighbouring areas. Finally, when using the geological record as proxy for perturbations in the future, a problem might arise, since not all perturbations in the host rock (*e.g.*, potential presence of intraformational faults; salinisation and freshening trends) are completely understood to date, although they might have an unknown link with the past climatologic evolution.

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### Roadmap – part of Section 10.3.2.1 – Bounded evolution, natural external events and processes (YC)

ONDRAF/NIRAS will pursue its technological watch on the long-term stability of Ypresian clays.

*For later SFCs*, ONDRAF/NIRAS will confirm the limited influence of natural events and processes on the stability of Ypresian clays.

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### Human actions

Human actions are by essence hardly predictable. However, reasonably foreseeable human actions in the northwest of Belgium include the exploration and exploitation of the underground for economic reasons.

The direct exploitation of mineral resources will not affect a disposal system in Ypresian clays, as these resources are available in large quantities at the surface or shallow sub-surface. The exploration and exploitation of other resources (such as water, geothermy and gas storage) require drilling of boreholes. Therefore, drilling is one of the main actions that can be expected. Faninbel mapped all the boreholes in northern Belgium (Faninbel, 2011). It appears from their maps that few boreholes reached or pierced the Kortrijk Formation at depth. These few boreholes (including the ON-Doel and ON-Kallo boreholes), are reconnaissance or monitoring wells. None of them is water well. The absence of deep-water wells and other deep targets can probably be related to the salinity of some of the aquifers and the absence of rocks or lack of conditions that are (presently) of particular economic interest.

The knowledge in this field acquired from the Boom Clay programme (Section 4.2.1.2) is transposable to Ypresian clays.

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### **Roadmap – part of Section 10.3.2.1 – Bounded evolution, human actions (YC)**

ONDRAF/NIRAS will follow up potential uses of the northwest of Belgium underground as this might play a role during the siting process. It will follow up the evolution of human interest in deep aquifers, development of pumping technology and pumping activity (number and depth of boreholes, pumping rate, etc.). It will also check future interest in coal and coal bed methane extraction, in geothermy, and in gas storage in deep geological reservoirs.

*During site selection*, ONDRAF/NIRAS will assess the consequences of foreseeable human actions in the context of conflict of use.

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### **10.3.2.2 The perturbations of Ypresian clays due to the excavation, construction, operation and post-closure evolution of the repository can be bounded**

The perturbations resulting from excavation and repository construction and operation in Boom Clay and their consequences are detailed in Section 4.2.2. This section focuses on the transposability of knowledge to the Ypresian clays.

#### **Excavation and repository construction and operation**

During the past decade, industrial tunnelling with an open excavation front and an immediate emplacement of the tunnel lining blocks once the tunnelling shield has moved forward, has given rise to satisfactory results for the Boom Clay at Mol (Section 5.2.2), so that its application in case of a potential radioactive waste disposal is very likely. This justifies why, at this stage of the research on Ypresian clays, the changes and perturbations related to excavation are evaluated assuming the application of this particular technique, with or without slight modifications.

#### **Stress evolution**

The excavation induces stress redistribution in the host formation as the clay converges towards the void left by the removed material. For the Ypresian clays, the difference in stress and fluid-pressure conditions between the natural conditions and the conditions in case of an excavation at depth would be significant. The elasto-plastic properties of the Ypresian clays are, to date, insufficiently known to characterise with precision the evolution through space and time of the fluid pressure and stress state. Relying on the basic geotechnical characteristics of both clays, a high degree of similarity with Boom Clay is expected.



### Extent of the plastic and elastic zones - fractures

Depending on the stress-strain response of the material, the reached stress and fluid-pressure levels at a certain point can, or cannot, be sustained by the rock, which, in the former case might give rise to solely elastic deformation, or, in the latter case, will result in – irreversible – ductile deformation or even brittle fracturing. The perturbations caused by the stress redistribution are limited to zones surrounding the excavation.

Both Boom Clay and Ypresian clays can exhibit ductile or fragile behaviour, depending on the conditions. Based on the current limited knowledge, the threshold for irreversible deformation of Ypresian clays is lower than of Boom Clay. A relatively weak behaviour of the Ypresian clays could require a higher over-excavation during tunnelling (than in Boom Clay), leading to larger deformations. This does not mean however that the fracture zone would be bigger, as Ypresian Clays might be more ductile.

The dimensions of the different zones of deformation cannot be transposed “as such” from Boom Clay to Ypresian clays. Additional geomechanical characterisation of Ypresian clays (among others their anisotropy) is needed.

### Pore-water pressure

Excavation leads to changes in the pore-water pressure due to the volumetric deformation of the clay. Section 4.2.2.1 details the results of the research in this field in Boom Clay. Although the original hydraulic properties of the Ypresian clays and the distribution of the perturbations around the gallery might be different for both host rocks, a high degree of similarity can be expected. These evolutions are temporary.

### Hydraulic conductivity

Outside the fractured zone, the changes in hydraulic conductivity can be expected to remain limited. Inside the fractured zone, the changes in porosity and permeability are more important, but will recover with time, due to the self-sealing capacity of clayey rock. Closure of the fractures will start as soon as the gallery lining is placed and all voids at the interface are closed by rock creep.

### Oxidation

During the construction and operation of a geological repository, the presence of air in the open galleries inevitably leads to oxidation of the host formation. The size of the area affected by the oxidation is, in the case of Boom Clay, closely related to the width of the area affected by fracturing and (after fracture sealing) by the rate of diffusion of oxygen into the host rock (Section 4.2.2.1). It is reasonable to suppose that the dimensions of the affected zone will also be limited in the case of the Ypresian clays. Closure of fractures (self-sealing) and closure of the galleries will set an end at the imposition of oxidising conditions.

### Evolution of the vapour pressure of the pore water as a consequence of ventilation

During the operational phase, the galleries will be ventilated. Since air is undersaturated with respect to water, the (oxidised) pore-water film on the gallery lining might evaporate and might leave its salts. This evaporation might cause desaturation of the clay having geomechanical consequences, but given the hydraulic gradient, fresh pore water can also be driven towards the gallery and the process of out-salting might continue. First of all, those salts with a low solubility will precipitate first, like gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) and jarosite ( $\text{KFe}_3(\text{OH})_6(\text{SO}_4)_2$ ), followed by other salts if evaporation is complete (halogenides, carbonates, sulphates, phosphates, (hydr-)oxides). The deposition of salts form a potential source of highly concentrated ions (solubility limit) at the lining-backfill interface, and might create a steep chemical gradient towards the host rock and/or towards the backfill and buffer as the salts dissolve again once the disposal system resaturates (at gallery closure). Such an ion-rich plume might affect the chemo-hydromechanical properties of the host rock and might be aggressive with respect to the cementitious and metal components in the engineered barrier system. The accumulation of salts deserves special attention in the case of the Ypresian clays, given the relatively high ionic strength of its pore water.

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### Roadmap – part of Section 10.3.2.2 – Bounded perturbations resulting from excavation and repository construction and operation (YC)

For *SFC1*, ONDRAF/NIRAS will perform a first evaluation of the extent of the damaged zones around disposal galleries in Ypresian clays.

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### Thermal output of the category C waste

The emplacement of heat-emitting waste in a repository will induce thermal perturbations in the host formation during the so-called thermal phase.

Section 4.2.2.2 details the thermal properties of Boom Clay and the impact of the thermal output of category C waste on Boom Clay properties and processes. RD&D results show that most effects of thermal loading and unloading are temporary.

The duration, intensity and spatial distribution of the thermal transient have not been calculated yet in the case of the Ypresian clays. There is a need of additional research to determine, among others, their volumetric heat capacity and thermal conductivity (Section 10.2.3.11).

#### 1. Chemical perturbations: effect on clay fraction and organic matter

As developed in Section 4.2.2.2, the thermal load will not affect Boom Clay's clay fraction. The heating of Boom Clay leads however to a degradation of its organic matter. The same effects are expected for the Ypresian clays. Further research is, however, needed at the level of organic matter characterisation and the effect of heating on dissolved species and the stability of carbonate minerals.

## 2. Physical perturbations

Due to heating both the pore fluid and the host rock particles will tend to expand, the former expanding more than the latter, thus generating an excess in pore fluid volume. This pore water might be obstructed to drain off and will in that case generate internal fluid pressures (completely undrained conditions). If, however, the pore-network is more permeable, the pore water might be drained off efficiently and pore pressures remains more or less constant (completely drained conditions).

In the former case (completely undrained conditions), during heating, volume expansion (essentially vertical) of host rock and pore fluid should be considered and possibly hydraulic fracturing (or fracture reactivation), if the fluid pressure exceeds the maximum fluid pressure sustainable by the rock. During cooling, the undrained rock will decrease its volume again.

In the latter case (completely drained conditions), the volume expansion of only the solid particles has to be considered. For an over-consolidated rock this expansion (elastic deformation) will persist until a certain temperature, at which it will lose its strength and will keep its volume by accommodating the volume expansion of the grains by reducing the pore volume or even shrink by collapsing the pore structure (inelastic deformation). For normally consolidated rocks the two latter phenomena (pore-volume consumption and pore-collapse), indicated as thermal consolidation, will start very soon. In a drained rock, cooling of the host rock will be accommodated by shrinkage (and water-uptake) which is directly proportional to the shrinkage of the solid particles.

Whether the Ypresian clays will behave as drained or undrained depends on the competition between the progression rate of the thermal front (thermal diffusivity) and the rate of fluid expulsion (hydraulic diffusivity). There, however, still exists uncertainty about basic parameters like the thermal conductivity, and the unexpected observation that the hydraulic conductivity increases during heating (exceeding the increase due to the decrease in water viscosity) should be explained (Lima, 2011).

For the physical processes described here, mainly the rate and difference of temperature change are of importance, rather than the duration. Potential perturbations are therefore mainly expected to occur in a limited zone around the gallery, but the present knowledge of Ypresian clays does, however, not allow specifying the real dimensions.

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### **Roadmap – part of Section 10.3.2.2 – Thermal output (YC)**

*For SFC1*, ONDRAF/NIRAS does not plan specific tests to study the perturbations of Ypresian clays due to the excavation, construction, operation and post-closure evolution of the repository. ONDRAF/NIRAS will focus on the determination of basic parameters of Ypresian clays, including the thermal conductivity.

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### Alkaline plume

When considering diffusion as main transport mechanism, the evolution of the alkaline plume might be partly different in the Ypresian clays in Doel when compared to Boom Clay in Mol, given the different pore-water chemistry resulting in different chemical gradients. For  $\text{OH}^-$  and  $\text{K}^+$  comparable gradients (towards host rock) can be assumed. For  $\text{Na}^+$  the gradient will be opposite and for  $\text{Ca}^{2+}$  it will be opposite as long as  $[\text{OH}^-]$  is determined by dissolution of KOH and NaOH (young cement water), but it will invert as soon as  $[\text{OH}^-]$  is determined by dissolution of  $\text{Ca}(\text{OH})_2$ . Additional research is recommended to better characterise the evolution of the cement water. The evolution of the chemical conditions might, moreover, be influenced by the different evolution of the cementitious materials (deterioration versus clogging) caused by different pore-water chemistry and the potential presence generated by salt precipitation during ventilation of the galleries. These elements also influence on the timing and duration of the alkaline plume.

#### 1. Extent of alkaline plume

The dimensions of the affected zone are relatively limited, because of the consumption of the migrating ions by cation exchange and mineral transformation, but also due to the slow transport and radial geometry of the disposal system. Although the exact mineralogy and other elements will probably play a role, it is reasonable to suppose similar dimensions as for Boom Clay. A component of advective transport or an anisotropy in apparent diffusion coefficient might, however, influence the shape of the affected zone.

#### 2. Properties of the disturbed zone

Given the different pore-water chemistry, the higher smectite content (sensitivity to cation exchange) and the unknown composition of the organic matter, additional research on the Ypresian clays might be necessary in order to better characterise the changes in properties in the zone affected by the alkaline plume.

For *SFC1*, ONDRAF/NIRAS does not plan specific tests to study the perturbations of Ypresian clays due to the alkaline plume.

### Disposal of Eurobitum

The Eurobitum wastes are essentially composed of a mixture of salts (mostly  $\text{NaNO}_3$ ) and hard, blown bitumen. Upon hydration with groundwater, this waste swells and can exert significant pressures on its surroundings while it will simultaneously release large amounts of dissolved  $\text{NaNO}_3$ . Section 4.2.2.4 presents how these wastes interact with Boom Clay.

Despite the differences in (modified) pore-water chemistry of both host rocks at their reference sites for RD&D, they can probably be considered as sufficiently alike compared to the  $\text{NaNO}_3$ -brines inside the bitumen, so that the swelling pressures of the bitumen in function of water uptake can be transposed from Boom Clay to the Ypresian clays. The mechanical response of the host rock, however, depends on the *in-situ* stress conditions

and geomechanical properties of the host rock and is thus specific for site and host rock. Ultimately, the evaluation of the perturbations might give rise to a modification of the design (reduction of the number of drums per section) if the mechanical perturbations turn out to be important and insurmountable for the current design.

Concerning the chemical perturbations related to the release of  $\text{NaNO}_3$ , mainly the ingress of nitrate is a matter of concern, which in contrast to sodium, is a very uncommon species for the disposal system, since being thermodynamically unstable at the prevailing  $E_h$ -pH conditions. The nitrate ions might reduce and react to other nitrogen-species ( $\text{NO}_2^-$ ,  $\text{NO}$ ,  $\text{N}_2\text{O}$ ,  $\text{N}_2$ ,  $\text{NH}_3/\text{NH}_4^+$ ) while oxidising other compounds of the disposal system (e.g., pyrite, organic matter, metallic parts) and consequently lower their reducing buffering capacity. If the  $\text{N}_2$ -production rate, moreover, exceeds the  $\text{N}_2$ -consumption and -removal rate (diffusion), the pressurisation of the fluid pressure should be considered, potentially giving rise to mechanical perturbations.

With respect to the oxidation in the disposal system by nitrate reduction, the natural redox buffering capacity per volume unit of Ypresian clays is insufficiently known, to date to evaluate the degree and dimensioning of the zone of influence in the Ypresian clays. Considering eventual pressurisation by  $\text{N}_2$ , hydromechanical data as the air-entry value and rock-failure criteria should be better documented (see next section: Gas).

For *SFC1*, ONDRAF/NIRAS does not plan specific tests to study the perturbations of Ypresian clays due to the disposal of Eurobitum.

## Gas

The generation of gas is inevitable after closure of the disposal gallery, due to anaerobic corrosion of metals, radiolysis, (bio-)chemical degradation of wastes and radioactive decay<sup>93</sup>. Initially, gas generated in the near field of a repository in clay will dissolve in the pore water and will be transported away from the repository by diffusion as dissolved species. However, if the gas generation rate exceeds the capacity for diffusive transport of dissolved gas, a free gas phase will develop, leading to a gas pressure build-up. This pressure build-up may then result in gas transport either by two-phase flow through the existing pore network of the host rock or by the creation of additional discrete gas-specific pathways<sup>94</sup>. These processes occur once the gas pressure exceeds specific thresholds, which depend on the hydromechanical properties of the host rock (gas entry value, tensile strength, cohesion and angle of internal friction) and on the local stresses and pore water pressure conditions. The process with the lowest threshold value will prevail. Two-phase flow may thus occur in some rocks while discrete gas pathways may open first in other rocks.

The approach developed for dealing with the gas issue for Boom Clay, presented in Section 4.2.2.5, is transposable to Ypresian clays. It consists of four steps:

1. Identification of main gas sources, for all disposal packages identified as potentially problematic;

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93 Some (bio-)chemical processes in the near field may also consume a fraction of the gas produced.

94 It is assumed here that all the gas has to be removed through the host rock (possibly through the excavation damaged zone), as the current disposal concept does not include an engineered gas transport system.

2. Quantification of gas production and production rate;
3. Estimation of the diffusive removal capacity of the system for dissolved gas;
4. Comparison of results from points 2 and 3.

If the comparison indicates that all gas can be evacuated, there is no issue to deal with. If not, then the results of concomitant RD&D on possible transport modes of free gas through the host rock and EBS components will serve as basis to evaluate consequences.

Section 4.2.2.5 also summarises the results of this four-step approach in the case of Boom Clay. Whether these results can be transposed to Ypresian clays depends on the considered parameter/process:

- The main processes that generate gas are similar (and can thus be transposed).
- The amount and rate of produced gas due to radioactive decay are similar.
- The amount and rate of produced gas due to anaerobic corrosion of metals may differ (and can thus not be transposed). Indeed, the different pore-water chemistry and evolution of the pore-water chemistry at the reference locations for RD&D in the Ypresian clays (Doel) compared to Boom Clay (Mol), do not allow, to date, to transpose the corrosion behaviour, and thus the H<sub>2</sub> production, from one host rock to the other (Section 10.3.2.3).
- The amount and rate of produced gas due to (bio-)chemical degradation of materials may differ. The microbial degradation of organics for instance depends on the specificity of the conditions needed to allow a particular group of microbes to be effective and knowledge in this field can thus not be transposed. The net amount and rate of produced gas due to radiolysis may differ.
- The net amount and rate of produced gas due to radiolysis may differ.

Dissolution and diffusion are transposable, although the diffusion coefficient might differ to some extent. The knowledge of transport modes of free gas through the host rock and EBS components cannot be transposed, due to the poor knowledge of the gas entry pressure and other geomechanical properties of Ypresian clays. There are indications that two-phase flow could occur in this host rock as the pressure sufficient to induce fracturing of the material (pressure locally exceeding the minimal component of the principal tensor of total stresses) could be higher than the one required for the occurrence of a two-phase flow (pore water pressure + gas entry pressure). The gas could thus drive the water out the pores of the host rock, with the advancement of a de-saturation front.

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#### **Roadmap – part of Section 10.3.2.2 – Gas (YC)**

For SFC1, ONDRAF/NIRAS will provide a value for the diffusion coefficient of hydrogen in Ypresian clays. It will also determine their air entry value. The determination of the gas source terms will take into account the specificities of the pore water composition of this host rock.

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## Microbes

During the operational phase and after closure, sulphate-reducing, nitrate-reducing, and/or methane-producing microbes might be introduced into the near field or become active again if several conditions are met: microbes (of their endospores) must be present, there is a supply of nutrients (organic matter, H<sub>2</sub>), sulphate (marine origin or pyrite oxidation) or nitrate (bituminised waste) is accessible and there is enough space for them to grow.

There are indications that, in Ypresian clays, a very slow reduction of sulphates by microbes has taken place (Section 10.2.3.12). A certain activity can thus not be excluded for the future in a disturbed environment. As in Boom Clay, the possible activity of microbes around a repository will depend on whether the specific conditions in the near field are fulfilled. The near-field conditions for microbial activity in Ypresian clays can significantly differ than those in Boom Clay, limiting transposability of information from one host rock to the other.

For *SFC1*, ONDRAF/NIRAS does not plan tests to study the perturbations of Ypresian clays due to microbes.

### 10.3.2.3 The evolution of the engineered barrier system with time can be bounded

The engineered barrier system will evolve with time. Section 4.2.3 details the evolution of the different parts of the EBS for a repository built in Boom Clay. This section focuses on the transposability of knowledge to Ypresian clays.

## Evolution of the cementitious materials

The EBS contains large quantities of cementitious materials, whose properties evolve with time (as detailed Section 4.2.3.1 for disposal in Boom Clay). The lining, the backfill, the buffer of the supercontainer (category C waste) and the monolith (category B waste) are dominantly composed of cementitious materials. At closure of the galleries, these materials will not entirely be saturated and, by the high fluid pressures prevailing in the far field and the capillary suction, the clay pore water will be driven towards the disturbed zone and engineered barrier system. The infiltrating water is formation water modified by the period of oxidation and ventilation and might thus be characterised by concentrations close to the solubility limit of certain salts. Once hydrogeological contact is achieved, migration of dissolved chemical species might also occur by diffusion, on the one hand, from engineered barrier system towards the host rock (see paragraph on alkaline plume), and, on the other hand, from the host rock towards the engineered barrier system (this section). The pore water infiltrating into the engineered barrier system will be rich in sulphate, partly due to oxidation of pyrite, but in the case of the Ypresian clays, also due to its high natural sulphate content, which may induce chemical reactions leading to the deterioration of the concrete. The pore water infiltrating into the engineered barrier system will, in the case of the Ypresian clays at the reference location for RD&D (Doel), moreover contain chloride and Mg<sup>2+</sup> ions. In the absence of envelope, the important differences in pore-water chemistry between the reference sites for RD&D in Boom Clay (Mol) and Ypresian clays (Doel), do not allow transposing the evolution of

the cementitious materials from one host rock to the other (apart for the contribution of oxidised pyrite). Knowledge transfer from other situations (*e.g.*, marine conditions) might be more relevant. The presence of an envelope may reduce some uncertainties.

For category C waste, a key component of the cementitious EBS is the concrete buffer, designed to establish and maintain a chemical environment around the overpack that is favourable to achieving the desired performance (containment of contaminants during the thermal phase). The pH surrounding the overpack will most probably remain elevated for thousand of years in both host rocks.

In the case of category C waste, heat and radiation are introduced into the system, leading towards a temperature elevation and irradiation of the different concrete layers. Knowledge of the thermal evolution of the concrete is currently not transposable as it depends, among others, on the thermal conductivities of Ypresian clays, which are not well known yet. Furthermore, most chemical transformations occurring in the concrete can be expected to be temperature-sensitive and might thus accelerate (or slow down) during the thermal phase.

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#### **Roadmap – part of Section 10.3.2.3 – Evolution cementitious materials (YC)**

*For SFC1*, ONDRAF/NIRAS will perform exploratory calculations to estimate the pH evolution around the envelope (if present) and the overpack in the event of disposal in Ypresian clays.

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#### **Evolution of the overpack**

The overpack is designed to assure the containment of the wastes during the thermal phase. Assessing its evolution with time is thus of prime importance. ONDRAF/NIRAS has launched a RD&D corrosion programme to collect evidence that the integrity of the carbon steel overpack will not be jeopardised during the thermal phase (Section 4.2.3.3). The current programme evaluates the corrosion evolutionary path for Boom Clay pore water in Mol (reference site for RD&D) at the present time in certain conditions and research is ongoing to assess the corrosion behaviour of the overpack in these conditions.

In the absence of an envelope surrounding the buffer, the results from the research on Boom Clay are not directly transposable to Ypresian clays, due to their significantly different pore-water composition.

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#### **Roadmap – part of Section 10.3.2.3 – Evolution of the overpack (YC)**

*For SFC1*, ONDRAF/NIRAS will define the corrosion evolutionary path in case of disposal in Ypresian clays. It will also perform a literature review about the corrosion behaviour of carbon and stainless steel at conditions relevant for the anaerobic phase in Ypresian clays, focussing on the effect of combining chlorides and sulphur-aggressive species.

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### Evolution of the wastes

The waste components will evolve with time. After failure of the overpack (category C waste) or resaturation of the monolith (category B waste), they will progressively degrade due to interaction between the waste and the pore water, resulting in a release of contaminants. Assessing the release rate of contaminants from the waste components and understanding their dissolution behaviour is of primary importance. For SFC1, RD&D focuses on the dissolution of irradiated fuel and of vitrified high-level waste, and on the compatibility of bitumen with the host formation, for a disposal system in Boom Clay. The transposability to Ypresian clays of the research results for these three types of waste is detailed hereafter.

#### Irradiated fuel dissolution

The irradiated fuel is made of different parts presenting different dissolution behaviours: the matrix dissolution, the instant release fraction and the structure and cladding releases.

Most results of the RD&D programme on the matrix dissolution, detailed in Section 4.2.3.4, are transposable from Boom Clay to Ypresian clays, as the current research focuses on the interaction of the waste with concrete (mostly stages I and II of concrete degradation) without taking into account the composition of the pore water.

The instant release fraction solely depends on the history of the irradiated fuel and can therefore entirely be transposed.

In the case of the structure and/or cladding releases, an influence of the chemical composition of the evolved pore water and environment, might be expected but must be assessed. A complete transposition of these releases seems therefore premature.

#### Vitrified high-level waste dissolution

By failure of the overpack and canister, pore water, having a signature representative for its interaction with host rock, lining, backfill and buffer, might come into contact with vitrified waste. At high pH, the dissolution rate of borosilicate glass is relatively high, so that the evolution of the vitrified wastes is dominantly determined by the chemistry of the buffer. Most results of the RD&D programme on the dissolution of vitrified high-level waste, detailed in Section 4.2.3.4, are transposable from Boom Clay to Ypresian clays, as the current research focuses on the interaction of the waste with non-degraded concrete (most penalising case) without taking into account the composition of the pore water.

#### Bituminised waste degradation

The evolution of the bituminised waste can be summarised as a progressive swelling and recompaction, associated with dissolution and leaching of salts out of the bituminised waste. If the salts containing radionuclides have similar solubility as the salts responsible for osmosis (dominantly  $\text{NaNO}_3$ ), the release of radionuclides is concurrent to the leaching of these salts. If the solubility is less, a very slow migration out of the

recompacted wastes might be expected. There are no fundamental reasons to suppose important differences between the two host rocks.

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**Roadmap – part of Section 10.3.2.3 – Evolution of the wastes (YC)**

*For SFC1*, ONDRAF/NIRAS will carry out a literature review about the corrosion rates of the different structure and cladding materials for conditions relevant in Ypresian clays. ONDRAF/NIRAS will not perform specific tests about the wastes evolution in Ypresian clays for SFC1.

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**Criticality safety**

Category C and most category B waste contain fissile radionuclides. These nuclides could cause a spontaneous and sustained nuclear chain reaction, producing large amount of energy and heat. In order to occur, criticality requires sufficient quantities of fissile isotopes in a suitable geometry and a neutron moderator such as water. Section 4.2.3.5 details how the current design minimises the probability of occurrence of a critical event.

The work performed to date on this subject concentrated on the geometry of the disposal system and characteristics of the waste, rather than on the particular prevailing physico-chemical conditions. The results are therefore supposed to be valid and transposable to the Ypresian clays.

## **10.4 The repository can be constructed, operated and closed safely**

ONDRAF/NIRAS considers that the disposal concept proposed for category B&C waste is valid for disposal in poorly indurated clay, being Boom Clay or Ypresian clays. At this stage of the programme, it is expected that most aspects of the current repository design and layout developed for disposal in Boom Clay, detailed in Section 3.2, can be transposed to disposal in Ypresian clays. Some points however, as those listed hereafter, will require more investigation.

### **10.4.1 Feasibility of disposal waste package fabrication**

Significant differences in thermal properties between Boom Clay and Ypresian clays might require adaptation of the supercontainer design (e.g., number of primary packages per disposal package).

### **10.4.2 Feasibility of repository construction**

#### **10.4.2.1 Shaft construction**

Shaft construction requires a good knowledge of among others the hydromechanical properties of the Ypresian clays and overlying rock and the prevailing conditions. If these are in a similar range as the properties and conditions prevailing in a Boom Clay context in Mol, a high degree of transposability of the reference techniques, successfully applied in Boom Clay, can be expected. However, during drilling of the ON-Doel and ON-Kallo boreholes, large drill-hole diameter anomalies were observed within some parts of the Ypresian clays (De Ceukelaire *et al.*, 2012). These anomalies, which were not observed when crossing Boom Clay, might point to instability, but the hydromechanical properties are insufficiently documented to distinguish the cause. A more detailed evaluation is, therefore, required.

#### **10.4.2.2 Access gallery and disposal gallery construction**

Good knowledge of the hydromechanical properties of the Ypresian clays is needed for construction of the access and disposal galleries. As noticed for the shaft construction, there is, at present, a gap in knowledge to explain the drill-hole diameter anomalies in the Ypresian clays, possibly having consequences for the feasibility of gallery construction. There is moreover much uncertainty on the results of the hydromechanical tests. Transposability of the reference techniques applied in Boom Clay should be evaluated in function of potential differences of these basic host rock properties.

Shafts and galleries are important contributors to the overall cost (see (ONDRAF/NIRAS, 2009d)). Thus, changes herein can significantly affect the cost of a repository.

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**Roadmap – Section 10.4 – Feasibility of repository construction, operation and closure (YC)**

*For SFC1*, ONDRAF/NIRAS will focus on specific aspects of Ypresian clays that may influence the safety and feasibility of a repository. It will thus pay special attention to the acquisition of basic geotechnical data as it may affect feasibility. Based on these geotechnical data, it will analyse the transposability of construction techniques considered for building shafts and access and disposal galleries in Boom Clay in the Mol-Dessel area to the Ypresian clays. It will in particular analyse the large drill-hole diameter anomalies that occurred during the drilling of boreholes through Ypresian clays, as these anomalies are a source of concern about the feasibility of drilling shaft and galleries in Ypresian clays.

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## **10.5 The long-term safety of a disposal system in Ypresian clays can be assessed**

ONDRAF/NIRAS considers that its safety approach is valid for disposal in poorly indurated clay, thus in Boom Clay and in Ypresian clays. As described in Chapter 2, the disposal system must fulfil the long-term safety functions of containment (for category C waste), delay and attenuation of the releases, and isolation. It is currently premature to perform safety calculations to evaluate whether a disposal system built in Ypresian clays would fulfil these safety functions. There is indeed a need, at this stage of the programme, for a complete transposability analysis of knowledge from Boom Clay to Ypresian clays, for exploratory calculations with “envelope” parameters and for additional experimental data of key parameters. The output of the transposability analysis might lead to refine the safety strategy, the management strategy and/or the management system for SFC1.

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### **Roadmap – Section 10.5 – The long-term safety of a disposal system in Ypresian clays can be assessed**

*For SFC1*, ONDRAF/NIRAS will perform safety assessments on the geological disposal in Ypresian clays. It will thus continue analysing the transposability of knowledge from Boom Clay to Ypresian clays and perform exploratory calculations with “envelope” parameters and additional experimental results of key parameters.

*For SFC1*, ONDRAF/NIRAS will adapt its safety concept to a disposal system in Ypresian clays, if necessary (see Chapter 2).

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## 11 The societal aspects can be taken into account

When developing long-term management solutions for radioactive waste, ONDRAF/NIRAS pays particular attention to societal aspects. In accordance with the participation principle, it invites the population to share their concerns and requirements from the very start of the decision-making process. This approach naturally leads to interactions between the many interested parties, such as technical experts, political representatives and local authorities. ONDRAF/NIRAS strives for a model where the technical and societal aspects are continuously interacting and influencing one another. Discussions between the various parties help to win the confidence of all those involved and lead to a common perception of the issue of radioactive waste management.

This chapter is divided in three sections. The first section summarises the initiatives conducted by ONDRAF/NIRAS during the development of the Waste Plan. The second section contains the basic principles of the participative decision-making process relating to the implementation of the solution recommended in the Waste Plan, and mentions the normative system in which this process could be included. The third section gives an insight into the measures ONDRAF/NIRAS is currently taking (both internally and in consultation with academic experts) to develop the societal aspects of the B&C programme. A roadmap defining actions to be conducted over the coming years closes the chapter.

### 11.1 Initiatives conducted within the framework of the Waste Plan

When drawing up the Waste Plan and the Strategic Environmental Assessment (SEA) on which it is based, ONDRAF/NIRAS elected to carry out a societal consultation broader than that required by the Law of 13 February 2006 relating to the assessment of the environmental impact of certain plans and programmes and public participation in their drafting (Moniteur belge, 2006).

To this end, a series of *dialogues* and an *interdisciplinary conference* were organised in 2009 in order to give civil society organisations, experts and interested citizens the opportunity to express their concerns and expectations with regard to the long-term management of B&C waste. For additional societal input, ONDRAF/NIRAS asked the King Baudouin Foundation to organise an independent participatory process. The foundation chose to use a *citizens' conference*, representative of the diversity of Belgian society. Over three weekends, from November 2009 to January 2010, a group of 32 citizens debated the following question: "How to decide about the long-term management of high-level and long-lived radioactive waste?"

These societal consultations organised by ONDRAF/NIRAS preceded the public consultation required by the Law of 13 February 2006. In addition to public opinion, opinions were also requested from the SEA Advisory Committee, the Federal Council for Sustainable Development, the Regional governments and the Federal Agency for Nuclear Control.

Consideration of the views collected as part of these participative processes, resulted in ONDRAF/NIRAS matching its recommended management solution to conditions in terms

of the waste's retrievability, monitoring the proper functioning of the disposal system and transferring knowledge of the facility, conditions for which the exact scope is still to be defined in consultation with all interested parties (Chapter 9).

## **11.2 Waste Plan: basic principles of the participative decision-making process**

A participative decision-making process can be defined as a “*way of developing a policy, according to which an authority involves citizens and societal organisations, companies and/or other authorities at as early a stage as possible so that it can prepare, define, implement and/or assess the policy with them, using an openly interactive and/or collaborative method*” (Pröpper and Steenbeeck, 1999). The decision-making process relating to the implementation of the solution recommended in the Waste Plan is unusual insofar as it will extend over a period of approximately one hundred years as of the decision in principle.

### **11.2.1 Key elements in the decision-making process**

Based on the experience built within the scope of the category A disposal programme and on best practices observed internationally, ONDRAF/NIRAS defined key elements for the decision-making process relating to the long-term management of B&C waste. This process must

- *progress in steps*: the journey towards the complete closure of the repository is broken down into a series of steps. Each step has its own *intermediate objective*. To achieve this intermediate objective, a *framework* is defined at the beginning of each step. This framework takes account of the consequences of previous decisions and defines for instance the stakeholders to be involved, their respective roles and responsibilities, the participation methods to be used and the decision-aiding documents to be established. The steps are subdivided into several *sub-steps*, which enable the stakeholders to form an opinion about the subject and lead to *intermediate decisions*. Each step in the decision-making process will be completed by a *key decision* made by one or more competent authorities based on arguments taking account of the level of knowledge in terms of safety, feasibility and environmental protection, the concerns and requirements arising from society and the intermediate decisions made within the sub-steps;
- *be participative*: all stakeholders must have a say in the issue. It means waste producers, safety and environmental protection authorities, local, provincial and regional authorities, local communities, the general public, the scientific world, professional organisations, non-governmental organisations, ONDRAF/NIRAS and foreign parties. It is necessary to provide a space for the stakeholders so that they can establish their own definition of the problem. The stakeholders and type of participative process will vary depending on the step/sub-step of the process under consideration;
- *be adaptable*: the decision-making process must be able to take into account scientific and technical evolution, the results of safety and environmental impact assessments, cost control requirements, societal, legal and regulatory changes and the effects of the successive decisions, while retaining its momentum.;

- *be transparent and credible*: since ONDRAF/NIRAS is both the initiator of and an actor in the decision-making process, it wants this process to be monitored by an institutionally guaranteed, independent body. The process must also be fully documented: the key data and methods used will be submitted to the stakeholders and the scientific and technical knowledge will be submitted for peer review. The arguments that underpin all the decisions made will also have to be subject to independent monitoring;
- *ensure continuity*: interactions with society have to be recurrent and firmly established institutionally. Given the estimated length of the decision-making process, some replacement of the people involved will be needed. This requires reflecting on the management and transfer of information and knowledge, in particular on the traceability and accessibility of the elements enabling to get from one phase to another.

### **11.2.2 Outline of reference decision-making process and inclusion in a normative system**

On the premise that the decision in principle will confirm the decision of geological disposal in poorly indurated clay, ONDRAF/NIRAS drafted an outline of reference decision-making process. This reference decision-making process, which is a basis for discussion that must be refined, will have to receive the support of the stakeholders in order to be implemented.

Within this framework, ONDRAF/NIRAS identified a series of key decisions necessary for implementing the recommended solution. These decisions concern

- the launch of the siting process,
- the development of one or more preliminary integrated disposal projects,
- the launch of the project phase,
- the licences and permits required to begin the construction phase, and
- the acceptance reports and licences necessary for the operational and post-closure phases of the repository.

These decisions will be made by different competent authorities at different decision levels: Federal level (Federal Government, the supervisory authority of ONDRAF/NIRAS, the Belgian nuclear safety authority, etc.), regional level (environmental protection authorities, regional Governments, etc.) or local level (municipalities). They will be made based on reports, such as Safety and Feasibility Cases (SFCs) and environmental impact assessments (EIAs).

ONDRAF/NIRAS recommends including the decision-making process in a normative system. This system must fill the legal void that currently exists between, on the one hand, the provisions of the Law of 13 February 2006 relating to the assessment of the environmental impact of certain plans and programmes and public participation in their drafting, and, on the other hand, the existing nuclear licence system. The normative system should specify, in the outline, who will decide what and using what methods and provide for the creation of the above-mentioned independent monitoring body.



Council Directive 2011/70/Euratom of 19 July 2011 establishing a Community framework for the responsible and safe management of irradiated fuel and radioactive waste, which must be transposed before 23 August 2013, constitutes a window of opportunity for embedding the milestones of the decision-making process in a normative system. For this purpose, particular attention will be paid to the following provisions (EU, 2011):

- Article 1, § 3: *[This Directive] ensures the provision of necessary public information and participation in relation to irradiated fuel and radioactive waste management while having due regard to security and proprietary information issues.*
- Article 5, § 1 (g): *Member States shall establish and maintain a national legislative, regulatory and organisational framework ("national framework") for irradiated fuel and radioactive waste management that allocates responsibility and provides for coordination between relevant competent bodies. The national framework shall provide for [...] national requirements for public information and participation.*
- Article 10, § 2: *Member States shall ensure that the public be given the necessary opportunities to participate effectively in the decision-making process regarding irradiated fuel and radioactive waste management in accordance with national legislation and international obligations.*

In the meantime, and pending the decision in principle to be made by the Federal Government, ONDRAF/NIRAS must implement a series of recommendations that were defined by its supervisory authority in its letter of 3 October 2011. Most of these recommendations concern the societal aspects of the B&C programme:

- *further define the gradual, adaptable, participative, transparent and continuous decision-making process that will take place in parallel with the development and implementation of the management solution; this process will start a priori with the making of a decision in principle;*
- *develop a proposal for a normative system framing the implementation of the Waste Plan; this system should include the creation of an independent monitoring body entrusted with ensuring that the decision-making process advances in completely documented stages, that it is adaptable and transparent, and that it ensures continuity and integration of the social and technical aspects;*
- *develop the societal dimension of the B&C programme and ensure the related financing;*
- *specify, in consultation with all stakeholders, the demands arising from the consultations concerning operational reversibility and retrievability of the waste disposed of, monitoring of the proper functioning, transfer of knowledge of the repository, including the memory of its location, and on the waste it contains (translation ONDRAF/NIRAS).*

### 11.3 On-going actions

ONDRAF/NIRAS intends to make the participative process an integral part of the B&C programme. For this purpose, it develops initiatives with university research teams and other experts in order to outline the decision-making process to be followed, the stakeholders to be involved and the participative methods to be used. Since the publication of the Waste Plan, two main academic projects have been launched: the first is a research project entitled “Socio-political Processes and Plan Management in a Controversial Question – Proposal for Application to the Long-Term Management Plan for B&C Waste” (translation ONDRAF/NIRAS); the second is a doctoral thesis on the “Co-Construction of a Participation and Communication Dialogical Process” (translation ONDRAF/NIRAS).

The implementation of the one-year research project on socio-political processes was entrusted to *Universiteit Antwerpen* (UA) and *Université de Liège* (ULg). This research project aimed at determining favourable conditions for implementing an action plan (in this case, the Waste Plan) in a realistic, efficient and socially acceptable manner. It was divided into five main axes: a prospective analysis of the decision-making process, an assessment of the process of developing the Waste Plan (including the consultation process), an analysis of the media coverage of the Waste Plan, an international comparison of the decision-making processes and an analysis of the legal and institutional framework of the decision-making process. The planned RD&D programme takes into account the conclusions of this project (available in (Fallon *et al.*, 2013)) (see roadmap).

The kick-off meeting of the above-mentioned doctoral thesis took place on 28 November 2012. During the meeting, the doctoral student from ULg explained the subject and objectives of the thesis and presented a RD&D Planning. The project, which will spread over a period of four years and will be followed up by two ONDRAF/NIRAS employees (the doctoral student will report half-yearly to ONDRAF/NIRAS), aims at answering the following question: “*how to organise the communication programme as a participative and innovative structure while remaining in sync with the legal decision-making sequence?*” (translation ONDRAF/NIRAS). Following a double approach based on efficiency and legitimacy, this project will more specifically help define the roles of the different stakeholders and determine the factors impacting the collective learning process, with a particular emphasis on information and memory management.

Besides the initiatives developed with universities, and without pre-empting the decision in principle to be made by the Federal Government, ONDRAF/NIRAS works (both internally and in collaboration with independent experts) on improving and refining the decision-making process as outlined in the Waste Plan. The reflection has till now been focused on defining the stakeholder roles (including ONDRAF/NIRAS), creating the independent body entrusted with ensuring the process transparency and developing the first step of the decision-making process (*i.e.*, the siting process).

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## Roadmap – Chapter 11 – The societal aspects can be taken into account

Within the framework of the Waste Plan, ONDRAF/NIRAS has laid the foundations of a participative process, which must continue throughout the decision-making process. In order to strengthen and maintain societal support, this participative process must be firmly established as part of the B&C programme.

For *SFC1*, ONDRAF/NIRAS has thus decided:

- to refine and improve the existing outline of the decision-making process through dialogue with stakeholders;
- to develop and implement participative working methods intended to help stakeholders:
  - ▶ familiarise themselves with the different aspects of the long-term management of B&C waste, then get a sense of ownership of the case,
  - ▶ specify the concerns expressed during the Waste Plan procedure (retrievability, monitoring etc.).

To this end, ONDRAF/NIRAS will take the following measures:

- observation of foreign participative decision-making processes relating to the development and implementation of management solutions for radioactive waste and participation in international workshops and platforms devoted to the exchange of best practices (INSOTEC<sup>95</sup>, FSC<sup>96</sup>,...) (see Inset 1);
- analysis of participative processes in fields other than radioactive waste management (and assessment of their potential transfer to geological disposal);
- launch and follow-up of academic research projects (including one on the ethical evaluation of technologies) and establishing of long-term relationships with academic actors;
- transposing experiences gained in the category A programme to category B&C.
- organisation of information and consultation events in order to give stakeholders the opportunity to express their concerns and expectations.

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95 INSOTEC: (International) Socio-Technical Challenges for implementing geological disposal (EU project).

96 FSC: Forum on Stakeholder Confidence (NEA).

## **12 ONDRAF/NIRAS follows up long-term management options discarded in the Waste Plan**

In parallel with the development and implementation of the geological disposal solution it recommends, ONDRAF/NIRAS continues to follow up developments regarding long-term management options that were examined in the Waste Plan but were discarded. So it continues to

- follow the evolution of knowledge of schistose formations on their own and as possible host formations, in order to maintain a fallback solution on Belgian territory if poorly indurated clay are eventually rejected;
- follow the evolution of knowledge of disposal in deep boreholes, in order to have, if needed, a solution for the long-term management of very limited amounts of waste, the retrieval of which one would like to make particularly difficult;
- follow, through international institutions, the evolution in the development of geological repositories shared by several European Union Member States in order to understand policies on this matter and their potential impact on the Belgian programme;
- maintain a technology watch on national and international developments in the field of advanced nuclear technologies, although these technologies will not make any contribution to the long-term management of existing and planned conditioned waste. This technology watch is justified by the fact that, on the one hand, the policy for the management of commercial irradiated fuel from the current nuclear estate has not yet been determined, and, on the other hand, the research facilities dedicated to advanced nuclear technologies will themselves generate waste that will have to be managed in the long term.



## Roadmaps



## 13 Roadmaps

ONDRAF/NIRAS intends to develop its geological disposal facility for B&C waste in a cautious, stepwise process, punctuated by the submission of key documents to the relevant authorities providing them with the necessary materials to take a position on the requested decision at each stage. These documents will consist of Safety and Feasibility Cases (SFC). A Safety and Feasibility Case is the synthesis of evidence, analyses and arguments that quantify and substantiate the claim that the disposal facility can be constructed and be safe after closure and beyond the time when active control of the disposal facility can be relied on. ONDRAF/NIRAS is working on the preparation of a first Safety and Feasibility Case (SFC1).

The decision that will be requested with the SFC1 and the precise scope of this document will fundamentally depend on the policy decision on the long-term management of B&C waste yet to be taken based on the ONDRAF/NIRAS Waste Plan. According to ONDRAF/NIRAS's current hypotheses, the SFC1 is intended to ask the competent authorities for the green light to launch the siting process.

Considering these uncertainties, the first Safety and Feasibility Case (SFC1) should in any case focus on:

- testing the safety assessment methodologies;
- refining the design of disposal facility located in Boom Clay;
- providing a first evaluation of the safety and feasibility of a disposal facility located in Ypresian Clays;
- providing a first integration of societal concerns like retrievability, controllability, etc.

The RD&D Plan identifies the RD&D priorities with a view to establishing this first Safety and Feasibility Case (SFC1). At the end of the sections in the main text, a "roadmap" summarises the disposal-related RD&D needs, sorted into four categories:

- RD&D to be conducted *now*, because its first results are necessary for developing SFC1, to close open questions that need to be addressed *for SFC1*.
- RD&D in progress or to launch before SFC1 but whose final results will be integrated in *later SFCs*. The final results of this RD&D are not required for developing SFC1 because, for instance, SFC1 safety assessments can use conservative assumptions. Later SFCs may rely on more realistic assumptions.
- RD&D to launch during the *siting process or after site selection* (beyond SFC1). Some RD&D is site-specific by nature and can only start during the site selection process or even after selection of the site for geological disposal.
- RD&D carried out for *confidence building*: the knowledge is sufficient for the purpose (current stage of the programme) but further RD&D may reduce remaining uncertainties, provide multiple lines of evidence and/or complete the assessment basis. This concerns topics important for both safety and feasibility. Available results will be integrated in SFC1 and subsequent SFCs.

In some fields, the current knowledge is considered sufficient for the purpose of SFC1.



## Roadmaps

Given the continued development of a geological disposal facility and its gradual implementation span over several decades, the future RD&D programme needs to be flexible and evolve according to developments in the societal, scientific, technical, economic and regulatory context.

This chapter contains all the roadmaps present in the main text, organised according to the four categories of disposal-related RD&D needs.

### 13.1 RD&D planned for SFC1

This section groups the RD&D to be conducted *now*, because its first results are necessary for developing SFC1, to close open questions that need to be addressed *for SFC1*.

#### **ONDRAF/NIRAS develops an approach for the development of a geological repository ensuring safety and feasibility** (Chapter 2)

*For SFC1*, ONDRAF/NIRAS will interact with the Federal Agency for Nuclear Control or FANC. ONDRAF/NIRAS will in particular:

- take into account the regulator's expectations regarding the scope, content and level of detail of the SFC1;
- check whether its methodologies comply with the regulator's guidance's;
- discuss specific points of guidance and methodology with the regulator.

ONDRAF/NIRAS will then further complete the derivation of the alternative cases and the altered scenarios. For instance, the development of the human intrusion scenario specific to geological disposal requires input from the regulator, as it is not possible to predict human intrusion activity over an extensive period.

*For SFC1*, ONDRAF/NIRAS will further develop its requirement management system (RMS), especially for feasibility aspects (and related statements). The RMS will document and describe the requirements of the disposal system and its components. In accordance with the safety strategy and the management principles, the RMS will also keep track of changes to the system or the requirements and the reasons for these changes. As the implementation of the disposal system will take several decennia and as new requirements will undoubtedly be added, the RMS is a crucial tool in guaranteeing the traceability of changes and lines of reasoning behind the different requirements.

*For SFC1*, ONDRAF/NIRAS will further implement tools and procedures for supporting its methodology such as:

- the geo-scientific information system (GSIS) and the Open Text knowledge management system, to guarantee the traceability and organisation into a hierarchy of assumptions, decisions and data.
- the QA analysis of the calculation tool chains (assumptions, codes and succession of tools) and of the data clearance system.
- the documentation of the various steps for implementing the optimisation process in order to guarantee its traceability.

*For SFC1*, ONDRAF/NIRAS will adapt its safety concept to a disposal system in Ypresian clays, if necessary.

### **The conditioned wastes can be characterised** (Section 3.1)

The inventory for SFC1 will include all existing and forecast category B&C waste. *For SFC1*, ONDRAF/NIRAS will therefore continue to update its technical inventory on a regular basis, based on the provisions from the waste producers. It will also verify that new types of anticipated waste do not raise new issues in relation to those already taken into account in the studies.

The selection of impacting families is not straightforward for the specific case of wastes conditioned in the cement matrix. It could be advisable to build up “dummy” families whose conservative characteristics encompass those of the cemented wastes.

For specific wastes with major radiological impact, the radiological inventory and its evolution with time are based on calculations. The associated uncertainties result from both the input data and code system performance. The evaluation of these uncertainties is a current research topic (*for SFC1*), which includes comparisons with inventories from other countries (*e.g.*, CSD-V and CSD-C are present in the inventories of Andra and Nagra). This research is based on published documents (such as (Nagra, 2002b)) and on collaboration with international organisations, such as the Expert Group on Assay Data of Spent<sup>97</sup> Nuclear Fuel (ADSNF) under the auspices of the NEA. The goal of this research is to guarantee that the ONDRAF/NIRAS inventory is reasonably conservative and coherent with inventories of similar waste families present in other countries.

### **The other parts of the engineered barrier system can be characterised** (Section 3.2)

*For SFC1*, ONDRAF/NIRAS will further refine the design of the engineered barrier system (EBS). It will focus in particular on developing backfill and seals. It will examine the measures that could facilitate the possible retrieval of the waste after partial or complete closure of the disposal facility and highlight the technical limitations of retrievability, because it cannot occur at the expense of radiological safety, physical security and non-proliferation measures for nuclear materials (safeguards). (Enhancing retrievability could also have an impact on the cost of the disposal facility.) ONDRAF/NIRAS will then specify the requirements for the retrievability of disposed waste in collaboration with other stakeholders (by use of a participative method). After specification of these requirements (not necessarily before SFC1), ONDRAF/NIRAS will refine its backfill design and its sealing strategy and design.

*For SFC1*, ONDRAF/NIRAS will further characterise the EBS properties taking into account the evolution of its design if relevant (materials, manufacturing processes etc.).

### **The geological barrier can be characterised** (Section 3.3)

ONDRAF/NIRAS currently analyses existing geophysical data in the light of updated techniques. For instance, it reprocesses the seismic data with new numerical software, with a focus on the observation of discontinuities within Boom Clay and aquifers. In addition to providing additional lines of evidence about Boom Clay geology, this work will

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97 Irradiated fuel is called spent fuel when declared as waste.

also help the organism to select state-of-the-art investigation techniques to use during the siting process (Section 3.3.2).

The transferability of geotechnical properties to other locations in Boom Clay and to greater depths in particular is an ongoing research topic in preparation for the siting process.

Additionally, data from the new borehole, to be drilled in 2014, will bring valuable information. Studies will be launched and the first results, if available, will be included in SFC1. The new borehole will help to:

- increase the resolution of data;
- confirm the lateral continuity of Boom Clay formation;
- characterise with more precision the vertical layers in terms of, for instance, migration parameters and thermal parameters;
- apply the best available techniques for sampling, taking into account the anisotropic properties of the clay.

The new borehole will also allow reviewing the borehole geophysical tools and techniques that could be applicable to the characterisation of potential sites.

#### **The environment can be characterised** (Section 3.4)

The new drilling will allow ONDRAF/NIRAS to better characterise the layers around the Boom Clay (transitional formations between Boom Clay and the Neogene aquifer; alternating permeable and impermeable layers of the Oligocene aquifer) in terms of hydraulic properties, for a more realistic description of the system. It will also allow characterising better the Ypresian formation in Mol, which is used as a boundary of the lower Rupelian aquifer in hydrogeological modelling). The first results might be included in SFC1.

#### **The biosphere can be stylised** (Section 3.5)

Future developments of the biosphere stylisation within the B&C programme will take account of remarks from:

- the regulator on biosphere treatment in the category A programme, whose licence application is currently under review;
- the independent review of the current B&C biosphere approach (review under progress).

For SFC1, the B&C programme will meanwhile develop a reference biosphere for cold climate with permafrost (not considered in the frame of category A programme) and study the transferability of the transfer factors (from the soil of the reference site for RD&D in Mol to other types of soil in the Campine).

**The perturbations of Boom Clay due to the excavation, construction, operation and the post-closure evolution of the repository can be bounded** (Section 4.2.2)

For *SFC1*, because of their potential impact on retrievability, ONDRAF/NIRAS will continue to follow up the evolution of the stresses on the lining in HADES and investigate in particular the respective roles of consolidation and creep. It will further study the mechanical properties of Boom Clay within the damaged zone, because they may condition the reaction of the clay to the swelling of Eurobitum. These mechanical properties are also of importance in case of possible transport of free gas (Section 4.2.2.1).

ONDRAF/NIRAS will include the first results from the PRACLAY Heater Test *in SFC1*. This test intends to confirm the capacity of Boom Clay and the gallery linings to support the thermal load imposed by heat-emitting waste and, in particular, to verify that the clay will not be destabilised by the thermal transient and that its permeability will not be significantly affected (Section 4.2.2.2).

For *SFC1*, ONDRAF/NIRAS will check whether the host rock retains its self-sealing capacity even after perturbation by an alkaline plume. A first assessment of the possible effects of combined perturbations will also be carried out.

For *SFC1*, ONDRAF/NIRAS will evaluate the gas source terms for a selection of wastes and associated engineered barrier system, considering the evolving conditions in the disposal system.

For *SFC1*, ONDRAF/NIRAS will investigate the limitations of microbial activity in Boom Clay due to space restriction. To bound the possible evolution of the disposal system, ONDRAF/NIRAS will perform "envelope calculations" (*e.g.*, supposing the complete conversion of sulphate to sulphide) estimating the maximal amount of reaction products due to microbial activity.

**The evolution of the cementitious materials with time can be bounded (BC)** (Section 4.2.3.1)

For *SFC1*, ONDRAF/NIRAS will perform a first assessment of the evolution of the EBS, regarding:

- the ageing processes within the buffer (decalcification and pH evolution);
- the thermo-hydro-mechanical evolution of the buffer (*e.g.*, thermal stress field due to thermal gradient, influence of temperature on the structural characteristics and properties of concrete, confirmation of the absence of through-going cracks).

For *SFC1*, ONDRAF/NIRAS will propose a backfill compatible with retrievability. (The requirements must still be defined in collaboration with other stakeholders. For later SFCs, adaptations might thus be required.)

**The evolution of the seals with time can be bounded (BC)** (Section 4.2.3.2)

*For SFC1*, ONDRAF/NIRAS will define requirements on the seals, taking into account the current concerns of other stakeholders, and select a design fulfilling these requirements. (These concerns will be formalised during the societal dialogue and/or interactions with the regulator.) The RD&D on THMC (thermo-hydro-mechanical and-chemical) behaviour of the seals will then resume. Preliminary results might be available for SFC1, in function of the selected design.

**The evolution of the overpack with time can be bounded (BC)** (Section 4.2.3.3)

*For SFC1*, ONDRAF/NIRAS will pursue its work on assessing the evolution of the overpack, in order to collect evidence that the integrity of the carbon steel overpack will not be jeopardised at least during the thermal phase. ONDRAF/NIRAS will continue its work to demonstrate that the combination of aggressive chloride and sulphur species does not affect uniform and localised corrosion (within the defined corrosion evolutionary path) (Section 4.2.3.3).

*For SFC1*, a model is under development to assess the long-term evolution of the corrosion products layer, of the corrosion potential and of the uniform corrosion rate. Experiments are ongoing to determine the parameters of the model.

ONDRAF/NIRAS will perform localised corrosion tests to assess the susceptibility of the carbon steel overpack (with welds and heat-affected zones) to localised corrosion under conditions relevant for the supercontainer, in order to demonstrate the validity of the exclusion principle. (This includes assessing the impact of temperature excursion above 100°C on the potential occurrence of stress-corrosion cracking.). The first results might be included in SFC1.

**The evolution of the wastes with time can be bounded (BC)** (Section 4.2.3.4)

**UOX** *For SFC1*, ONDRAF/NIRAS will refine knowledge of the dissolution of UOX irradiated fuel in a cement environment. ONDRAF/NIRAS will also continue to collaborate as end-user in the European Union project FirstNuclides<sup>98</sup> whose overall objective is to improve understanding of the Instant Release Fraction from (mainly) high-burnup UOX irradiated fuel. (The FirstNuclides project also includes studies on the leaching of MOX irradiated fuel.)

**Glass** *For SFC1*, ONDRAF/NIRAS will refine knowledge of the dissolution of glass matrices in a cement environment, focusing on the interpretation and modelling of experimental data. Unlike irradiated fuel, glass evolution is sensitive to chemical evolution of cementitious materials.

**Eurobitum** *For SFC1*, ONDRAF/NIRAS will collect lines of evidence about the respective leaching rates of radionuclides and nitrates. (It is expected that the radionuclides leaching rates are lower than the nitrates leaching rates.)

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98 FirstNuclides: Fast / Instant Release of Safety Relevant Radionuclides from Spent Nuclear Fuel (EU project).

**Other B waste** For *SFC1*, ONDRAF/NIRAS will make a preliminary assessment of the degradation processes (chemical, biological, gas production) in other category B waste. Indeed, some components of this waste, such as phthalates or cellulose, may influence the EBS properties.

**The evolution of the engineering barrier system with time in terms of criticality safety can be bounded** (Section 4.2.3.5)

For *SFC1*, ONDRAF/NIRAS plans to develop a methodology for handling criticality safety for category B&C waste. It will include a review of the existing post-closure criticality studies, the analysis of the fissile inventory of all families of category B&C waste, the identification of penalising families and, if necessary, specific criticality calculations.

ONDRAF/NIRAS will check the methodologies of other waste management agencies on this topic. It will also follow up international activities related to the use of burnup credit for geological disposal of irradiated fuel.

**The repository can be constructed in Boom Clay, operated and closed safely** (Chapter 5)

For *SFC1*, ONDRAF/NIRAS will address several issues regarding supercontainer fabrication. It will check how to weld the top plate of the overpack onto the overpack cylinder and how to centre the overpack within the concrete buffer. It will pursue research on the filler (define the most appropriate composition and ways to install it) and on the concrete buffer (define the most appropriate composition, ways to construct it and looking for a type of reinforcement material compatible with concrete, if needed) (Section 5.1.1).

For *SFC1*, ONDRAF/NIRAS will also check what are the thermal and radiological conditions and stresses in the supercontainer components (envelope, concrete buffer, filler, concrete lid and overpack) during fabrication, storage, transport, disposal and potential retrieval of the supercontainer. It will assess the time required to fabricate a supercontainer (primary waste package emplacement and supercontainer closure included).

For *SFC1*, ONDRAF/NIRAS will assess the thermal and radiological conditions and stresses in the monolith B components (pre-cast caisson, mortar filler and lid) during fabrication, storage, transport and disposal and potential retrieval of monolith B (Section 5.1.2).

For *SFC1*, ONDRAF/NIRAS will assess the feasibility of constructing a sufficiently large shaft, the waste shaft, to permit transfer of disposal waste packages from the surface to the disposal depth and its intersection with the access gallery. ONDRAF/NIRAS will also address the issue of achieving waterproofing of the shaft lining in the aquifer sands (Section 5.2.1).

For *SFC1*, ONDRAF/NIRAS will perform a preliminary analysis of the potential transferability of the shaft construction techniques considered for Boom Clay in the Mol-Dessel area to other disposal depths.

*For SFC1*, ONDRAF/NIRAS will study how to construct the crossings between the access gallery and the disposal galleries. It will also check the impact of heat generated by the waste on the design of the lining of the disposal gallery (Section 5.2.2).

*For SFC1*, ONDRAF/NIRAS will perform a preliminary analysis of the potential transferability of the access and disposal galleries construction techniques considered for application at the reference site for RD&D in the Boom Clay to other disposal depths.

*For SFC1*, ONDRAF/NIRAS will calculate the minimum internal diameters for access and disposal galleries, the shaft dimensions and hoisting system required for the transport of disposal waste packages (Section 5.3.2).

*For SFC1*, ONDRAF/NIRAS will solve issues regarding the tilting of disposal waste packages (from a vertical into a horizontal position and, for reversibility purposes, from a horizontal into a vertical position), transport of the disposal waste packages along the shaft (both downwards as upwards) and transport of the disposal waste packages in the underground repository from the shaft until their final disposal position and back, for reversibility purposes.

*For SFC1*, ONDRAF/NIRAS will also list the requirements for the floors in the access gallery and disposal galleries to allow transport and installation of the disposal waste packages.

*For SFC1*, ONDRAF/NIRAS will search for the most appropriate materials composition for the backfill material for the disposal galleries, access gallery and shafts, taking into account retrievability. It will study how to perform the backfill operations and how to check the success of the backfill operations (Section 5.4.1).

*For SFC1*, ONDRAF/NIRAS will define which materials should be used as seals, taking into account retrievability, and how to install seals in the disposal galleries, access gallery and shafts, taking into account retrievability (Section 5.4.2).

*For SFC1*, ONDRAF/NIRAS will evaluate the radiological and non-radiological risks associated with the repository construction and operation and the measures required to mitigate against these risks. ONDRAF/NIRAS will evaluate in greater detail the impact of operational safety on the layout (number of access galleries and shafts, length of disposal galleries etc.) (Section 5.6.1 and Section 5.6.2).

*For SFC1*, ONDRAF/NIRAS will define the accident scenarios to be taken into account and the measures required to mitigate against the risks associated with these scenarios (Section 5.6.3).

*For SFC1*, ONDRAF/NIRAS will define the safeguard requirements for the disposal of fissile materials. It will perform a global evaluation as to how the appropriate security, safeguards and criticality management measures can be implemented, based on the waste inventory and the design of the disposal waste packages. International guidance for safeguards application is under development. National and international approaches and requirements for managing fissile materials will be reviewed and their applicability to the Belgian disposal design will be considered (Section 5.6.4).



**The long-term safety of the disposal system can be assessed** (Chapter 6)

ONDRAF/NIRAS will first pursue the preparatory phase of the SFC1 (including, for instance, the development of performance-assessment models and further iterations of the reference case accounting for the evolving conditions and transferability issues, the alternative cases and altered scenarios and sensitivity analyses). It will then perform the formal assessment phase. This phase will include the full range of scenarios and performance-assessment calculation cases necessary to demonstrate the safety and feasibility of geological disposal in poorly indurated clay.

**The long-term radiological impact can be assessed** (Chapter 7)

For SFC1, ONDRAF/NIRAS continues to follow the evolution of ICRP<sup>99</sup> recommendations and analyses how these may affect its assessments. It will take into account the regulator's recommendations on safety and performance indicators.

**The environmental impact can be assessed** (Chapter 8)

For SFC1, ONDRAF/NIRAS will continue to monitor the evolution of regulations and laws applicable to the protection of the environment surrounding a disposal system in Boom Clay or Ypresian clays. It will evaluate their impact on the disposal system as needed. In line with the law and regulations, ONDRAF/NIRAS will continue its investigations on the protection of the aquifer resources, among others, and will develop them as needed:

- For SFC1, studies will confirm that the impact of chemical contaminants released by the disposal system is low, so as to ensure, in particular, that this impact does not endanger the quality of the water resources and, more generally, does not unacceptably affect the disposal system's environment, including the surface environment, and man.
- For SFC1, ONDRAF/NIRAS will update calculations of thermal output of category C waste with realistic values. It will then revise the description of the thermal evolution of the disposal system and its potential environmental consequences (particularly within the aquifers). It will also re-evaluate the uplift above a repository for heat-emitting wastes using a more realistic model and results from laboratory experiments.

**Other external requirements can be met** (Chapter 9)

For SFC1, ONDRAF/NIRAS examines the measures that could facilitate the possible retrieval of the waste after partial or complete closure of the disposal facility for a period that is yet to be defined by stakeholders. ONDRAF/NIRAS also examines the measures to monitor the proper functioning of the repository. ONDRAF/NIRAS prepares the transfer of knowledge of the repository and the waste it contains to future generations. ONDRAF/NIRAS currently takes part in the international project of the NEA Radioactive Waste Management Committee called Preservation of Records, Knowledge and Memory

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99 ICRP: International Commission on Radiological Protection.

across generations<sup>100</sup>. The project aims to compare approaches, test potential solutions and build common references in this field (see Chapter 11).

### **The Ypresian clays are a potential host rock** (Chapter 10)

*For SFC1*, ONDRAF/NIRAS will continue analysing the transposability of knowledge from Boom Clay to Ypresian clays.

*For SFC1*, ONDRAF/NIRAS will focus on the determination of basic parameters of Ypresian clays.

*For SFC1*, ONDRAF/NIRAS will clarify the characteristics of the Mont-Hérribu Member. If the Mont-Hérribu Member is restricted to the lower-most, coarse-grained or heterogeneous deposits as described in the literature, ruling it out of the definition the Ypresian clays should be considered (Section 10.2.3).

Stratigraphic knowledge is of prime importance for transferability. ONDRAF/NIRAS will thus continue stratigraphic studies to increase knowledge of the depth and the thickness distribution of the Ypresian clays and of separate members. It intends to clarify (at national or international level) whether the Egemkapel Member/bed is a separate, formal member and whether it is part of the Ypresian clays. Other points of concern are the correlation of geophysical logs and the correlation of local stratigraphic subdivision in neighbouring countries, in order to demonstrate the lateral continuity and possibly transfer information (Section 10.2.3).

It is important *for SFC1* to check the continuity of Ypresian clays, in order to check for the potential presence of discontinuities. (Discontinuities have been observed in outcrops.) ONDRAF/NIRAS will therefore start a literature review to collect information about the presence of features that might disturb the continuity of the Ypresian clays. Based on this literature review, ONDRAF/NIRAS will then focus on understanding the formation mechanisms of the features, *e.g.*, intraformational faults, in collaboration with neighbouring countries (Section 10.2.3).

*For SFC1*, ONDRAF/NIRAS will document the vertical variability – and lateral correlation – of the admixture of certain minerals and organic material in order to check the continuity of Ypresian clays. Their presence should be understood (Section 10.2.3).

*For SFC1*, ONDRAF/NIRAS will pay attention to the mineralogy of Ypresian clays, as this may affect the retention and transport processes of contaminants. ONDRAF/NIRAS will integrate data from ON-Doel and ON-Kallo boreholes and/or perform re-measurements of samples, with more precise and standardised techniques. ONDRAF/NIRAS will document the spatial (vertical and lateral) variability of the grain size, the mineralogic composition and the organic matter content. ONDRAF/NIRAS will initiate a study to document the nature (authigenic or detrital) of smectite (Section 10.2.3).

*For SFC1*, ONDRAF/NIRAS will pursue the current research on the plastic and liquid limit and the calculated plasticity index of the Ypresian clays (Section 10.2.3).

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100 Website: <http://www.oecd-nea.org/rwm/rkm/> (Last visit: 2 February 2013).

*For SFC1*, ONDRAF/NIRAS will integrate available data on the hydraulic conductivity of Ypresian clays and surrounding rocks. It will start additional analyses to specify, among others, its vertical variability and its anisotropy. The first results might be integrated in SFC1 (Section 10.2.3).

*For SFC1*, ONDRAF/NIRAS will further investigate the composition and chemistry of the pore water from Ypresian clays. ONDRAF/NIRAS will in particular focus on solving analytical problems encountered (large discrepancy of results between samples, between laboratories). It will improve documentation of the regional trends and the vertical variability (among others by resampling of piezometers) (Section 10.2.3).

ONDRAF/NIRAS will start studies before SFC1 on the effective diffusion coefficient and the speciation of relevant radionuclides in Ypresian clays. In particular, ONDRAF/NIRAS will focus on the anisotropy and vertical variability of the effective diffusion coefficient. ONDRAF/NIRAS will also investigate whether the speciation of relevant radionuclides in Ypresian clays differs from the one in Boom Clay. It will check whether knowledge from the literature and other argillaceous rocks (Opalinus clay, Callovo-Oxfordian clay, bentonites) is transposable to Ypresian clays. The first results might be available for SFC1 (Section 10.2.3).

*For SFC1*, ONDRAF/NIRAS will gather information on basic geotechnical parameters (to document, among others, their (an)isotropy and their lateral and vertical variabilities) and better characterise the mechanical properties of the Ypresian clays in order to predict the elasto-plastic response of the rock to an underground excavation (Section 10.2.3).

Data on the *in-situ* stress state and hydro-mechanical behaviour of Ypresian clays is still scarce. *For SFC1*, ONDRAF/NIRAS will check under which conditions the quantified parameters are valid. It will also perform an integration exercise and a critical interpretation of available data (Section 10.2.3).

*For SFC1*, ONDRAF/NIRAS will evaluate the thermal properties of Ypresian clays and surrounding layers as they may affect the design and layout of a repository (Section 10.2.2).

*For SFC1*, ONDRAF/NIRAS will develop a simplified hydrogeological model of the environment of Ypresian clays to estimate a dilution factor (Section 10.2.4).

*For SFC1*, ONDRAF/NIRAS will perform a first evaluation of the extent of the damaged zones around disposal galleries in Ypresian clays (Section 10.3.2.2).

*For SFC1*, ONDRAF/NIRAS will provide a value for the diffusion coefficient of hydrogen in Ypresian clays. It will also determine their air entry value. The determination of the gas source terms will take into account the specificities of the pore water composition of this host rock (Section 10.3.2.2).

Concerning the evolution of the EBS with time, *for SFC1*, ONDRAF/NIRAS will perform exploratory calculations to estimate the pH evolution around the envelope (if present) and the overpack in the event of disposal in Ypresian clays (Section 10.3.2.3).

*For SFC1*, ONDRAF/NIRAS will define the corrosion evolutionary path in case of disposal in Ypresian clays. It will also perform a literature review about the corrosion behaviour of carbon and stainless steel at conditions relevant for the anaerobic phase in Ypresian clays, focussing on the effect of combining chlorides and sulphur-aggressive species (Section 10.3.2.3).

*For SFC1*, ONDRAF/NIRAS will carry out a literature review about the corrosion rates of the different structure and cladding materials for conditions relevant in Ypresian clays. ONDRAF/NIRAS will not perform specific tests about the wastes evolution in Ypresian clays for SFC1 (Section 10.3.2.3).

*For SFC1*, ONDRAF/NIRAS will focus on specific aspects of Ypresian clays that may influence the safety and feasibility of a repository. It will thus pay special attention to the acquisition of basic geotechnical data as they may affect feasibility. Based on these geotechnical data, it will analyse the transposability of construction techniques considered for building shafts and access and disposal galleries in Boom Clay in the Mol-Dessel area to the Ypresian clays. It will in particular analyse the large drill-hole diameter anomalies that occurred during the drilling of boreholes through Ypresian clays, as these anomalies are a source of concern about the feasibility of drilling shaft and galleries in Ypresian clays (Section 10.4).

*For SFC1*, ONDRAF/NIRAS will perform safety assessments on the geological disposal in Ypresian clays. It will thus continue analysing the transposability of knowledge from Boom Clay to Ypresian clays and perform exploratory calculations with "envelope" parameters and additional experimental results of key parameters (Section 10.5).

### **The societal aspects can be taken into account** (Chapter 11)

Within the framework of the Waste Plan, ONDRAF/NIRAS has laid the foundations of a participative process, which must continue throughout the decision-making process. In order to strengthen and maintain societal support, this participative process must be firmly established as part of the B&C programme. *For SFC1*, ONDRAF/NIRAS has thus decided:

- to refine and improve the existing outline of the decision-making process through dialogue with stakeholders;
- to develop and implement participative working methods intended to help stakeholders:
  - ▶ familiarise themselves with the different aspects of the long-term management of B&C waste, then get a sense of ownership of the case,
  - ▶ specify the concerns expressed during the Waste Plan procedure (retrievability, monitoring etc.).

To this end, ONDRAF/NIRAS will take the following measures:

- observation of foreign participative decision-making processes relating to the development and implementation of management solutions for radioactive waste

and participation in international workshops and platforms devoted to the exchange of best practices (INSOTEC<sup>101</sup>, FSC<sup>102</sup>,...) (see Inset 1);

- analysis of participative processes in fields other than radioactive waste management (and assessment of their potential transfer to geological disposal);
- launch and follow-up of academic research projects (including one on the ethical evaluation of technologies) and establishing long-term relationships with academic actors;
- transposing experiences gained in the category A programme to category B&C.
- organisation of information and consultation events in order to give stakeholders the opportunity to express their concerns and expectations.

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101 INSOTEC: (International) Socio-Technical Challenges for implementing geological disposal (EU project).

102 FSC: Forum on Stakeholder Confidence (NEA).

## 13.2 RD&D for later SFCs

This section groups RD&D already under way or to be launched before SFC1 but whose final results will be integrated in *later SFCs*.

### **The conditioned wastes can be characterised** (Section 3.1)

*For later SFCs*, ONDRAF/NIRAS will continue to characterise historical waste by analysing production data sheets and other available documents. This may highlight specific needs for further characterisation of some packages.

*For later SFCs*, ONDRAF/NIRAS will continue to characterise irradiated fuels, taking into account their intrinsic evolution during the storage period needed for cooling, and considering this evolution in the studies relating to their conditioning and post-conditioning. It will pursue its selection of "impacting families". It will for instance pay attention to the presence of components such as phthalates or cellulose in category B waste, as their degradation may affect the EBS properties and gas production.

*For later SFCs*, RD&D is also under way to determine how to handle the uncertainties inherent to the characterisation of low- and medium-level conditioned waste. This is of particular interest for instance for wastes with a large dispersion of as-measured nuclide contents. The results of this RD&D enable a decision as to which deviation from the mean value is acceptable or whether another value should be used for safety assessments.

### **The other parts of the engineered barrier system (EBS) can be characterised** (Section 3.2)

ONDRAF/NIRAS will study the transport of solutes and fluids (water, gas) in the EBS *for later SFCs*.

### **The geological barrier can be characterised** (Section 3.3)

ONDRAF/NIRAS has initiated studies about the pore water composition whose results will be integrated in *later SFCs*:

- ONDRAF/NIRAS works to improve the characterisation of dissolved organic matter (DOM) and evaluate the potential genetic links between part of the kerogen and DOM, because DOM affects transport of some radionuclides.
- ONDRAF/NIRAS will test the geochemical model on samples from Essen, where the pore water composition is more saline than in the Mol area, in order to assess the transferability of this model to locations other than Mol and determine the limits of validity of the model.

Concerning the solutes transport, ONDRAF/NIRAS will start experiments to evaluate the impact of different geochemical conditions on the sorting of radionuclides in groups of elements with similar migration and retention behaviour under Boom Clay present-day geochemical conditions.

ONDRAF/NIRAS will start studies to improve the correlation between migration parameters and lithology. Results will be included in later SFCs (Section 3.3.9).

*For later SFCs*, ONDRAF/NIRAS will perform a literature review on the impact of saline water on transport and retention processes in clays (analysing, among others, data from Opalinus clay). ONDRAF/NIRAS investigates the surface diffusion phenomena, among others in the frame of the CATCLAY project. It plans to refine knowledge of the mobility of dissolved organic matter (DOM). Results will be included in later SFCs.

ONDRAF/NIRAS continues to characterise the stress state and the hydro-mechanical properties of Boom Clay. The results of these characterisations will be integrated in subsequent SFCs. In particular, ONDRAF/NIRAS will continue to assess the combined effects of the different types of anisotropy (*in-situ* stresses, Boom Clay stiffness and strength) as this may build confidence in the long-term evolution of the system and support optimisation of construction techniques. ONDRAF/NIRAS will also pursue the integration of the large amount of data collected over more than 30 years of research in support of the development of constitutive models.

ONDRAF/NIRAS will investigate the effect of space restriction on microbial activity. Because microbes are present around HADES, this experiment will aim to determine the response of microbes initially in a favourable environment (with space and nutrients) to a progressive spatial restriction, corresponding to the expected consolidation of the clay around the disposal galleries. Results of this study will be integrated in *later SFCs*.

#### **The environment can be characterised** (Section 3.4)

ONDRAF/NIRAS will refine knowledge of burial history of the Campine area, in particular during the last million years (to improve the resolution of data). Results of this study are not expected before SFC1 but will be introduced in *later SFCs*.

ONDRAF/NIRAS will better characterise the layers around Boom Clay (transition zone between Boom Clay and the Neogene aquifer; alternating permeable and impermeable layers of the Oligocene aquifer) in terms of geometry, for a more realistic description of the system. Results of this study are not expected before SFC1 but will be introduced in *later SFCs*.

The new borehole will provide samples for the direct measurement of thermal parameters of the formations below and above Boom Clay. (These parameters are currently deduced from indirect measurements.) This knowledge will be used for re-evaluating the uplift above a repository for heat-emitting wastes. The results on these samples might only be available for later SFCs.

*For later SFCs*, topics to focus on are the understanding of geochemical variations, equilibration time between sea water and aquifers, water dating, and integrating data from the Netherlands, in order to refine the hypotheses behind its geochemical models, as suggested by (Colenco, 2009) and (Olsthoorn, 2011) (Section 3.4.2).

**The biosphere can be stylised** (Section 3.5)

ONDRAF/NIRAS will extend results from the category A programme about the potential radiological impact of releases from the repository on the local fauna and flora (non-human biota) to category B&C waste.

**The evolution of the disposal system due to changes in its environment can be bounded** (Section 4.2.1)

For *later SFCs*, ONDRAF/NIRAS will continue its research on the long-term stability of Boom Clay. It will also continue refining and integrating knowledge of the burial history, through, among others, increasing the stratigraphic resolution and integrating all relevant geological studies about the Campine basin (including work from VITO, Belgian Geological Survey, Universities, neighbouring countries etc.).

Beyond SFC1, ONDRAF/NIRAS will study the influence of climate changes on Boom Clay properties and on hydrogeology (e.g., assessing the impact of pore water composition on the sorting of radionuclides in groups of elements with similar migration and retention behaviour under Boom Clay present-day geochemical conditions, the transport and retention processes).

**The evolution of the disposal system due to the excavation, construction, operation and the post-closure evolution of the repository can be bounded** (Section 4.2.2)

ONDRAF/NIRAS pursues studies about the perturbations resulting from excavation whose results will be integrated in *later SFCs*. Interpretation of data collected during excavation of the Connecting gallery and PRACLAY gallery using 3D-models has started. Work is also going on to refine the characterisation of material and *in-situ* stress anisotropy and their influence on the hydro-mechanical behaviour of the Boom Clay around excavations.

ONDRAF/NIRAS will start studies about the impact of the C-waste thermal output, whose results will be integrated *in later SFCs*:

- It will check the validity of the thermo-hydromechanical (THM) models of Boom Clay behaviour at the scale of disposal galleries, by comparison with the measurements around the PRACLAY gallery and further develop them if necessary.
- It will study the thermal decomposition of organic matter upon heating and production of CO<sub>2</sub>, in order to clarify the role of the buffering capacity of Boom Clay with respect to the CO<sub>2</sub> produced. Will the production of small organic molecules by the thermal degradation of organic matter significantly increase the amount of mobile organic matter in Boom Clay?
- It will investigate the possible dissolution/precipitation of carbonates near a gallery with heat-emitting waste.



Several long-term studies are ongoing with regard to the disposal of Eurobitum, whose results will be integrated *in later SFCs*. These studies aim to:

- confirm the compatibility of the bitumen matrix with disposal in Boom Clay. It focuses on the evolution of the swelling pressure of bitumen in repository conditions. This test will allow determining the number of Eurobitum drums to be placed per monolith B in a more realistic way.
- continue investigating the effects of nitrates – including those resulting from microbially mediated reactions –, on Boom Clay and to verify that the results obtained for each component separately are still valid for a natural Boom Clay mixture.
- check whether near-field conditions around a disposal gallery with Eurobitum waste can affect the speciation of radionuclides sensitive to redox potential, as this may affect their transport properties.
- confirm that the mechanical properties of Boom Clay and of Boom Clay affected by a NaNO<sub>3</sub> plume are comparable.

Laboratory experiments and *in-situ* tests are being conducted in order to investigate the possible free gas transport modes and to confirm that no significant pore water displacement is associated with the transport of free gas (if any). Results of these studies will be integrated *in later SFCs*. For *later SFCs*, ONDRAF/NIRAS will check possible gas sink terms (consumption by microbes, hydrate formation (in presence of zirconium), etc.).

ONDRAF/NIRAS will continue its work, the results of which will be integrated *in later SFCs*, on the development and validation of conceptual models for the transport of free gas through the disposal system (through the clay, through EBS components and along interfaces), in order to assess the consequences of such transport. *If necessary*, ONDRAF/NIRAS will investigate design options that would simplify the description of the evolution of the system with respect to gas production and transport. For instance, ONDRAF/NIRAS could use an engineered gas transport system made of adapted/suitable backfill and seal materials.

For *later SFCs*, additional experimental work about microbial activity may lead to a more realistic description of the possible evolution of the system.

### **The evolution of the engineered barrier system with time can be bounded**

(Section 4.2.3)

After the assessment of the evolution of the EBS performed for SFC1, ONDRAF/NIRAS will study the interactions between the waste components and the cementitious materials of the EBS (for instance the acidification processes resulting from biodegradation or radiolysis (in particular carbonation)) and their potential impact on properties. Results will be integrated in *later SFCs*.

Later SFCs will integrate any study about the evolution of backfill properties, if needed (Section 4.2.3.1).

*For later SFCs*, ONDRAF/NIRAS will look at the consequences of the ageing processes in cementitious materials on fluid and solute transport parameters.

ONDRAF/NIRAS will, *for later SFCs*, check the influence of waste components, their degradation products and additives (such as superplasticiser) on contaminants transport in the EBS.

*For later SFCs*, the model developed for SFC1 to assess the long-term evolution of the corrosion products layer, of the corrosion potential and of the uniform corrosion rate will be extended to include the pitting by chlorides.

ONDRAF/NIRAS has initiated studies to check whether the corrosion behaviour of the overpack is still determined by passive corrosion at high temperature (up to 130°C) (this is of importance for the disposal of MOX irradiated fuel). SFC1 will integrate the first results from these studies. The complete results will be integrated in later SFCs (Section 4.2.3.3).

ONDRAF/NIRAS will continue its investigations on gas production by degradation of Eurobitum, in particular by radiolysis and, possibly, through microbial activity. Results of this research are *not expected for SFC1*.

*After SFC1*, ONDRAF/NIRAS will check whether other salts present in Eurobitum may influence its behaviour.

**Other B waste** *For later SFCs*, the impact of the evolution of cementitious materials on waste components will be assessed.

### **The repository can be constructed, operated and closed safely** (Chapter 5)

*For later SFCs*, regarding the supercontainer fabrication, ONDRAF/NIRAS will focus on issues regarding the closure of the concrete buffer (design, composition, method to place it) and the envelope (need for, design, fabrication process). *For later SFCs*, ONDRAF/NIRAS will analyse how to fill the overpack with filling material after insertion of the primary waste packages for vitrified high-level waste or irradiated fuel. (This is an optimisation issue as frit emplacement is considered to be feasible.)

*For later SFCs*, ONDRAF/NIRAS will address issues regarding specific waste types, assessing for instance the number of waste packages that can be included in a monolith B. It will also check how to include an internal gastight overpack in the monolith B design for specific waste types if needed (*e.g.*, to avoid release of gaseous radionuclides during the operational phase).

*For later SFCs*, ONDRAF/NIRAS will assess the time required to fabricate a monolith B (primary waste package emplacement and monolith closure included).

*For later SFCs*, ONDRAF/NIRAS will identify the specific issues regarding ageing and longevity of the surface buildings. (This is an optimisation issue.)

*For later SFCs*, ONDRAF/NIRAS will estimate the impact of subsequent installation of seals in the shaft, access and disposal galleries with regard to their respective design

and construction. It will also assess the impact on the lining and floor structure of the progressive filling of a disposal gallery with disposal waste packages.

*For later SFCs*, ONDRAF/NIRAS will evaluate the impact of backfilling on the disposal waste packages and on the disposal galleries, access gallery and shafts.

*For later SFCs*, ONDRAF/NIRAS will check whether a large-scale seal (in the waste shaft) can be constructed with features similar to Boom Clay.

*For later SFCs*, ONDRAF/NIRAS will check the safety guidelines to follow during repository construction, backfill and seal installation and the requirements for the air quality and ventilation system. It will also evaluate whether the number of shafts is sufficient and estimate the maximum allowable length of the blind (dead-end) disposal galleries. Another issue to solve concerns managing the large volume of excavated spoil.

*For later SFCs*, ONDRAF/NIRAS will evaluate the impact of underground conditions on radiation backscattering and find ways to secure the surface and the underground facilities. It will estimate whether a gastight overpack is required in monolith B to ensure safety when handling gas-producing waste.

*For later SFCs*, ONDRAF/NIRAS will list the external events that can pose a risk to the repository and provide design answers for the system to be resistant to such an event.

#### **The environmental impact can be assessed** (Chapter 8)

*For later SFCs*, the model to evaluate the uplift above a repository for heat-emitting wastes will be further adapted to include knowledge gained from the PRACLAY Heater Test and from the thermal properties of layers surrounding the Boom Clay.

### **The Ypresian clays are a potential host rock** (Chapter 10)

ONDRAF/NIRAS will start studies to increase its knowledge of the geomechanical properties of Ypresian clays; properties that can be used as an approximation for the past in order to check whether the Ypresian clays in the northwest of Belgium have ever been at unstable conditions necessary for forming deformation structures. ONDRAF/NIRAS will also compile information about the tectonic, burial and denudation history of northwest of Belgium and surroundings, necessary to reconstruct the evolution of the stress state.

*For later SFCs*, it could be interesting to further characterise the organic matter of Ypresian clays, to better document the link between mineralogic clay content and grain-size distribution and/or geophysical properties, and, for the understanding of geomechanical processes, to document the fabric of the host rock and the potential occurrence of diagenetic products.

*For later SFCs*, ONDRAF/NIRAS will study the evolution through time and space of the pore water (salinisation/freshening/residence time), integrating transport properties and models. Other research areas concern the characterisation of organic matter (size, functional groups, stability as colloid) and the evaluation of the proposed synthetic pore waters.

*For later SFCs*, if necessary, ONDRAF/NIRAS will perform a few speciation analyses of radionuclides in Ypresian clays conditions.

*For later SFCs*, ONDRAF/NIRAS could perform calorimetric studies, for measuring volumetric heat capacities and their variability according to depth, collect data about the present-day temperature distribution, and increase its knowledge of the drained and undrained thermal expansion coefficients of the Ypresian clays and their sensitivity to temperature.

*Later SFCs* will include more information about the geological history of Ypresian clays and geological setting (actual stress state, displacement rates, tilting etc.).

*For later SFCs*, ONDRAF/NIRAS will integrate available data on hydrogeological setting, from all sources. It will also further refine the hydrogeological models, as these do not fit measured parameters such as hydraulic conductivities. This will require better documentation of the hydrogeological complexity of the area around Doel and Kallo (proximity of Scheldt River, transition between different groundwater systems). Furthermore, diffusive-advective transport modelling should be matched up with the observed marine and estuarine influx of marine salts, in order to better understand the freshening and salinisation history.

*For later SFCs*, ONDRAF/NIRAS will perform experiments, in order to confirm the significant self-sealing and chemical buffering capacities of the Ypresian clays (Section 10.3.1.2).

*For later SFCs*, ONDRAF/NIRAS will confirm the limited influence of natural events and processes on the stability of Ypresian clays (Section 10.3.2.1).

### **13.3 RD&D to launch during the *siting process or after site selection* (beyond SFC1)**

This section groups a few RD&D fields to launch during the *siting process or after site selection* (beyond SFC1).

*During the siting process*, ONDRAF/NIRAS will perform detailed characterisation of potential sites for disposal in Boom Clay or Ypresian clays, and will, among others:

- refine and confirm the depth of the base and top of the host formation at the investigated sites;
- refine the characterisation of horizontal distribution of some septaria layers (for Boom Clay only);
- refine the lateral continuity at small scale (layers that can be differentiated) among others by comparing available core information and geophysical logs;
- further characterise the vertical layers in terms of, among others, granulometry and mineralogy;
- further characterise the vertical and horizontal variability of density and water content.

ONDRAF/NIRAS will follow up technological watch on possible conflicts of use. *During the siting process*, ONDRAF/NIRAS will assess the consequences of foreseeable human actions in the context of conflict of use.

*After site selection*, ONDRAF/NIRAS will check the vertical variability of the hydraulic conductivity at the chosen site.

### 13.4 RD&D for confidence building

This section groups the RD&D carried out for *confidence building*: the knowledge is sufficient for the purpose (current stage of the programme), but further RD&D may reduce remaining uncertainties, provide multiple lines of evidence and/or complete the assessment basis.

#### **ONDRAF/NIRAS develops an approach for the development of a geological repository ensuring safety and feasibility** (Chapter 2)

*For confidence building*, ONDRAF/NIRAS will continue its active involvement in the European platform IGD-TP, in the NEA (through the Integration Group for the Safety Case (IGSC), where best practices for the development of safety cases are collected, discussed and adopted), and in the IAEA (to follow up methodological developments and international guidance).

#### **The geological barrier can be characterised** (Section 3.3)

*For confidence building*, ONDRAF/NIRAS will further refine the understanding of some observed discontinuities, such as the sub-vertical joints in outcrop areas.

*For confidence building*, ONDRAF/NIRAS will pursue research on Boom Clay microstructure (e.g., characterisation in 3 dimensions of the lateral and vertical variability of pore size, distribution, structure and connectivity of the porosity) as this allows linking Boom Clay properties at macroscopic scale with the microstructure.

*For confidence building*, ONDRAF/NIRAS will refine the geochemical model of the pore water composition in Mol, focussing on site occupancies by cations, based on, among others, additional *in-situ* measures of pH and  $E_h$ .

*For confidence building*, ONDRAF/NIRAS will start migration experiments on a few radionuclides not yet studied to confirm their expected migration behaviour and their sorting in groups of elements with similar migration and retention behaviour under Boom Clay present-day geochemical conditions. ONDRAF/NIRAS follows up the evolution of thermochemical databases at an international level. It will update MOLDATA, if necessary. It will assess the impact of colloids (in particular of organic colloids) on the solubility of some elements not yet studied.

*For confidence building*, ONDRAF/NIRAS wants to refine the understanding of the retention phenomena of radionuclides and chemical contaminants by Boom Clay. It will integrate the available knowledge of interactions between radionuclides and the various components of Boom Clay and perform additional batch experiments. The experiments, first with pure phases and then with Boom Clay, enable investigation into whether the component additivity approach can be used in thermodynamic models, the final aim being to develop a thermodynamic sorption model for Boom Clay. ONDRAF/NIRAS also pursues the long-term migration experiments (e.g., CP1 and TRIBICARB-3D).

**The environment can be characterised** (Section 3.4)

*For confidence building*, ONDRAF/NIRAS will pursue its technological watch on seismic monitoring and follow up the development of knowledge of geological settings on the Western European scale.

**The evolution of the disposal system due to changes in its environment can be bounded** (Section 4.2.1)

ONDRAF/NIRAS will monitor the evolution of the knowledge basis about the climate changes. It will reassess results from previous projects (such as the BIOCLIM project) in the light of current knowledge (e.g., carbon cycle).

*For confidence building*, ONDRAF/NIRAS will follow up potential uses of the Campine underground as this might play a role during the siting process. It will follow up the evolution of human interest in deep aquifers, development of pumping technology and pumping activity (number and depth of boreholes, pumping rate, etc.). It will also check future interest in coal and coal bed methane extraction, in geothermy, and in gas storage in deep geological reservoirs.

**The perturbations of Boom Clay due to excavation, construction, operation and the post-closure evolution of the repository can be bounded** (Section 4.2.2)

*For confidence building*, ONDRAF/NIRAS will investigate the localisation mechanisms occurring in the clay during excavation, linking these to the observed fracture patterns in the EDZ and to the anisotropy of mechanical stresses and mechanical properties.

*For confidence building*, ONDRAF/NIRAS will assess the consequences of the alkaline plume on the hydro-mechanical properties of Boom Clay. It will analyse the porosity changes in the zone affected by the alkaline plume and the properties of the interface EBS/clay.

*For confidence building*, ONDRAF/NIRAS will continue to follow up the development of monitoring techniques. It will further develop its monitoring strategy (including consideration of when/where measurements need to be conducted, for how long, and how monitoring will assist in decision-making), with societal input to identify potential stakeholder requirements for monitoring. It will also define the monitoring strategy to be followed (what will be measured at which stage in the disposal programme) and the way to implement it. Available results will be integrated in SFC1 and subsequent SFCs.

**The evolution of the wastes with time can be bounded (BC)** (Section 4.2.3.4)

**Eurobitum** *For confidence building*, ONDRAF/NIRAS will pursue confirmation experiments on Eurobitum. They aim, among other things, to confirm that the upscaling hypotheses used in calculations are valid:

- ONDRAF/NIRAS will continue to characterise the swelling of Eurobitum and the release of salts in the range of conditions expected in a repository;

- ONDRAF/NIRAS will continue to investigate the leaching of organic molecules due to the chemical and radiolytic degradation of Eurobitum and other products and characterise the organic degradation products.
- ONDRAF/NIRAS will also start a large-scale experiment (whose *results are expected in decades*) to confirm that the knowledge gained from small-scale laboratory tests can be transposed to the behaviour of Eurobitum waste at the scale of a disposal gallery.

### **The Ypresian clays are a potential host rock** (Chapter 10)

ONDRAF/NIRAS will follow up current studies on the geological setting of Ypresian clays and integrate them in the SFCs (Section 10.2.4).

ONDRAF/NIRAS will pursue its technological watch on the long-term stability of Ypresian clays (Section 10.3.2.1).

ONDRAF/NIRAS will follow up potential uses of the northwest of Belgium underground as this might play a role during the siting process. It will follow up the evolution of human interest in deep aquifers, development of pumping technology and pumping activity (number and depth of boreholes, pumping rate, etc.). It will also check future interest in coal and coal-bed methane extraction, in geothermy, and in gas storage in deep geological reservoirs (Section 10.3.2.1).

ONDRAF/NIRAS will start migration experiments on a few radionuclides not yet studied to confirm their expected migration behaviour in Ypresian clays and their sorting in groups of elements with similar migration and retention behaviour.





## **Annexes**



## A1 Current Safety and Feasibility Statements

### We have confidence in the long-term safety

Indeed,	The system is known
Indeed,	The system components can be characterised
Indeed,	The conditioned wastes can be characterised
and,	The other parts of the engineered barrier system can be characterised
and,	The geological barrier can be characterised
and,	The environment can be characterised
and,	The evolution can be bounded
Indeed,	Siting and design favour stability
Indeed,	Limited number of drivers
and	Robust features
and	For those drivers than cannot be avoided, the changes in properties and conditions can be bounded
indeed	The evolution of the disposal system due to changes in its environment can be bounded
and	The evolution of Boom Clay due to repository excavation, operation and closure can be bounded
and	The evolution of the EBS with time can be bounded
and,	The safety functions that have been defined are relied upon
Indeed,	Isolation of the system is ensured during the period of concern
Indeed,	Overburden above the system remains sufficient
and,	Human intrusion is unlikely
and,	Containment is ensured during at least the thermal phase
Indeed,	No loss of integrity
and,	Rate of radionuclides transport is low and some radionuclides are delayed
Indeed,	The release rates from the waste forms are limited
Indeed,	Waste forms have a limited degradation rate
and	The solubility of many radionuclides is limited
and,	Water flow is limited
Indeed,	No permanent bypass
and	Limited driving forces
and	Limited availability of mobile water
and,	Transport is retarded for many radionuclides
Indeed,	Host formation displays sorption capacity for many radionuclides
and	Dissolved NOM does not excessively reduce the retardation
and,	The performance of the disposal system meets the requirements
Indeed,	The radiological impact meets the regulatory requirements
and,	The environmental impact meets the regulatory requirements
and,	The disposal system meets conditions arising from the consultations and included in the technical solution
and,	The remaining/residual uncertainties are identified and manageable (by RD&D, conservative assumptions, scenarios, etc.). The irreducible uncertainties do not impact the overall knowledge, understanding and safety of the disposal system.

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**FS The proposed disposal system can be constructed, operated and progressively closed taking into account operational safety issues and with adequate funding**

<b>Indeed,</b>	<b>FS 1 The engineering practicability of the disposal system is proven</b>
Indeed,	FS 1.1 The disposal waste packages can be fabricated
Indeed,	FS 1.1.1 The supercontainer can be fabricated
and	FS 1.1.2 The monolith B can be fabricated
and	FS 1.1.3 The post-conditioning facilities for category B&C waste can be constructed, operated, decommissioned and dismantled
and,	FS 1.2 The repository for category B&C waste can be constructed
Indeed,	FS 1.2.1 The shafts can be constructed
and,	FS 1.2.2 The category B disposal area can be constructed
indeed	FS 1.2.2.1 The access gallery and the crossings with the disposal galleries of the category B disposal area can be constructed
and	FS 1.2.2.2 The disposal galleries for category B waste can be constructed
and,	FS 1.2.3 The category C disposal area can be constructed
indeed	FS 1.2.3.1 The access gallery and the crossings with the disposal galleries of the category C disposal area can be constructed
and	FS 1.2.3.2 The disposal galleries for category C waste can be constructed
and,	FS 1.3 The repository for category B&C waste can be operated
Indeed,	FS 1.3.1 The primary waste packages can be removed, handled and transported from interim storage facilities to the post-conditioning facility
and,	FS 1.3.2 The disposal waste packages can be handled and transported from the post-conditioning facility to their final destination in the disposal galleries including reversibility of these operations
and,	FS 1.4 The repository for category B&C waste can be closed
Indeed,	FS 1.4.1 The repository for category B&C waste can be backfilled
and,	FS 1.4.2 The repository for category B&C waste can be sealed
and,	FS 1.5 The performance of the disposal system can be monitored
<b>and</b>	<b>FS 2 The safety of workers, the public and the environment can be guaranteed during the operational phase</b>
Indeed,	FS 2.1 The non-radiological risks associated with a normal operating scenario can be mastered
and,	FS 2.2 The radiological risks associated with a normal operating scenario can be mastered
and,	FS 2.3 The risks resulting from accident scenarios and external events can be mastered
and,	FS 2.4 Fissile materials can be handled appropriately from a security, safeguards and criticality perspective
<b>and</b>	<b>FS 3 The costs for the construction, operation and closure of the repository can be covered</b>
Indeed,	FS 3.1 The costs for construction, operation and closure of the disposal facility for category B&C waste, including decommissioning of the site surface installations, have been evaluated
and,	FS 3.2 Waste tariffs and current funding mechanisms are adequate to cover the required costs taking into account escalation
<b>and</b>	<b>FS 4 The remaining/residual uncertainties are identified and manageable (by RD&amp;D, modification of design, etc.). They do not impact the feasibility and safety of the system</b>

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## **A2      Origins and characteristics of B&C waste**

B&C waste comes from a diverse range of origins and has various characteristics. The table hereafter gives an estimate, at the end of 2010, of existing and planned B&C waste (mainly within the scope of the 40-year operation of the seven current nuclear commercial reactors and their decommissioning) (ONDRAF/NIRAS, 2011b). It does not cover the modifications that would result from the transfer of waste between categories A and B, those that would result from the declaration of enriched fissile materials and plutonium-bearing materials as waste, and those relating to potential modifications in the inventory of category B radium-bearing waste. This table presents the waste inventory per class of waste.

## Origin and characteristics of wastes of categories B and C

Production and provisions at end 2010

Origin	Category	Class	Description	Matrix	Primary package (PP) Number	Type	
<b>a - Fuel fabrication</b>							
a-1	B	LAGAL	Low-level alpha-bearing solid waste	cement	<b>1090</b>	steel, 400 litres	
<b>b - Electricity production</b>							
<i>b1 - Nuclear power plants</i>							
Operation	b1-1	B	MAGAL	Tihange, thermocompacted resins	cement	<b>440</b>	steel, 400 litres
	b1-2	B	M / L AGAL	Doel/Tihange, various medium- and low-level solid waste	cement	<b>40</b>	steel, 400 litres
	b1-3	B	LAGAL	Doel/Tihange, various low-level solid waste	cement	<b>47</b>	reinforced concrete, 1000 litres
	b1-4	B	LAGAL	Doel/Tihange, various low-level solid waste	cement	<b>24</b>	reinforced concrete, 1600 litres
Dismantling	b1-5	B	MAGAL	Doel/Tihange, solid components of reactor cores	--	<b>850</b>	cast iron, MOSAIK, 1300 litres
<i>b2 - Irradiated fuel from nuclear power plants</i>							
Reprocessing (1)	b2-1	C	ZAGALC	Doel1/2 and Tihange 1, main dissolution stream of fuel reprocessing at The Hague	glass	<b>387</b>	steel, CSD-V, 180 litres
	b2-2	B	HAGALC2	Doel1/2 and Tihange 1, compacted structural waste of fuel reprocessing at The Hague	--	<b>432</b>	steel, CSD-C, 180 litres
	b2-3	B	HAGALC3	Doel1/2 and Tihange 1, secondary streams of fuel reprocessing at The Hague	glass	<b>62</b>	steel, CSD-B, 180 litres
Possible further reprocessing of irradiated fuel assemblies (1)	b2-4	C	ZAGALC	All power reactors, main dissolution stream of fuel reprocessing at The Hague	glass	<b>2828 (2)</b>	steel, CSD-V, 180 litres
	b2-5	B	HAGALC2	All power reactors, compacted structural waste of fuel reprocessing at The Hague	--	<b>3760 (2)</b>	steel, CSD-C, 180 litres
or	b2-6	C	ZAGALS	MOX irradiated fuel assemblies (all unloaded today)	(3)	<b>144</b>	steel box, 275 litres
Irradiated fuel assemblies	b2-7	C	ZAGALS	UOX irradiated fuel assemblies	(3)	<b>10250</b>	steel box, 200 to 325 litres
<b>c - Research, development and nuclear pilots - Waste management</b>							
<i>c1 - Irradiated fuel from research reactors: not reprocessed</i>							
	c1-1	C (3)	ZAGALS (3)	BR3 and VENUS irradiated fuel (UOX and MOX)	(3)	<b>85 (3)</b>	(3)
	c1-2	B	MAGAL	THETIS (UOX) irradiated fuel and fresh UOX powder	cement	<b>7</b>	steel, 400 litres
	c1-3	B	LAGAL	BR1 irradiated fuel, uranium metal	(3)	<b>70 (3)</b>	(3)
<i>c2 - Irradiated fuel from research reactors: reprocessing abroad</i>							
	c2-1	C	ZAGALC	Main dissolution stream of BR2 fuel reprocessing at The Hague	glass	<b>5</b>	steel, CSD-V, 180 litres
	c2-2	B	HAGALC2	Compacted structural waste of BR2 fuel reprocessing at The Hague	--	<b>6</b>	steel, CSD-C, 180 litres
	c2-3	B	MAGALD	Main dissolution stream of BR2 fuel reprocessing at Dounreay	cement	<b>123</b>	steel, 500 litres
<i>c3 - Irradiated fuel reprocessed at the Eurochemic plant</i>							
	c3-1	B	HAGALP1	Main dissolution effluents from Eurochemic reprocessing of high enriched fuel, conditioning in Pamela	glass	<b>934</b>	steel, 60 litres
	c3-2	B	HAGALP1	Main dissolution effluents from Eurochemic reprocessing of low enriched fuel, conditioning in Pamela	glass	<b>467</b>	steel, 60 litres
	c3-3	B	HAGALP1	Main dissolution effluents from Eurochemic reprocessing of low enriched fuel, conditioning Pamela VITROMET	glass / lead	<b>100</b>	steel, 60 litres
	c3-4	B	HAGALP2	Main dissolution effluents from Eurochemic reprocessing of high enriched fuel, conditioning in Pamela	glass	<b>702</b>	steel, 150 litres
	c3-5	B	HAGALP3	Eurochemic undissolved residues (fuel, claddings, structures)	cement	<b>115</b>	steel, 150 litres
	c3-6	B	MAGALE	Eurochemic medium-level effluents, conditioning in Eurobitum	bitumen	<b>11487</b>	steel, 220 litres

c - Research, development and nuclear pilots - Waste management (continued)							
<i>c3 - Irradiated fuel reprocessed at the Eurochemic plant</i>							
c3-7	B	MAGALE	Eurochemic medium-level solid waste, conditioning in Eurobitum	bitumen	82	steel, 220 litres	
c3-8	B	MAGALE	Eurochemic medium-level solid waste, high reactivity metal, conditioning in Eurobitum	bitumen	17	steel, 200 litres	
c3-9	B	MAGALE	Eurochemic medium-level effluents, conditioning in Eurobitum	bitumen	9	steel, 330 litres	
<i>c4 - Operation and dismantling</i>							
c4-1	B	HAGALBE	Beryllium metal and stainless steel components, BR2 reactor	sand / cement	17	steel, 150 litres	
c4-2	B	MAGALBE	Beryllium metal components, BR2 reactor	sand / cement	41	steel, 400 litres	
c4-3	B	MAGALE	Medium-level effluents, various origins (4), conditioning in Eurobitum	bitumen	1950	steel, 220 litres	
c4-4	B	MAGAL	Medium-level solid waste, various origins (4), conditioning in Pamela or HRA Solarium	cement	400	steel, 400 litres	
c4-5	B	M / L AGAL	Medium- and low-level effluents, various origins (4), conditioning in Mummie	bitumen	140	steel, 400 and 220 litres	
c4-6	B	MAGAL	Operational and dismantling waste of the Pamela vitrification unit, medium level	cement	277	steel, 200 litres	
c4-7	B	MAGAL	Medium-level solid waste from BR3 dismantling and BR2 operation	cement	67	steel, 400 litres	
c4-8	B	MAGAL	Medium-level effluents	(3)	1350 (3)	steel, 400 litres	
c4-9	B	MAGAL	Medium-level solid waste	(3)	100 (3)	steel, 400 litres	
c4-10	B	LAGAL	Eurochemic low-level solid waste, conditioning in 123	cement	52	steel / cement, 2200 litres	
c4-11	B	LAGAL	Eurochemic and SCK•CEN low-level solid waste, conditioning in 123	cement	167	steel, 400 litres	
c4-12	B	LAGAL	Low-level solid waste, various origins (4), conditioning in Pamela or HRA Solarium or CILVA	cement	1230	steel, 400 litres	
c4-13	B	LAGAL	Low-level solid waste, various origins (4), conditioning in HRA Solarium	cement	21	steel / cement, 2500 / 3300 litres	
c4-14	B	LAGAL	Low-level solid waste, various origins (4), conditioning in alpha-room	bitumen	1650	steel, 220 litres, overpacked	
c4-15	B	LAGAL	Low-level solid waste, various origins (4), conditioning in alpha-room, further reconditioned	bitumen / (cement)	109	steel, 220 litres, overpacked	
c4-16	B	LAGAL	Low-level solid waste and compacted ashes, various origins (4)	bitumen	571	steel, 220 litres, overpacked	
c4-17	B	LAGAL	Low-level waste	(3)	600 (3)	steel, 400 litres	
c4-18	B	LAGAL	Low-level waste, characterization underway	(3)	32	steel, 600 litres	
c4-19	B	RAGAL (5)	Dismantling waste of the SCK•CEN "Actinium" programme	cement	72	steel, 400 litres, overpacked	
c4-20	B	RAGAL (5)	Solid radium-bearing waste, conditioning in HRA Solarium	cement	160	steel, 430 litres	
c4-21	B	RAGAL (5)	Radium-bearing effluents, conditioning in HRA Solarium	cement	120	steel, 430, 1400 and 3300 litres	
c4-22	B	RAGAL (5)	Radium-bearing waste, conditioning in CILVA	cement	3200	steel, 400 litres	
c4-23	B	RAGAL (5)	Radium-bearing effluents, conditioning in Mummie	bitumen	636	steel, 400 litres	
c4-24	B	RAGAL (5)	Radium-bearing waste	(3)	200 (3)	steel, 400 litres	
<b>d - Others</b>							
d-1	B	MAGAL	Medium-level effluents (mainly from IRE)	(3)	150 (3)	steel, 400 litres	
d-2	B	M / L / RAGAL (5)	Radioactive sources, lightning conductors, radium needles, smoke detectors, ..., conditioning in CILVA	cement	800	steel, 400 litres	
d-3	B	RAGAL (5)	Dismantling waste of the radium production unit, Olen site	cement	222	steel, 400 litres, overpacked	
d-4	B	RAGAL (5)	Radium-bearing waste from the Belgian army	sand / cement	35	steel, 400 litres	

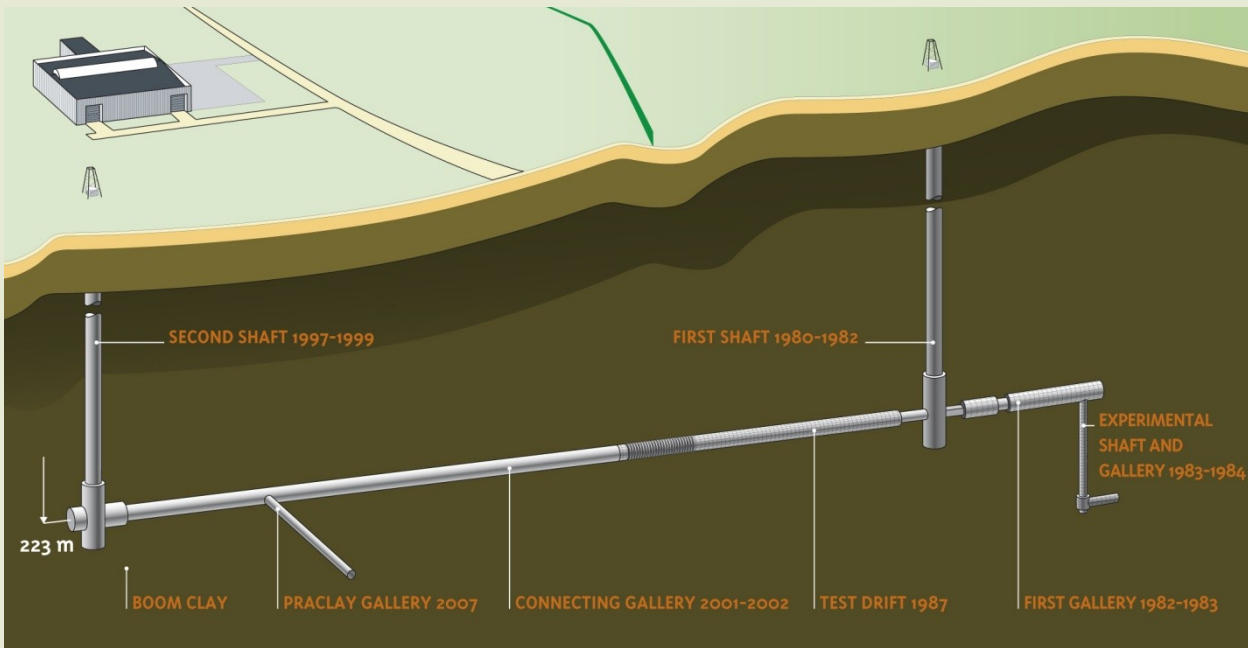
■ The production of primary packages is completed.

■ The type of waste depends on whether reprocessing resumes or is abandoned.

- (1) The extracted uranium and plutonium are valued.
- (2) This information will be adapted based on production feedback, as follows: 3732 PP type CSD-V and 3153 PP type CSD-C.
- (3) Treatment / conditioning still to be confirmed.
- (4) Contains mainly wastes from origin "c"; contains some wastes from other origins.
- (5) Radium-bearing waste will be the subject of a dedicated plan, which might impact the current category B waste inventory. The radium-bearing waste present at the Umicore site is presently not part of this inventory.



### A3 History of HADES URF construction



Freezing the soil with a view to constructing the first shaft



Excavating and fitting the lining of the first HADES URF gallery



First HADES URF gallery



Fitting the lining at the end of the second gallery, called "Test Drift"



Constructing the second shaft



Constructing the chamber at the base of the second shaft



Constructing the Connecting gallery using a tunnel boring machine



Connecting gallery



Sealing the PRACLAY experiment

**Figure 78** – History of the construction of the HADES underground research facility. HADES is used for fundamental *in-situ* research experiments, long-term confirmation experiments and semi-industrial or industrial demonstration experiments. HADES URF is also a communication tool: every year, the underground laboratory is visited not only by Belgian and foreign specialists, but also by groups of people from a wide range of backgrounds (sources: SCK•CEN and EURIDICE).

## A4 PRACLAY “demonstration and confirmation experiments”

Started in 1995, the PRACLAY project aims to demonstrate (full-scale) that the implementation of a geological repository containing heat-emitting waste is feasible in Boom Clay. More specifically, the PRACLAY “Demonstration & confirmation experiments” pursue three goals (EURIDICE, 2011):

- To demonstrate the feasibility of underground constructions in Boom Clay;
- To demonstrate the feasibility of the disposal concept for high-level waste in Boom Clay;
- To confirm and expand knowledge of the thermo-hydro-mechanical (-chemical) behaviour of Boom Clay and the gallery lining.

Experiments are performed both *in-situ* and on surface, with support of European projects (Table 31) and in collaboration with several universities:

- *In-situ* demonstration experiments focused on excavation techniques and construction work. The excavation of the Connecting gallery using a tunnelling machine, for example, demonstrated the feasibility of constructing galleries on an industrial scale. In 2007, the excavation (using the tunnelling technique combined with an expanded concrete segmental lining) of the PRACLAY gallery, with a diameter of 2,5 metres, perpendicular to the Connecting gallery, was an important advance in terms of feasibility, because it demonstrated the possibility of building gallery crossings. Most of the demonstration experiments are now finished.
- *In-situ* confirmation experiments focus on confirming that the heat output from the waste will not damage the clay surrounding the repository. The Heater test in the PRACLAY gallery is the main experiment in this regard. This test will be used to simulate the heat production of category C waste on a large scale. In this way, researchers can observe and analyse the thermo-hydro-mechanical and chemical behaviour of the Boom Clay after excavation and subsequent large-scale heating. For this purpose, part of the PRACLAY gallery (30 metres) is sealed and will be heated for a period of 10 years at a temperature of 80°C at the point of contact between the gallery lining and the clay. After design and installation of the seal (2007 – 2010), the heater system was installed in 2010 and 2011. The exact timing of the heater switch-on will be determined by the seal performance (swelling pressure and permeability evolution of the bentonite ring in the seal structure).
- On-surface experiments focus on the engineered parts of a repository. They include laboratory tests to characterise the different components and their interactions. Tests are currently performed on different scales to demonstrate the feasibility of the construction of a supercontainer.

**Table 31** – Main experiments within the PRACLAY project

Type of experiment	Schedule
<b><i>In-situ demonstration</i></b>	
Construction of the second shaft	Completed (1999)
Construction of the Connecting gallery	Completed (2002)
Construction of the PRACLAY gallery and of the crossing	Completed (2007)
Supporting studies: European Commission’s CLIPEX project	Completed (2003)
<b><i>In-situ experiments</i></b>	
ATLAS IV	Ongoing
FORGE (EU project)	Completed (2012)
Sealing test	Installation completed (2011) Sealing is under way
Heater test	To be switched on *
Supporting studies EDZ test (EU SELFRAC and TIMODAZ projects)	Completed (2010)
<b><i>On-surface experiments</i></b>	
OPHELIE (SAFIR2 design)	Completed (2002)
Half-scale tests (Supercontainer design)	Ongoing
Annular backfill test in ESDRED project (Supercontainer design)	Completed (2009)

\* The heater’s switch on depends on seal performance.

## A5 Lists of EU-funded and NEA projects and additional *in-situ* experiments

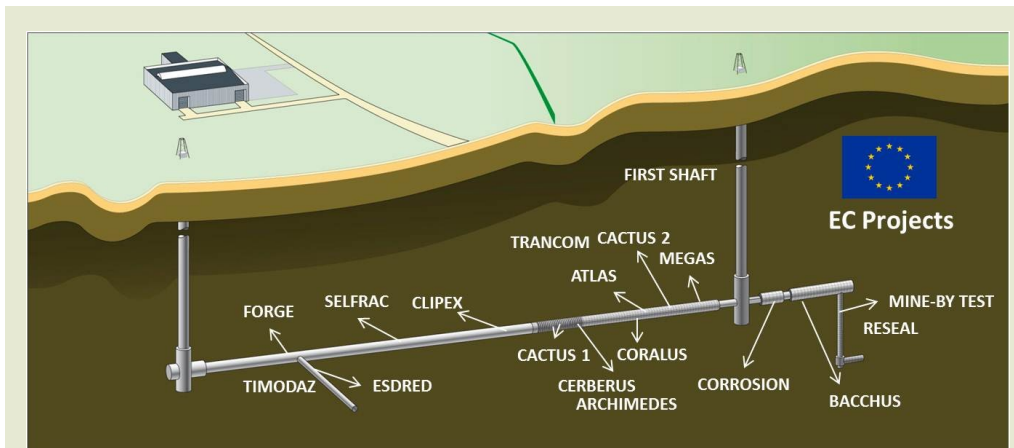
Acronym	Short description	Type of project
AMIGO (2003 – 2008)	NEA Approaches and Methods for Integrating Geological Information in the Safety Case	NEA
ARCHIMEDE-ARGILE (1991 – 1996)	Acquisition and regulation of pore-water chemistry, study of water/rock interactions and microbial activity in Boom Clay	EU
ATLAS (1992 – 1996) (1997 – 2007)	Admissible thermal loading for argillaceous storage, part of the INTERCLAY project	EU
BACCHUS (1988 – 1993)	Backfilling control experiment for high-level wastes in underground storage	EU
BACCHUS II (1991 – 1995)	Demonstration of the <i>in-situ</i> application of an industrial clay-based backfill material	EU (FP 2)
BENCHPAR	Guidance document on THM coupled processes in performance assessment	EU (FP 5)
BENIPA (2000 – 2003)	Bentonite barriers in integrated performance assessment	EU (FP 5)
BIOMOSA (2001 – 2003)	Biosphere Models for Safety Assessment of Radioactive Waste Disposals based on the Application of the Reference Biosphere Methodology	EU
CACTUS (1990 – 1993)	Characterisation of clay under thermal loading for underground storage	EU
CARBOWASTE (2008 – 2013)	Treatment and Disposal of Irradiated Graphite and other Carbonaceous Waste	EU (FP 7)
CARD (2006 – 2008)	A Co-ordination Action on Research, Development and Demonstration, Priorities and Strategies for Geological Disposal	EU (FP 6)
CATCLAY (2010 – 2014)	Processes of Cation Migration in Clayrocks	EU (FP 7)
CATSIUS CLAY (1996 – 1998)	Calculation and testing of behaviour of unsaturated clay	EU
CERBERUS (1985 – 1998)	Control Experiment with Radiation of the Belgian Repository for Underground Storage	EU
CLAYTRAC (2005 – 2009)	Natural Tracer Profiles Across Argillaceous Formations	NEA
CLIPEX (1997 – 2003)	Clay instrumentation programme for the extension of an underground research facility	EU
COBECOMA (2001 – 2003)	State-of-the-art document on the COrrOsion BEhaviour of COntainer Materials	EU (FP 5)
CORALUS (1997 – 2000) (2000 – 2003) (2004 – 2008) (2009 – 2014)	Integrated <i>in-situ</i> test on the corrosion of alpha active glass in contact with dense clay at high swelling pressure. Leaching from glass and migration in clay of radionuclides. Phase I to IV	EU
ECOCLAY (1997 – 2000) (2000 – 2003)	Effects of Cement on CLAY barrier performance	EU
ESDRED (2004 – 2009)	Engineering Studies and Demonstration of Repository Designs	EU (FP 6)

<b>Acronym</b>	<b>Short description</b>	<b>Type of project</b>
EVEGAS (1990 – 1994)	European validation exercise of gas migration models through geological media	EU
EVEREST (1991 – 1995)	Evaluation of Elements Responsible for the Effective Engaged Dose Rates Associated with the Final Storage of Radioactive Waste	EU
FEBEX (1996 – 1999) (2000 – 2004)	Full-scale Engineered Barriers EXperiment in crystalline host formation	EU (FP4&5)
FEPCAT (1998 – 2003)	Features, Events and Processes CATalogue for argillaceous media)	NEA
FIRSTNUCLIDES (2012 – 2015)	Fast / Instant Release of Safety Relevant Radionuclides from Spent Nuclear Fuel	EU (FP 7)
FIRSTSPENTFUELPA (1991 – 1995)	First performance assessment of the disposal of spent fuel in a clay layer	EU
FORGE (2009 – 2012)	Fate of repository gases. Investigation of process of gas generation and transport and their potential impact on a disposal system.	EU (FP 7)
FSC (since 2000)	Forum on Stakeholder Confidence	NEA
FUNMIG (2005 – 2008)	Fundamental Processes of Radionuclide Migration	EU (FP 6)
GASNET (2003)	A thematic network on gas issues in safety assessment of deep repositories for radioactive waste	EU
GEOVAL	Symposium, 1990, 1994 about Safety Assessment of radioactive waste repositories: validation of geosphere flow and transport models	NEA
GLAMOR (2002 – 2006)	A Critical Evaluation of the Dissolution Mechanisms of High-level Waste Glasses in conditions of Relevance for Geological Disposal	EU (FP 5)
GLASTAB (2000 – 2003)	Long-term behaviour of glass: improving the glass source term and substantiating the basic hypotheses	EU (FP 5)
INSOTEC (2011 – 2013)	(International) Socio-Technical Challenges for implementing geological disposal	EU (FP 7)
INTERCLAY (1989)	The CEC benchmark Interclay on rheological models for clays – Pilot phase	EU
INTERCLAY II (1990 – 1995)	A coordinated benchmark exercise on the rheology of clays	EU
INTESC (2005 – 2009)	International Experiences in Safety Cases for Geological repositories	NEA
INTRAVAL (1987 – 1996)	Developing Groundwater Flow and Transport Models for Radioactive Waste Disposal	NEA
MEGAS (1992 – 1997)	Modelling and experiments on gas migration in repository host rocks (under the umbrella of the PEGASUS project)	EU
MICADO (2006 – 2009)	Model uncertainty for the mechanism of dissolution of irradiated fuel in a nuclear waste repository	EU (FP 6)
MIRAGE (1986, 1989)	Migration of radionuclides in the geosphere	EU
MODERN (2009 – 2013)	Monitoring Developments for Safe Repository Operation and Staged Closure	EU (FP 7)
MODEX – REP (2000 – 2006)	Development of Hydro-mechanical Models of the Callovo-Oxfordian Argillites for the Geological Disposal of Radioactive Waste	EU (FP 5)

Acronym	Short description	Type of project
NET.EXCEL (2002 – 2004)	Network of excellence in nuclear waste management and disposal	EU (FP 5)
NF-PRO (2004 – 2007)	Understanding and Physical and Numerical Modelling of the Key Processes in the Near Field and their Coupling for Different Host formations and Repository Strategies	EU (FP 6)
PACOMA (1986 – 1990)	Performance Assessment of Geological Disposal of Medium-Level and Alpha Waste in a Clay Formation in Belgium	EU
PAGIS (1982 – 1987)	Performance Assessment of Geological Isolation Systems	EU
PAMINA (2006 – 2009)	Performance Assessment Methodologies in Application to Guide the Development of the Safety Case	EU (FP 6)
PHEBUS (1992 – 1995)	Phenomenology of hydrological transfer between atmosphere and underground storage	EU
PHYMOL (1997 – 1999)	Palaeohydrogeological study of the Mol site	EU
PROGRESS (1996 – 1999)	Research into gas generation and migration in radioactive waste repository systems	EU
RADWASTOM3 (1986 – 1989)	<i>In-situ</i> characterisation of the behaviour of deep clay layers (performed by Andra)	EU (FP 1)
RED-IMPACT (2004 – 2007)	Impact of Partitioning, Transmutation and Waste Reduction Technologies on the Final Waste Disposal	EU (FP 6)
RESEAL (1996 – 1999)	A large-scale <i>in-situ</i> demonstration test for repository sealing in an argillaceous host formation	EU
RESEAL II (2000 – 2005)	A large-scale <i>in-situ</i> demonstration test for repository sealing in an argillaceous host formation – Phase II	EU (FP 5)
RK&M (2011 – 2014)	Preservation of Records, Knowledge and Memory Across Generations	NEA (RWMC)
SELFRACT (2002 – 2003)	Fractures and Self-healing within the Excavation Disturbed Zone in Clays	EU (FP 5)
SFS (2001 – 2004)	Irradiated fuel stability under repository conditions	EU (FP5)
SMARAGD (2008)	Study of mineral alterations of clay barriers used for radwaste storage and its geological disposal	EU (FP 6)
SOMOS (2001 – 2004)	Safety and Operational Monitoring of Nuclear Waste Repositories with Fibre Optic Sensing Systems	EU (FP 5)
Sorption (1997 – ongoing)	Study of the potential of chemical thermodynamic models for improving representation of sorption phenomena in the long-term safety analysis of radioactive waste repositories	NEA
SPA (1996 – 1999)	Irradiated fuel Performance Assessment	EU
SPIN (1998 – 2002)	Testing of safety and performance indicators	EU (FP 5)
TDB (1984 – 2014)	Thermochemical Database	NEA
TIMODAZ (2006 – 2010)	Thermal Impact on the Damaged zone around a radioactive waste disposal in clay host formations	EU (FP 6)
TRANCOM-CLAY (1996 – 1998)	Transport of radionuclides due to complexation with organic matter in clay formations	EU
TRANCOM-II (2000 – 2003)	Migration Case Study: Transport of radionuclides in a reducing Clay Sediment	EU (FP 5)

**Table 32** – *In-situ* experiments not in the frame of EU or NEA projects

Name of the experiment	Description
ATLAS III (2007 – 2008) and IV (2011 – ongoing)	Admissible thermal loading for argillaceous storage
Cemented Waste Forms (1998)	Study degradation processes of cements in contact with Boom Clay, in function of time and temperature
CP1 (1986, ongoing)	Concrete Plug 1 experiment, Migration <i>in-situ</i> , part of INTRAVAL project
MINE-BY-TEST	A long-term monitoring programme around an underground structure in the Boom Clay
MORPHEUS (2001)	Mobile organic matter and pore water extraction in HADES
OPHELIE mock-up (1997-2002)	On surface Preliminary Heating simulation experimenting later instruments and equipment (instrumented mock-up of the PRACLAY experiment, built in the HADES-PRACLAY hall, in Mol)
ORPHEUS (2000, piezometer still in use)	<i>In-situ</i> study of the geochemistry of undisturbed Boom Clay pore water (online pH, Eh)
PEGASUS (2004, piezometer still in use)	Partial pressure Evolution of dissolved GASEs in real Underground Situations
PRACLAY (1995 – ongoing)	Preliminary demonstration test for clay disposal of high-level radioactive waste (see Annex A4)
PRETEL (1994 – 2004)	PRE-Tensioned lining (design and test of a new lining system allowing micro-tunnelling in cohesive soils like Boom Clay).
TRIBICARB-3D (1995 – ongoing)	TRItium and BICARBonate migration experiment, Migration <i>in-situ</i>



**Figure 79** – Localisation of EU projects in HADES URF.



## A6 Acronyms

Andra	<i>Agence nationale pour la gestion des déchets radioactifs</i> (National Agency for Radioactive Waste Management) (France)
BC	Boom Clay
CEA	<i>Commissariat à l'énergie atomique et aux énergies alternatives</i> (Atomic Energy and Alternative Energies Commission) (France)
CoRWM	Committee on Radioactive Waste Management (United Kingdom)
COVRA	<i>Centrale Organisatie Voor Radioactief Afval</i> (Central Organisation for Radioactive Waste) (The Netherlands)
CSD-B	Standard container for secondary streams from reprocessing equipments produced at La Hague embedded in a glass matrix
CSD-C	Standard container for compacted waste (without matrix) produced at La Hague
CSD-V	Standard container for vitrified high-level waste produced at La Hague embedded in a glass matrix
EBS	Engineered barrier system, the whole of engineered barriers of a multi-barrier system, thus excluding the natural barrier
EIA	Environmental Impact Assessment
EIG	Economic Interest Grouping
EURIDICE	European Underground Research Infrastructure for Disposal of nuclear waste In Clay Environment, economic interest grouping created by ONDRAF/NIRAS and SCK•CEN in 1995, principally to manage the HADES URF
FANC	Federal Agency for Nuclear Control ( <i>Federaal Agentschap voor Nucleaire Controle / Agence fédérale de Contrôle nucléaire</i> ) (Belgium)
HADES URF	High-Activity Disposal Experimental Site (Underground research facility in Mol)
IAEA	International Atomic Energy Agency (United Nations)
ICRP	International Commission on Radiological Protection
MOX	Mixed-Oxide Fuel
Nagra	<i>Nationale Genossenschaft für die Lagerung radioaktiver Abfälle</i> (National Cooperative for the Storage of Radioactive Waste) (Switzerland)
NEA	OECD Nuclear Energy Agency
OECD	Organisation for Economic Cooperation and Development

ONDRAF/NIRAS	<i>Organisme national des déchets radioactifs et des matières fissiles enrichies / Nationale instelling voor radioactief afval en verrijkte splijtstoffen</i> (National Organisation for Radioactive Waste and Enriched Fissile Materials) (Belgium)
ON-Doel, ON-Kallo	Exploratory boreholes drilled by ONDRAF/NIRAS respectively in Doel and Kallo. The Doel–Kallo area is the reference zone for RD&D in Ypresian clays
RD&D	Research, Development and Demonstration
RWMC	Radioactive Waste Management Committee, main body advising the NEA member countries in the area of radioactive waste management
SAFIR	Safety Assessment and Feasibility Interim Report (1989)
SAFIR2	Safety Assessment and Feasibility Interim Report 2 (2001)
SCK•CEN	<i>Studiecentrum voor Kernenergie / Centre d'Etudes de l'Energie Nucléaire</i> (Nuclear Research Centre) (Belgium)
SEA	Strategic Environmental Assessment
SFC	Safety and Feasibility Case
SKB	Swedish Nuclear Fuel and Waste Management Company (Sweden)
tHM	ton Heavy Metal
THM	thermo-hydromechanical
UOX	Uranium-Oxide Fuel
VHLW	Vitrified High-Level Waste
VITO	Vlaamse instelling voor technologisch onderzoek (Belgium)
WIPP	Waste Isolation Pilot Plant (United States of America)
YC	Ypresian clays

## A7 References

(Aerts, 2008) Aerts S., *Use of inhibitors to prevent bacterial artefacts in experiments*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-65, 2008

(Aerts, 2009) Aerts S., *Effect of Geochemical Conditions on Bacterial activity*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-75, 2009

(Aerts et al., 2009b) Aerts S., Jacops E. and Dewel A., *Microbial activity around the Connecting Gallery*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-61, 2009

(Aertsens et al., 2005) Aertsens M., Dierckx A., Put M., Moors H., Janssen K., Van Ravestyn L., Van Gompel Marc, Van Gompel Maria and De Cannière P., *Determination of the hydraulic conductivity, the product  $\eta R$  of the porosity  $\eta$  and the retardation factor  $R$  and the apparent diffusion coefficient  $D_p$  on Boom Clay cores from the Mol-1 drilling, Final report for Task 2-7*, Restricted contract report of the Belgian Nuclear Research Centre SCK•CEN R-3503, 2005

(Aertsens et al., 2005b) Aertsens M., Dierckx A., Put M., Moors H., Janssen K., Van Ravestyn V., Van Gompel M., Van Gompel M. and De Cannière P., *Determination of the Hydraulic conductivity,  $\eta R$  and the apparent diffusion coefficient on Ieper Clay and Boom Clay cores from the Doel-1 and Doel-2b drillings*, Restricted contract report of the Belgium Nuclear Research Centre SCK•CEN R-3589, 2005

(Aertsens et al., 2008) Aertsens M., De Cannière P., Lemmens K., Maes N. and Moors H., *Overview and consistency of migration experiments in clay*, Physics and chemistry of the Earth 33, pp. 1019-1025, 2008

(Aertsens, 2011) Aertsens M., *Migration in Clay: experiments and models*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-165, 2011

(Aertsens, 2013) Aertsens M., *Overview of migration experiments in the HADES Underground Research Facility*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-164, 2013

(Alonso et al., 1990) Alonso E.E., Gens A. and Josa A., *A constitutive model for partially saturated soils*, Géotechnique, 40(3), pp. 405-430, 1990

(Altmann et al., 2012) Altmann S., Tournassat C., Goutelard F., Parneix J-C., Gimmi T. and Maes N., *Diffusion-driven transport in clayrock formations*, Applied Geochemistry, Vol. 27, Issue 2, pp. 463-478, 2012

(Andra, 2005) Andra, *Dossier 2005 Argile – Tome Evolution phénoménologique du stockage géologique*, Collection Les Rapports, Andra, 2005

(Andra, 2005b) Andra, *Dossier 2005 Argile – Synthesis: Evaluation of the feasibility of a geological repository in an argillaceous formation*, Andra Report Series, Andra, 2005

(Andra, 2005c) Andra, *Référentiel des matériaux d'un stockage de déchets à haute activité et à vie longue/Tome 2: Matériaux cimentaires*, Andra, 2005

(Antea-BG, 2010) Antea-BG, *B&C Techno Project - LOT 2 Task 2-140: Feasibility to Construct Large Shafts*, Antea-BG Report to ONDRAF/NIRAS, A59018 First Draft, Version 1, 2010

(Angst et al., 2009) Angst U., Elsener B., Larsen C. K. and Vennesland Ø., *Critical chloride content in reinforced concrete — A review*, Cement and Concrete Research 39, pp. 1122–1138, 2009

(ARCHIMEDE-ARGILE, 1996) Griffault, L., Merceron, T., Mossmann, J. R., Neerdael, B., De Cannière, P., Beaucaire, C., Daumas, S., Bianchi, A. and Christen, R. *Acquisition et régulation de la chimie des eaux en milieu argileux pour le projet de stockage de déchets radioactifs en formation géologique, Projet « Archimède argile », Rapport final*, EUR 17454 FR, 1996

(Areias et al., 2010) Areias L., Craeye B., De Schutter G., Van Humbeeck H., Wacquier W., Villers L. and Van Cotthem A., *Half-scale test: an important step to demonstrate the feasibility of the Belgian supercontainer concept for disposal of HLW*, Proceedings of the 13<sup>th</sup> International Conference on Environmental Remediation and Radioactive Waste Management, ICEM2010, Tsukuba, Japan, ICEM2010-40119, 3-7 October 2010

(Areias et al., 2011) Areias L., Van Humbeeck H., Gens R., Van Cotthem A. and Villers L., *First Half-Scale Test, Construction and Test Results*, Final report, Rev. 0, Project nr EWETOPDEU-041, ESV EURIDICE GIE and ONDRAF/NIRAS, 2011

(Areias et al., 2013) Areias L., Gens R., Van Marcke P., Van Humbeeck H., Villers L., Van Cotthem A., *Surface Tests to Demonstrate the Construction Feasibility of the Belgian Supercontainer*, International Workshop NUCPERF 2012: Long-Term Performance of Cementitious Barriers and Reinforced Concrete in Nuclear Power Plant and Radioactive Waste Storage and Disposal (RILEM Event TC 226-CNM and EFC Event 351), EDP Sciences, 2013

(Atkins and Glasser, 1992) Atkins M. and Glasser F.P., *Application of Portland cement-based materials to radioactive waste immobilization*, Waste Management, Vol. 12, pp 105-131, 1992

(Atkinson, 2000) Atkinson J.H., *Non-linear soil stiffness in routine design*, Géotechnique, 50(5), pp. 487-508, 2000

(Babcock Noell Nuclear, 2005) Babcock Noell Nuclear (Keller J.), *Basic Design of an Air Cushion Technology Based Waste Transportation and Disposal System for the Belgian HLW and LILW-LL Repository*, Report No. 10CA001 to ONDRAF/NIRAS, 2005

(Baldi et al., 1987) Baldi G., Borsetto M. and Hueckel T., *Calibration of mathematical models for simulation of thermal, seepage and mechanical behaviour of Boom Clay*, Commission of the European Communities. Nuclear science and Technology EUR 10924, 1987

(Baldi *et al.*, 1991) Baldi, G, Hueckel T., Peano A. and R Pellegrini, *Developments in Modelling of Thermo-hydro-geomechanical Behaviour of Boom Clay and Clay-based Buffer Materials*, Report EUR 13365, Vol. 1 and 2, Commission of the European Communities, Nuclear Science and Technology, 1991

(Bastiaens, 2003) Bastiaens W., *Invloed van aardbevingen op het ondergronds onderzoekslaboratorium HADES te Mol*, Versie 2.0, interne nota EURIDICE, 4 p., 2003

(Bastiaens *et al.*, 2003) Bastiaens W., Bernier F., Buyens M., Demarche M., Li X.L., Linotte J.M. and Verstricht J., *The Connecting gallery, The extension of the HADES underground research facility at Mol*, Belgium, EURIDICE report 03-294, December 2003

(Bastiaens *et al.*, 2006) Bastiaens W., Bernier F. and Li X.L., *An overview of long-term HM measurements around HADES URF*, Proc. Intern. Symp., Liège, 2006, 9-12 May, pp. 15-26, 2006

(Bastiaens *et al.*, 2007) Bastiaens W., Bernier F. and Li X.L., *SELFAC: Experiments and conclusions on fracturing, self-healing and self-sealing processes in clays*, Physics and Chemistry of the Earth 32, pp. 600-615, 2007

(Becker *et al.*, 2009) Becker D.A., Cormenzana J.L., Delos A., Duro L., Grupa J., Hart J., Landa J., Marivoet J., Orzechowski J., Schröder T.J., Vokal A., Weber J., Weetjens E. and Wolf J., *Safety indicators and performance indicators. Deliverable 3.4.2 of the PAMINA project*, 2009

(Belem *et al.*, 2008) Belem T. and Benzaazoua M., *Design and Application of Underground Mine Paste Backfill Technology*, Geotechnical and Geological Engineering, Vol. 26, issue 2, pp. 147-174, April 2008

(Belgatom, 2003) Belgatom, *Faisabilité de stockage de déchets radioactifs à Mol et Dessel (Fiche 47) – Influence d'un séisme sur un concept de stockage profond à Mol-Dessel*, Report to ONDRAF/NIRAS, 2003

(Belgatom, 2005) Belgatom, *Conceptual layout for a disposal facility for category B&C waste in Belgium: Stage 1 – Overview*, Report to ONDRAF/NIRAS, 2005

(Belgatom, 2006) Belgatom, *Design for Overpacks for Vitrified Waste Canisters and Irradiated fuel Assemblies*, Belgatom Report 0501170/950 – 2, 2006

(Belgatom, 2007) Belgatom, *Demonstration of the Supercontainer Design for Irradiated fuel Waste Disposal, Stage 2 – Concrete characterization – Adaptation and large scale tests*, Report to ONDRAF/NIRAS, 2007

(Belgatom, 2008) Belgatom, *Demonstration of the Supercontainer Design for Irradiated fuel Waste Disposal, Stage 1 – Concrete characterization – Concrete Tests synthesis*, Report to ONDRAF/NIRAS, 2008

(Bennett and Gens, 2008) Bennett D.G. and Gens R., *Overview of European concepts for high-level waste and irradiated fuel disposal with special reference waste container corrosion*, Journal of Nuclear Materials 379, pp. 1-8, 2008

(Benvegna *et al.*, 1988) Benvegna, F., Brondi, A., Polizzano, C., *Natural analogues and evidence of long-term isolation capacity of clays occurring in Italy*, CEC-EUR 11896 EN, 1988

(Bernier *et al.*, 1997) Bernier F., Volckaert G., Alonso E, Villar M., *Suction-controlled experiments on Boom clay*, Engineering Geology 47, pp. 325-338, 1997

(Bertolini *et al.*, 2004) Bertolini L., Elsener B., Pedferri P. and Polder R., *Corrosion of Steel in concrete, Prevention, Diagnosis, Repair*, Wiley-VCH, Weinheim, Germany, 2004

(Bevan and Hancock, 1986) Bevan T.G. and Hancock P.L., *A late Cenozoic regional mesofracture system in southern England and northern France*, Journal of the Geological Society, London, 143, pp. 355-362, 1986

(BGD, 2013) BGD, *Geologisch model van de Boomse Klei*, in opdracht van: ONDRAF/NIRAS, Koninklijk Belgisch Instituut voor Natuurwetenschappen, Belgische Geologische Dienst, 2013

(BIOCLIM, 2003) BIOCLIM, *Modelling sequential biosphere systems under climate change for radioactive waste disposal*, BIOCLIM conclusions, EC project 5<sup>th</sup> Euratom Framework Programme, <http://www.andra.fr/bioclim/proceedings.htm>, Contract FIKW-CT-2000-00024s, 2003

(Blanchart, 2011) Blanchart P., *Influence de l'oxydation et de la biodégradation anaérobie sur la matière organique de l'argile oligocène de Boom (Mol, Belgique) : conséquences sur la formation d'espèces organiques hydrosolubles*, thèse présentée pour l'obtention du titre de Docteur de l'INPL en Géosciences, Institut National Polytechnique de Lorraine, 2011

(Blanchart *et al.*, 2012) Blanchart P., Faure P., De Craen M., Bruggeman C. and Michels R., *Experimental investigation on the role of kerogen and clay minerals in the formation of bitumen during the oxidation of Boom Clay*, Fuel 97, pp. 344-351, 2012

(Blanchart *et al.*, 2012b) Blanchart P., Faure P., Bruggeman C., De Craen M., Michels R., *In situ and laboratory investigation of the alteration of Boom Clay (Oligocene) at the air-geological barrier interface within the Mol underground facility (Belgium): Consequences on kerogen and bitumen compositions*, Applied Geochemistry 27, pp. 2476-2485, 2012

(Blaser, 2007) Blaser P.C., *Tracermethoden in der Hydrogeologie – Kombination verschiedener Methoden und Anwendungen am Beispiel des Ledo-Paniselian-Aquifers in Belgien*, PhD thesis, Ghent University, 212p, 2007

(Blaser *et al.*, 2010) Blaser P.C., Coetsiers M., Aeschbach-Hertig W., Kipfer R., Van Camp M., Loosli H.H. and Walraevens K., *A new groundwater radiocarbon correction approach accounting for palaeoclimate conditions during recharge and hydrochemical evolution: The Ledo-Paniselian Aquifer, Belgium*, Applied Geochemistry, 25, pp. 437-455, 2010

(Bleyen *et al.*, 2013) Bleyen N., Mariën A. and Valcke E., *The geo-chemical perturbation of Boom Clay due to the NaNO<sub>3</sub> plume released from EUROBITUM bituminised radioactive waste*, External report of the Belgian nuclear research centre, SCK•CEN ER-221, 2013

(Blümling *et al.*, 2007) Blümling P., Bernier F., Lebon P. and Derek Martin C., *The excavation damaged zone in clay formations time-dependent behaviour and influence on performance assessment*, Physics and Chemistry of the Earth 32, pp. 588-599, 2007

(Blümling *et al.*, 2009) Blümling P., Aranyossy J.-F., Jing L., Li X.L., Marschall P., Rothfuchs T. and Vietor T., *Disturbed and damaged zones around underground openings - effects induced by construction and thermal loading*, EURADWASTE'08, 7<sup>th</sup> European Commission Conference on the Management and Disposal of Radioactive Waste, Community Policy and Research and Training Activities, Edited by C. Davies, EUR 24040, EURATOM, 2009

(Bottrell *et al.*, 2000) Bottrell S.H., Moncaster S.J., Tellam J.H., Lloyd J.W., Fisher Q.J. and Newton R.J., *Controls on bacterial sulphate reduction in a dual porosity aquifer system: the Lincolnshire Limestone aquifer, England*, Chemical Geology, 169, pp. 431-470, 2000

(Boulanger, 2010) Boulanger D., *Characterization of the irradiated fuel assembly for gas production evaluations*, Note NIROND-2010-1403, 2010

(Bouniol, 2005) Bouniol P., *Evaluation du Terme Source Hydrogène par Simulation de la Radiolyse dans le Béton d'un Superconteneur Comportant deux Colis Primaires*, CEA Report RT DPC/SCCME 04-689-A, 2005

(Bouniol, 2007) Bouniol P., *Radiolysis within the concrete of a supercontainer including two primary waste forms. Simulation at the concrete/steel interface at variable temperatures*, CEA Report RT DPC/SCCME 07-742-A, 2007

(Bouniol, 2009) Bouniol P., *Modelling of Water Radiolysis in Cement Media: Development of an "Iron" Module*, CEA Report RT DPC/SCCME 09-784-A, 2009

(Bouniol, 2010) Bouniol P., *Effect of Thiosulfate Contamination on Water Radiolysis in the Concrete Buffer of the ONDRAF supercontainer*, CEA Report RT DPC/SCCME 10-812-A, 2010

(Bradbury and Baeyens, 2000) Bradbury M. and Baeyens B., *A generalised sorption model for the concentration dependent uptake of caesium by argillaceous rocks*, Journal of Contaminant Hydrology, 42, pp. 141-163, 2000

(Bruggeman *et al.*, 2008) Bruggeman C., Salah S., Maes N., Wang L., Dierckx A. and Ochs M., *Outline of the experimental approach adopted by SCK•CEN for developing radionuclide sorption parameters*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-73, 2008

(Bruggeman *et al.*, 2010) Bruggeman C., Aertsens M., Maes N. and Salah S., *Iodine retention and migration Behaviour in Boom Clay. Topical report First full draft*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-119, 2010

(Bruggeman *et al.*, 2010b) Bruggeman C., Maes N., Aertsens M., Govaerts J., Martens E. and Jacobs E., *Technetium retention and migration behaviour in Boom Clay*, Topical Report, First full draft, External Report of the Belgian Nuclear Research Centre SCK•CEN ER-101, 2010

(Bruggeman *et al.*, 2010c) Bruggeman C., Liu D.J. and Maes N., *Influence of Boom Clay Organic Matter on the adsorption of Eu<sup>3+</sup> by illite – Geochemical modelling using the Component Additivity approach*, Radiochimica Acta 98, pp. 597-605, 2010

(Bruggeman and Maes, 2010d) Bruggeman C. and Maes N., *Uptake of Uranium(VI) by Pyrite under Boom Clay Conditions: Influence of Dissolved Organic Carbon*, Environmental Science and Technology, 44:11, pp. 4210-4216, 2010

(Bruggeman *et al.*, 2012) Bruggeman C., Salah S. and Maes N., *Americium retention and migration behaviour in Boom Clay*, Topical Report, First full draft, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-201, 2012

(Bruggeman *et al.*, to be published) Bruggeman C., Maes N and Aertsens M., *Tritiated water retention and migration behaviour in Boom Clay Topical Report Version 05/2012 – Final version – v2*, to be published

(Bruggeman and De Craen, 2012) Bruggeman C and De Craen M., *Boom Clay natural organic matter, Status Report 2011*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-206, 2012

(Burland, 1990) Burland J., *On the compressibility and shear strength of natural clays*, Rankine Lecture, Géotechnique, 40 (3), pp. 329-378, 1990

(Cachoir *et al.*, 2010) Cachoir C., Lemmens K. and Mennecart T., *Estimation of the effective surface area of UOX (MOX) irradiated fuel in supercontainer disposal conditions (status 2010)*, External report of the Belgian nuclear research centre, SCK•CEN ER-142, 2010

(Cachoir and Mennecart, 2011) Cachoir C. and Mennecart T., *Instant Release Fraction (Source and Expert ranges) for SFC-1, UOX 50 and 60 GWd/tHM, MOX 50 GWd/tHM*, External report of the Belgian nuclear research centre, SCK•CEN ER-166, 2011

(CACTUS, 1994) Picard J.M., Bazargan B. and Rousset G., *Essai thermo-hydro-mécanique dans une argile profonde – essai CACTUS*, Rapport final EUR15482, 1994

(Cambridge, 2004) CAMBRIDGE IN-SITU LTD, *SCK•CEN SELFRAC Project, Mol, Belgium, Ground investigation, Results of self boring pressuremeter tests*, report CIR 1117/04, 1 volume, 2004

(Cambridge, 2009) CAMBRIDGE IN-SITU LTD, *SCK•CEN Praclay Project Mol, Belgium, Ground investigation, Results of self boring pressuremeter tests*, report, CIR1224/09, 4 volumes, 2009

(Cammaer *et al.*, 2009) Cammaer Ch., Cockaerts G. and Schiltz M., *Drilling and Geological Report: ON-Kallo-1; ON-Kallo-2; ON-Kallo-3*, Report of Samsuffit bvba (Samsuffit R2009-01), commissioned by ONDRAF/NIRAS, 93, 2009

(Carbol *et al.*, 2009) Carbol P., Fors P., Van Winckel S and Spahiu K., *Corrosion of irradiated MOX fuel in presence of dissolved H<sub>2</sub>*, Journal of Nuclear Materials 392, pp. 45-54, 2009



(Cartwright, 1994) Cartwright J.A., *Episodic basin-wide fluid expulsion from geopressured shale sequences in the North Sea basin*, *Geology*, 22, pp. 447-450, 1994

(Cartwright and Dewhurst, 1998) Cartwright J.A. and Dewhurst D.N., *Layer-bound compaction faults in fine-grained sediments*, *Geol. Soc. Am. Bull.*, 110, pp. 1242-1257, 1998

(Cartwright et al., 2003) Cartwright J., James D. and Bolton A., *The genesis of polygonal fault systems: a review*, Eds. Van Rensbergen P., Hillis R.R., Maltman A.J. and Morley C.K., *Subsurface Sediment Mobilization*, Geological Society, London, Special Publications, 216, pp. 223-243, 2003

(Cartwright, 2011) Cartwright J., *Diagenetically induced shear failure of fine-grained sediments and the development of polygonal fault systems*, *Marine and Petroleum Geology*, 28, pp. 1596-1610, 2011

(Chacksfield et al., 2004) Cartwright J.A., *Episodic basin-wide fluid expulsion from geopressured shale sequences in the North Sea basin*, *Geology*, 22, pp. 447-450, 1994

(Chambre des représentants, 1993) Chambre des représentants, *Résolution 541/9-91/92 relative à l'utilisation de combustibles contenant du plutonium et de l'uranium dans les centrales nucléaires belges, ainsi qu'à l'opportunité du retraitement des barres de combustible*, adoptée le 22 décembre 1993

(Chen et al., 2010) Chen G., Maes T., Vandervoort F., Sillen X., Van Marcke P. and Honty M., *Thermal impact on damaged argillaceous rocks: Permeameter test and Isostatic test on Boom Clay and Opalinus Clay from the TIMODAZ project*, External report of the Belgian nuclear research centre, SCK•CEN ER-145, 2010

(Chen et al., 2011) Chen G.J., Sillen X., Verstricht J. and Li X.L., *Atlas III In-situ heating test in Boom Clay: Field Data, Observation and Interpretation*, *Computers and Geotechnics* 38(5), pp. 683–696, 2011

(Chen et al., 2012) Chen W., Jia S., Yu H. and Li X., *Back analysis of permeability parameters in Boom Clay*, Proceedings of the European Commission TIMODAZ THERESA International Conference, Impact of thermo hydro mechanical chemical (THMC) processes on the safety of underground radioactive waste repositories, Luxembourg, 29 September–1 October 2009, EUR 25527 EN, 2012

(Chen et al., 2013) Chen G. J., Maes T., Vandervoort F., Sillen X., Van Marcke P., Honty M., Dierick M. and Vanderniepen P., *Thermal Impact on Damaged Boom Clay and Opalinus Clay: Permeameter and Isostatic Tests with  $\mu$ CT Scanning*, *Rock Mechanics and Rock Engineering*: 1–13. doi:10.1007/s00603-012-0334-y, 2013

(Chivot, 2004) Chivot J., *Thermodynamique des produits de corrosion, Fonctions thermodynamiques, diagrammes de solubilité, diagrammes E-pH des systèmes Fe-H<sub>2</sub>O, Fe-CO<sub>2</sub>-H<sub>2</sub>O, Fe-S-H<sub>2</sub>O, Cr-H<sub>2</sub>O et Ni-H<sub>2</sub>O en fonction de la température*, Collection Sciences et Techniques, Andra, 2004

(Clausen et al., 1999) Clausen J.A., Gabrielsen R.H., Reksens P.A. and Nysæther E., *Development of intraformational (Oligocene-Miocene) faults in the northern North Sea:*

*influence of remote stresses and doming of Fennoscandia*, Journal of Structural Geology 21, pp. 1457-1475, 1999

(CLIPLEX, 2003) Bernier F., Li X.L., Verstricht J., Barnichon J.D., Labiouse V., Bastiaens W., Palut J.M., Ben Slimane K., Ghoreychi M., Gaombalet J., Huertas F., Galera J.M., Merrien K., Elorza F.J. and Davies C., *CLIPLEX: Clay instrumentation programme for the extension of an underground research facility*, Final report EUR 20619, EC project, 2003

(Cloetingh *et al.*, 2010) Cloetingh S., van Wees J.D., Ziegler P.A., Lenkey L., Beekman F., Tesauro M., Fröster A., Norden B., Kaban M., Hardebol N., Bonté D., Genter A., Guillou-Frottier L., Ter Voorde M., Sokoutis D., Willingshofer E., Cornu T. and Worum G., *Lithosphere tectonics and thermo-mechanical properties: An integrated modelling approach for Enhanced Geothermal Systems exploration in Europe*, Earth-Science Reviews, 102, pp. 159-206, 2010

(COBECOMA, 2004) Kursten B., Smailos E., Azkarate I., Werme L., Smart N.R. and Santarini G., *Cobecoma: State-of-the-art document on the Corrosion Behaviour of Container materials*, Final report EC project, 2004

(Coetsiers and Walraevens, 2009) Coetsiers M. and Walraevens K., *A new correction model for <sup>14</sup>C ages in aquifers with complex geochemistry – Application to the Neogene Aquifer, Belgium*, Applied Geochemistry, 24, pp. 768-776, 2009

(Colenco, 2009) Colenco, *Audit of the hydrogeological modeling of North-Eastern Belgium*, Technical Report, 1530, AF-Colenco Ltd, 2009

(Colenco, 2010) Colenco, *Geochemical Issues of the Ypresian clays*, Memorandum ME 1905/01, AF-Colenco Ltd, June 2010

(Colenco, 2010b) Colenco, *Geochemical Issues of the Ypresian clays – Detailed data analysis for the Doel and Kallo boreholes*, Memorandum ME 1905/03, AF-Colenco Ltd, November 2010

(Colenco, 2011) Colenco, *Geochemical Issues of the Ypresian clays – Geochemical modelling of pore water chemistry and comparison of the data for the Doel and Kallo boreholes*, Memorandum, ME 1905/04, AF Colenco Ltd, February 2011

(Coll, 2005) Coll C., *Endommagement des roches argileuses et perméabilité induite au voisinage d'ouvrage souterrains*, Ph.D. thesis, Université Joseph Fourier-Grenoble 1, Grenoble, 2005

(Cools *et al.*, 2006) Cools J., Meyus Y., Woldeamlak S.T., Batelaan O. and De Smedt F., *Large-scale GIS-based hydrogeological modeling of Flanders: a tool for groundwater management*, Environmental Geology, 50, pp. 1201-1209, 2006

(CORALUS, 2007) Valcke E., Smets S., Labat S., Lemmens K., Van Iseghem P., Gysemans M., Thomas P., Van Bree P., Vos B., Van den Berghe S., Godon N., Jollivet P., Mestre J.P., Parisot G., Bojat M., Boubals J.M., Deschanel X., Jockwer N., Wiczorek K., Pozo C., Petronin J.C. and Raynal J., *CORALUS-II: An integrated *in-situ* corrosion test on  $\alpha$ -active high-level waste (HLW) glass – Phase 2 (CORALUS-2)*, Final report to the EC, 2007

(Cornet, 2009) Cornet F.H., *In-situ Stress measurement Campaign*, SCK•CEN Underground Laboratory Boerentang-Mol March 2009, Final report, Ecole et Observatoire des Sciences de la Terre, Université de Strasbourg, 2009

(Craeye *et al.*, 2009) Craeye B., De Schutter G., Van Humbeeck H. and Van Cotthem A., *Early age behaviour of concrete supercontainers for radioactive waste disposal*, Nuclear engineering and design, Vol. 239, pp.23-32, 2009

(Craeye, 2010) Craeye B., *Vroegtijdig thermomechanisch gedrag van betonnen Supercontainers voor de berging van radioactief afval – Early-Age Thermo-Mechanical Behaviour of Concrete Supercontainers for Radwaste Disposal*, Proefschrift ingediend tot het behalen van de graad van Doctor in de Ingenieurswetenschappen: Bouwkunde, Faculteit Ingenieurswetenschappen, Universiteit Gent, Belgium, ISBN 978-90-8578-331-2, 2010

(Cui *et al.*, 2009) Cui Y., Le T., Tang A., Delage P. and Li X., *Investigating the time-dependent behaviour of Boom clay under thermomechanical loading*, Géotechnique, 59:4, pp. 319-329, 2009

(Cui *et al.*, 2012) Cui Y., Le T., Tang A., Delage P. and Li X., *An experimental study of the time dependent behaviour of Boom clay under thermo mechanical loading*, Proceedings of the European Commission TIMODAZ THERESA International Conference Impact of thermo hydro mechanical chemical (THMC) processes on the safety of underground radioactive waste repositories, Luxembourg, 29 September–1 October 2009, EUR 25527 EN, 2012

(Davies and Ireland, 2011) Davies R.J. and Ireland M.T., *Initiation and propagation of polygonal fault arrays by thermally triggered volume reduction reactions in siliceous sediment*, Marine Geology, Volume 289, pp. 150-158, 2011

(Davis and Selvadurai, 2005) Davis R.O. and Selvadurai A.P.S., *Plasticity and Geomechanics*, Cambridge University Press, 2005

(DBE-TEC, 2006) DBE-TEC, *Peer Review of ONDRAF/NIRAS repository concept*, Final report, DBE Technology GmbH, December 2006

(DBE-TEC, 2010) DBE-TEC, *Technical Support for the R&D Feasibility Programme for the Geological Disposal of Category B&C Radioactive Waste: R&D Study 3-310: Spatial Requirements on the Waste Shaft Diameter*, Final report, DBE-TEC Report to ONDRAF/NIRAS, TEC-08-2010-Z, 2010

(De Batist and Henriët, 1995) De Batist M. and Henriët J.P., *Seismic sequence of the Palaeogene offshore of Belgium, southern North Sea*, Journal of the Geological Society, London, 152, pp. 27-40, 1995

(De Bruyn *et al.*, 2001) De Bruyn D., Bernier F., Buyens M., De Craen M., Van Cotthem A., Ramaeckers C. and Van Schepdael J., *La construction du second puits à Mol : conception, attribution, exécution et enseignements*, ESV EURIDICE GIE 01-204, 2001

(De Bruyn and Labat, 2002) De Bruyn D. and Labat S., *The second phase of ATLAS: the continuation of a running THM test in the HADES underground research facility at Mol*, Engineering Geology 64, pp. 309-316, 2002

(De Cannière *et al.*, 1996) De Cannière P., Moors H., Lolivier P., De Preter P and Put M., *Laboratory and in-situ migration experiments in the Boom clay*, Final report, European Commission, Report EUR 16927 EN, 1996

(De Cannière *et al.*, 2010) De Cannière P., Maes A., Williams S., Bruggeman C., Beauwens T. and Maes N., *Behaviour of Selenium in Boom Clay: State-of-the-art report*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-120, 2010

(De Cannière *et al.*, 2011) De Cannière P., Kursten B., Druyts F, Moors H. and Gens R., *Sulphur-related issues in deep underground nuclear waste disposal systems*, SACNUC 2008, European Federation of Corrosion Event No. 59, pp. 165-169, 2011

(De Ceukelaire *et al.*, 2012) De Ceukelaire M., Vancampenhout P., Dusar M. and Lie S.F., *Wellbore integrity in Ypresian clays in Belgium with reference to geophysical well logs*, Report of the Royal Belgian Institute of Natural Sciences, Geological Survey of Belgium, commissioned by ONDRAF/NIRAS, coordinated by Faninbel, 2012

(De Craen, 1998) De Craen M., *The formation of septarian carbonate concretions in organic-rich argillaceous sediments*, KULeuven, Ph.D.-thesis, 1998

(De Craen *et al.*, 2004) De Craen M., Wang L., Van Geet M. and Moors H., *Geochemistry of Boom Clay pore water at the Mol site - status 2004*, Report of the Belgian Nuclear Research Centre, SCK•CEN BLG-990, 2004

(De Craen *et al.*, 2004b) De Craen M., Van Geet M., Wang L. and Put M., *High sulphate concentrations in squeezed Boom Clay pore water: evidence of oxidation of clay cores*, Physics and Chemistry of the Earth, 29, pp. 91-103, 2004

(De Craen *et al.*, 2006) De Craen M., Wemaere I., Labat S. and Van Geet M., *Geochemical analyses of Boom Clay pore water and underlying aquifers in the Essen-1 borehole*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-19, 2006

(De Craen *et al.*, 2008b) De Craen M., Van Geet M., Honty M., Weetjens E. and Sillen X., *Extent of oxidation in Boom Clay as a result of excavation and ventilation of the HADES URF: Experimental and modelling assessments*, Physics and Chemistry of the Earth, Vol. 33, pp. S350-S362, 2008

(De Craen, 2009) De Craen M., *Which climate evolution scenarios should be considered in the assessment of the long-term safety of a geological disposal system for radioactive waste?*, Restricted report of the Belgian Nuclear Research Centre, SCK•CEN-R-4826, 2009

(De Craen *et al.*, 2011) De Craen M., Honty M., Van Geet M., Weetjens E., Sillen X., Wang L., Jacques D. and Martens E., *Overview of the oxidation around galleries in Boom Clay (Mol, Belgium) – Status 2008*, NF-PRO Final activity report for SCK•CEN, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-189, 2011

(De Craen *et al.*, 2012) De Craen M., Beerten K., Honty M. and Gedeon M., *Geoscientific evidence to support the I2 isolation function (geology and long-term evolution) as part of the Safety and Feasibility Case 1 (SFC1)*, External report of the Belgian nuclear research centre, SCK•CEN ER-184, 2012

(De Craen *et al.*, 2012b) De Craen M., Beerten K., Gedeon M. and Vandersteen K., *Geoscientific evidence to support the I1 isolation function related to human actions, as part of the Safety and Feasibility Case 1 (SFC1)*, External report of the Belgian nuclear research centre, SCK•CEN ER-186, 2012

(Defra *et al.*, 2008) Defra, BERR and the devolved administrations for Wales and Northern Ireland, *Managing Radioactive Waste Safely A Framework for Implementing Geological Disposal*, A White Paper, Presented to Parliament by the Secretary of State for Environment, Food and Rural Affairs by Command of Her Majesty, Cm 7386, June 2008

(Dehandschutter, 2004) Dehandschutter B., *Faulting and Jointing in Clay – A Geological and Geotechnical Approach, Report of Investigation 2002-2004*, KULeuven, commissioned by ONDRAF/NIRAS, 156p, 2004

(Dehandschutter *et al.*, 2005) Dehandschutter B., Vandycke S., Sintubin M., Vandenberghe N and Wouters L., *Brittle fractures and ductile shear bands in argillaceous sediments: inferences from Oligocene Boom Clay (Belgium)*, Journal of Structural Geology 27, pp. 1095–1112, 2005

(Dehandschutter *et al.*, 2005b) Dehandschutter B., Gaviglio P., Sizun J.P., Sintubin M., Vandycke S, Vandenberghe N and Wouters L., *Volumetric matrix strain related to intraformational faulting in argillaceous sediments*, Journal of the Geological Society, London, Vol. 162, pp. 801–813, 2005

(Delage *et al.*, 2000) Delage P., Sultan N. and Cui Y.J., *On the thermal consolidation of Boom clay*, Canadian Geotechnical Journal 37 (2), pp. 343-354, 2000

(Delage *et al.*, 2004) Delage P., Cui Y.J. and Sultan N., *On the thermal behaviour of Boom clay*, Proceedings Eurosafe 2004 Conference, Berlin, CD Rom, 8 p., 2004

(Delage *et al.*, 2007) Delage P., Le T., Tang A., Cui Y.J. and Li X., *Suction effects in deep Boom Clay block samples*, Geotechnique symposium on stiff sedimentary clays - genesis and engineering behaviour, London, United Kingdom, 14-14 May 2007, Geotechnique, 57:1, pp. 239-244, ISSN 0016-8505, 2007

(Delage *et al.*, 2012) Delage P., Sultan N., Cui Y. and Li X., *Permeability changes of Boom clay with temperature*, Proceedings of the European Commission TIMODAZ THERESA International Conference Impact of thermo hydro mechanical chemical (THMC) processes on the safety of underground radioactive waste repositories, Luxembourg, 29 September–1 October 2009, EUR 25527 EN, 2012

(Delécaut, 2004) Delécaut G., *The geochemical behaviour of uranium in the Boom Clay*, Ph.D. thesis, Département de géologie et de géographie, Université Catholique de Louvain, 2004

(Deng *et al.*, 2012) Deng Y.F., Tang A.M., Nguyen X.P., Cui Y.J., *Hydro-Chemo-Mechanical Characterization of Boom clays at Essen*, research report, ENPC Ecole des Ponts, Paris, France, 2012

(Deng *et al.*, 2012b) Deng Y.F., Cui Y.J., Tang A.M., Li X.L. and Sillen X., *An experimental study on the secondary deformation of Boom Clay*, Applied Clay Science, Volume 59-60, pp. 19-25, 2012

(Deniau *et al.*, 2004) Deniau I., Derenne S., Beaucaire C., Pitsch, H. and Largeau C., *Occurrence and nature of thermolabile compounds in the Boom Clay kerogen (Oligocene, underground Mol Laboratory, Belgium)*, Organic Geochemistry, 35, pp. 91-107, 2004

(Deniau *et al.*, 2005) Deniau I., Behar F., Largeau C., De Cannière P., Beaucaire C. and Pitsch H., *Determination of kinetic parameters and simulation of early CO<sub>2</sub> production from the Boom Clay kerogen under low thermal stress*, Applied Geochemistry 20, pp. 2097-2107, 2005

(Deniau *et al.*, 2005b) Deniau I., Derenne S., Beaucaire C., Pitsch H. and Largeau C., *Simulation of thermal stress influence on the Boom Clay kerogen (Oligocene, Belgium) in relation to long-term storage of high activity nuclear waste – I. Study of generated soluble compounds*, Applied Geochemistry, 20, pp. 587-597, 2005

(Depaus and Capouet, 2012) Depaus C. and Capouet M., *The use of safety statements in the achievement of SFC1*, ONDRAF/NIRAS, note 2012-1390, 2012

(Desbois *et al.*, 2010) Desbois G., Urai J. and De Craen M., *In-situ and direct characterization of porosity in Boom Clay (Mol site, Belgium) by using novel combination of ion beam cross-sectioning, SEM and cryogenic methods*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-124, 2010

(De Smet and Olivier, 1996) De Smet D. and Olivier I., *Inventarisatie van de kennis van de Ieperaanklei in functie van onderzoek naar diepe berging van hoogradioactief afval – Eindrapport*, Report by Laboratorium voor Toegepaste Geologie en Hydrogeologie van UGent, commissioned by ONDRAF/NIRAS, TGO 94/40, 216 pp., 1996

(De Vos *et al.*, 1993) De Vos W., Verniers J., Herbosch A. and Vanguestaine M., *A new geological map of the Brabant Massif, Belgium*, Geological Magazine, 130, pp. 605-611, 1993

(Dizier, 2011) Dizier A., *Caractérisation des effets de température dans la zone endommagée autour de tunnels de stockage de déchets nucléaires dans les roches argileuses*, thèse présentée en vue de l'obtention du grade de Docteur en Sciences de l'Ingénieur, Université de Liège, 2011

(Dizier *et al.*, 2012) Dizier A., Collin F., Garitte B., François B., Chen G. and Sieffert Y., *Thermo hydro mechanical modelling of hollow cylinder laboratory experiments on Boom Clay*, Proceedings of the European Commission TIMODAZ THERESA International Conference Impact of thermo hydro mechanical chemical (THMC) processes on the safety of underground radioactive waste repositories, Luxembourg, 29 September-1 October 2009, EUR 25527 EN, 2012

(Dowding and Rozen, 1978) Dowding C.H. and Rozen A., *Damage to rock tunnels from earthquake shaking*, Journal of Geotechnical Engineering Division, American Society of Civil Engineers, Vol.104, No. GT2, 1978

(Duffo *et al.*, 2012) Duffo G.S., Arva E.A., Schulz F.M. and Vazquez D.R., *Durability of a reinforced concrete designed for the construction of an intermediate-level radioactive waste disposal facility*, Journal of Nuclear Materials 420, pp. 382-387, 2012

(Edvardsen, 1999) Edvardsen C., *Water permeability and autogenous healing of cracks in concrete*, Technical paper, ACI Materials Journal, Title no. 96-M56, pp. 448-454, July-August 1999

(ECOCLAY II, 2005) ECOCLAY II, *Effects of Cement on Clay Barrier Performance – Phase II, Final report*, EUR 21921, EC project, 2005

(Ecorem, 2008) Ecorem, *Impact of a long-term thermal stress on an aquifer, final report*, NOCA 2008-0118, Ecorem, 2008

(Ecorem, 2010) Ecorem, *Project betreffende de uitvoering van "Multi & single pomptests ten einde hydraulische parameters te bepalen in verschillende formaties" voor rekening van ONDRAF/NIRAS NOCA 2008-0966, Eindrapport pompproeven Doel en Kallo*, Ecorem, 2010

(Engelmann *et al.*, 1993) Engelmann H.-J., Khamis M., Lempert J., *Calculation of Neutron Dose Rates including Backscattering of a POLLUX Cask in Drifts of a Repository Mine*, Nuclear Engineering and Design 147, pp. 119-123, 1993

(ESDRED, 2009) ESDRED, *Final Summary Report and Global Evaluation of the Project*, ESDRED Deliverable D6 of Module 6, WP4, Integrated Project Engineering Studies and Demonstrations of Repository Designs, 6<sup>th</sup> Euratom Framework Programme for nuclear research and training (2002-2006) of the European Union - Management of Radioactive Waste, 2009

(EU, 1985) Council Directive 85/337/EEC of 27 June 1985 on the assessment of the effects of certain public and private projects on the environment, Official Journal L 175, 5 July 1985

(EU, 1992) Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora, Official Journal L 206, 22 July 1992

(EU, 1993) Commission decision of 1 October 1993 establishing the standard document for the supervision and control of shipments of radioactive waste referred to in Council Directive 92/3 Euratom, Official Journal L 268, 29 October 1993

(EU, 1996) Council Directive 96/29/Euratom of 13 May 1996 laying down the basic safety standards for the protection of the health of workers and the general public against the danger arising from ionizing radiation, Official Journal L 159, 29 June 1996

(EU, 1996b) Council Directive 96/61/EC of 24 September 1996 concerning integrated pollution prevention and control (IPPC), Official Journal L 257, 10 October 1996

(EU, 1997) Council Directive 97/11/EC of 3 March 1997 amending Directive 85/337/EEC on the assessment of the effects of certain public and private projects on the environment, Official Journal L 073, 14 March 1997

(EU, 1998) Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption, Official Journal L 330, 5 December 1998

(EU, 2001) Directive 2001/42/EC of the European Parliament and of the Council of 27 June 2001 on the assessment of the effects of certain plans and programmes on the environment, Official Journal L 197, 21 July 2001

(EU, 2003) Directive 2003/4/EC of the European Parliament and of the Council of 28 January 2003 on public access to environmental information and repealing Council Directive 90/313/EEC, Official Journal L 41, 14 February 2003

(EU, 2003b) Directive 2003/35/EC of the European Parliament and of the Council of 26 May 2003 providing for public participation in respect of the drawing up of certain plans and programmes relating to the environment and amending with regard to public participation and access to justice Council Directives 85/337/EEC and 96/61/EC, Official Journal L 156, 25 June 2003

(EU, 2006) Council Directive 2006/117/EURATOM of 20 November 2006 on the supervision and control of shipments of radioactive waste and irradiated fuel, Official Journal of the European Union, L 337, 5/12/2006

(EU, 2006b) Directive 2006/118/EC of the European Parliament and of the Council of 12 December 2006 on the protection of groundwater against pollution and deterioration, Official Journal of the European Union, L 372, 27/12/2006

(EU, 2008) Directive 2008/105/EC of the European Parliament and of the Council of 16 December 2008 on environmental quality standards in the field of water policy, amending and subsequently repealing Council Directives 82/176/EEC, 83/513/EEC, 84/156/EEC, 84/491/EEC, 86/280/EEC and amending Directive 2000/60/EC of the European Parliament and of the Council, Official Journal of the European Union, L 348, 24/12/2008

(EU, 2010) Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds, Official Journal of the European Union, L 20, 26/01/2010

(EU, 2011) Council Directive 2011/70/Euratom of 19 July 2011 establishing a Community framework for the responsible and safe management of irradiated fuel and radioactive waste, Official Journal L 199, pp. 48-56, 2 August 2011

(EURIDICE, 2001) EURIDICE, *HADES tour guide notebook*, ESV EURIDICE GIE, 2001

(EURIDICE, 2009) EURIDICE, *Praclay Gallery Sensors Data Report (Period until Dec. 31, 2008)*, ESV EURIDICE GIE internal report, March 2009

(EURIDICE, 2012) EURIDICE, *Activity Report 2011*, ESV EURIDICE GIE Doc. 12-118, 2012



(Eurofins, 2009) Eurofins, *Tussentijdse analyseresultaten, projectnummer 09/EALTER001-01/SLa/mvg/B-14*, Verslagnummer PR-09-RC-000081-02, Eurofins Belgium N.V., Hofstade, 5p., 2009

(Eurofins, 2009b) Eurofins, *Tussentijdse analyseresultaten and Bijlage jodium/lithium, projectnummer 09/EALTER001-01/SLa/mvg/B-2*, Verslagnummer PR-09-RC-000549-01, Eurofins Belgium N.V., Hofstade, 4p., 2009

(Eurofins, 2009c) Eurofins, *Tussentijdse analyseresultaten and Bijlage jodium/lithium, projectnummer 09/EALTER001-01/SLa/mvg/B-*. Verslagnummer AR-09-RC-000960-01, Eurofins Belgium N.V., Hofstade, 3p., 2009

(Fallon *et al.*, 2013) Fallon C., Zwetkoff C., Parotte C., Paile S., Bergmans A. and Van Berendoncks K., *Processus socio-politiques et Gestion de Plan en univers controversé – Application au Plan de gestion à long terme des déchets B&C. Rapport de Synthèse*, Université de Liège, Universiteit Antwerpen, 2013

(FANC, 2007) FANC, *Dépôts définitifs de déchets radioactifs – Note stratégique et politique d’instruction des demandes d’autorisation*, FANC note 007-020-F (rév. 1) (and successive revisions of the diagram), Federaal agentschap voor nucleaire controle, agence fédérale de contrôle nucléaire, 2007

(FANC, 2010) FANC, *Safety assessment: biosphere*, FANC note 008-217-N (rev. 3), Federaal agentschap voor nucleaire controle, agence fédérale de contrôle nucléaire, 2010

(FANC, 2010b) FANC, *Leidraad over de stralingsbescherming tijdens de operationele periode van een inrichting voor de eindberging van radioactief afval*, FANC note 008-007 N, herz. 5, Federaal agentschap voor nucleaire controle, agence fédérale de contrôle nucléaire, 2010

(FANC, 2012) FANC, *Guide technique « Critères de Radioprotection pour l’évaluation de la sûreté post-fermeture des dépôts de déchets radioactifs »*, FANC note 2011-06-28-CAD-5-4-3-FR, Federaal agentschap voor nucleaire controle, agence fédérale de contrôle nucléaire, 2012

(FANC, 2012b) FANC, *Projet de guide technique « Analyse de la sûreté post-fermeture des établissements de stockage définitif de déchets radioactifs »*, FANC note 2012-02-28-FLE-5-4-4-FR, Federaal agentschap voor nucleaire controle, agence fédérale de contrôle nucléaire, 2012

(FANC, 2013) FANC, *Veiligheidsvoorschriften voor de inrichtingen voor eindberging van radioactief afval (versies NL en FR)*, 2013-01-14-JME-5-1-1-NL, Federaal agentschap voor nucleaire controle, agence fédérale de contrôle nucléaire, 2013

(Faninbel, 2011) Faninbel, *Inventarisation and assessment of drilling and human activities in Northern Belgium subsoil. Evaluation of boreholes data from the geological archives for the assessment of future trends*, report prepared for SCK•CEN, Faninbel, 2011

(Federico, *et al.*, 2009) Federico A., Elia G. and Murianni A., *The at-rest earth pressure coefficient prediction using simple elasto-plastic constitutive models*, Computers and Geotechnics 36, pp. 178-198, 2009

(Ferrand, 2011) Ferrand K., *Assessment of the effective surface area of vitrified waste in Supercontainer disposal conditions*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-155, 2011

(Ferrand, 2013) Ferrand K., *Topical report on tests on vitrified (V)HLW waste in Supercontainer disposal conditions (status 2011)*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-195, 2013

(Ferry *et al.*, 2005) Ferry C., Poinssot C., Broudic V., Cappelaere C., Desgranges L., Garcia P., Jegou C., Lovera P., Marimbeau P., Corbel C., Miserque F., Piron J.-P., Poulesquen A., Roudil D., Gras J.-M. and Bouffieux P., *Référentiel scientifique sur l'évolution à long terme des combustibles usés*, CEA, 2005

(Ferry *et al.*, 2008) Ferry C., Piron J., Poulesquen A. and Poinssot C., *Radionuclide release from the irradiated fuel under disposal conditions: Re-evaluation of the Instant Release Fraction*, Mat. Res. Soc. Symp. Proc. Vol 1107, pp. 447-454, 2008

(Ferry *et al.*, 2010) Ferry C., Piron J.P. and Ambard A., *Effect of helium on the microstructure of irradiated fuel in a repository: An operational approach*, Journal of Nuclear Materials 407, pp.100-109, 2010

(Forsyth, 1997) Forsyth R., *The SKB Irradiated fuel Corrosion Programme: An evaluation of results from the experimental programme performed in the Studsvik Hot Cell Laboratory*, Forsyth Consulting, SKB Report TR-97-25, 1997

(François *et al.*, 2012) François B., Labiouse V., Dizier A., Marinelli F., Charlier R. and Collin F., *Hollow Cylinder Tests on Boom Clay: Modelling of Strain Localization in the Anisotropic Excavation Damaged Zone*, Rock Mechanics and Rock Engineering, Published online 16 December 2012

(Frederickson *et al.*, 1997) Frederickson J.K., McKinley J.P., Bjornstad B.N., Long P.E., Ringelberg D.B., White D.C., Krumholz L.R., Sufliata J.M., Colwell F.S., Lehman R.M. and Phelps T.J., *Pore-Size Constraints on the Activity and Survival of Subsurface Bacteria in a Late Cretaceous Shale-Sandstone Sequence, Northwestern New Mexico*, Geomicrobiology Journal 14, pp. 183-202, 1997

(Freeze and Cherry, 1979) Freeze A.R. and Cherry J.A., *Groundwater*, Prentice-Hall, 1979

(Frugier *et al.*, 2008) Frugier P., Gin S., Minet Y., Chave T., Bonin B., Godon N., Lartigue J.E., Jollivet P., Ayral A., De Windt L. and Santarini G., *SON68 nuclear glass dissolution kinetics: Current state of knowledge and basis of the new GRAAL model*, Journal of Nuclear Materials 380, pp 8-21, 2008

(Fukuda and Akashi, 1996) Fukuda T. and Akashi M., *Effect of  $[HCO_3^- + CO_3^{2-}]$  on corrosion crevice repassivation potential of carbon steel in simulated bentonite environment*, Mat. Res. Soc. Symp. Proc. Vol. 412, pp. 597-602, 1996

(Fukaya and Akashi, 1999) Fukaya Y. and Akashi M., *Passivation behavior of mild steel used for nuclear waste disposal package*, Mat. Res. Soc. Symp. Proc. Vol. 556, pp. 871-878, 1999

(Galson, 2004) Galson Sciences Ltd, *Techniques for Post-Closure Monitoring*, Galson Sciences Ltd and Golder Associates Report for Nirex 0358-1, Version 1.1., 2004

(Galson, 2010) Galson Sciences Ltd, *Higher Activity Waste – Interim Store Performance and Monitoring*, Galson Sciences Ltd Report to UKAEA Ltd, under contract to the Nuclear Decommissioning Authority, 0943-1, Version 1, 2010

(Galson, 2011) Galson Sciences Ltd, *R&D Feasibility Programme for the Geological Disposal of Category B&C Radioactive Waste: State-of-the-art Synthesis Report*, Galson Sciences Ltd Report to ONDRAF/NIRAS, 0910-2, Version 1, 2011

(Garavito *et al.*, 2007) Garavito A.M., De Cannière P. and Kooi H., *In-situ chemical osmosis experiment in the Boom Clay at the Mol underground research facility*, Physics and Chemistry of the Earth 32, pp. 421-433, 2007

(Garcia-Castellanos *et al.*, 2000) Garcia-Castellanos D., Cloetingh S. and van Balen R., *Modelling the Middle Pleistocene uplift in the Ardennes-Rhenish Massif: thermo-mechanical weakening under the Eifel?*, Global and Planetary Change 27, pp. 39-52, 2000

(Garitte *et al.*, 2012) Garitte B., Sillen X., Li X., Armand G., Vaunat J. and Gens A., *Comparative study of three in-situ heating tests in anisotropic media: the HE D, TER and ATLAS experiments*, Proceedings of the European Commission TIMODAZ THERESA International Conference Impact of thermo hydro mechanical chemical (THMC) processes on the safety of underground radioactive waste repositories, Luxembourg, 29 September–1 October 2009, EUR 25527 EN, 2012

(Gaucher *et al.*, 2004) Gaucher E., Blanc P., Matray J.M. and Michau N., *Modeling diffusion of an alkaline plume in a clay barrier*, Applied Geochemistry 19, pp. 1505-1515, 2004

(Gaucher *et al.*, 2010) Gaucher E., Flehoc C., Braibant G. and Proust E., *Mol underground research facility pCO<sub>2</sub> on core samples, CO<sub>2</sub> gas isotope, Calcite, dolomite and siderite isotopes, report of experiments*, BRGM/RP-57965-FR BRGM, 2010

(Gedeon, 2008) Gedeon M., *Neogene Aquifer Model*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-48, 2008

(Gedeon and Wemaere, 2009) Gedeon M. and Wemaere I., *Transient model of the confined aquifers located below the Boom Clay, Regional Hydrogeological Model for the Mol Site*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-72, 2009

(GEMIX, 2009) Groupe GEMIX, *Quel mix énergétique idéal pour la Belgique aux horizons 2020 et 2030 ?*, rapport final, 2009

(Ghafoori *et al.*, 2008) Ghafoori N., Diawara H. and Beasley S., *Resistance to external sodium sulphate attack for early-opening-to-traffic Portland cement concrete*, Cement and Concrete Composites, 30, pp. 444-454, 2008

(Gibbard, 2007) Gibbard P., *Europe cut adrift*, Nature 448, pp. 259-260, 2007

(Glaus *et al.*, 2007) Glaus M.A., Baeyens B., Bradbury M.H., Jakob A., Van Loon L.R. and Yaroshchuk A., *Diffusion of <sup>22</sup>Na and <sup>85</sup>Sr in montmorillonite: Evidence of interlayer diffusion being the dominant pathway at high compaction*, Environmental Science and Technology 41, pp. 478-485, 2007

(Godon, 2004) Godon N., *Dossier de référence sur le comportement à long terme des verres nucléaires*, CEA, rapport technique DTCD/2004/06, 2004

(Godon *et al.*, 2008) Godon N., Gin S., Minet Y., Grambow B., Lemmens K. and Aertsens M., *Part 1: Reference report on the state-of-the-art of glass properties and glass alteration during long term storage and under disposal conditions*, Deliverable 1.1.1 of RTD component 1, NF-PRO project, European Commission, 2008

(Goultly, 2001) Goultly N.R., *Mechanics of layer-bound polygonal faulting in fine-grained sediments*, Journal of the Geological Society of London, 159, pp. 239-246, 2001

(Goultly, 2008) Goultly N.R., *Geomechanics of polygonal fault systems: a review*, Petroleum Geoscience, 14, pp. 389-397, 2008

(Goultly and Swarbrick, 2005) Goultly N.R. and Swarbrick R.E., *Development of polygonal fault systems: a test of hypotheses*, Journal of the Geological Society, London, 162, pp. 587-590, 2006

(Govaerts *et al.*, 2010) Govaerts J., Weetjens E. and Marivoet J., *Preparative Safety Assessments in the Framework of SFC1: Reference case model calculations Version 1 Series 1*, Restricted Report of the Belgian Nuclear Research Centre, SCK•CEN-R-5305, 2010

(Govaerts and Weetjens, 2010b) Govaerts J. and Weetjens E., *Scoping Calculation: When and in which concentration will aggressive species reach the overpack surface?*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-133, 2010

(Govaerts *et al.*, 2011) Govaerts J., Weetjens E. and Beerten K., *Numerical simulation of Permafrost Depth at the Mol site*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-148, 2011

(Gupta *et al.*, 2007) Gupta S., Collier J.S., Plamer-Felgate A. and Potter G., *Catastrophic flooding origin of shelf valley systems in the English Channel*, Nature 448, pp. 342-346, 2007

(Hardy and Marivoet, 2000) Hardy L. and Marivoet J., *Sensitivity study on the local transport model of the Neogene aquifer*, Restricted Report of the Belgian Nuclear Research Centre, SCK•CEN R-3468, 2000

(Harju-Autti and Volckaert, 1995) Harju-Autti P. and Volckaert G., *Evaluation of the chemical-toxic consequences of geological disposal of radioactive waste*, Report of the Belgian Nuclear Research Centre, SCK•CEN R-3051, 1995

(Haverkamp *et al.*, 2012) Haverkamp B., Biurrun E., Nieder-Westermann G., Van Humbeek H. and Van Cotthem A., *Engineering for Operation of a Future Belgian Deep Geological Repository for ILW and HLW*, WM2012 Conference, Phoenix, Arizona, USA, February 26 – March 1, 2012

(He *et al.*, 2007) He H., Guo Z., Stroeve P., Stroeve M. and Sluys L.J., *Self-healing capacity of concrete – Computer simulation study of unhydrated cement structure*, Image Anal Stereol 26, pp. 137-143, 2007

(Hearn and Morley, 1997) Hearn N. and Morley C.T., *Self-sealing property of concrete – Experimental evidence*, Scientific reports, Materials and Structures/Matériaux et Constructions Vol. 30, pp. 404-411, August-September 1997

(Hemes *et al.*, 2011) Hemes S., Desbois G., Urai J., De Craen M. and Honty M., *Comparative study on porosity in fine- and coarse-grained Boom Clay samples (Mol-Dessel reference site, Belgium)*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-157, 2011

(Henriet *et al.*, 1982) Henriet J.P., D'Olier B. Auffret J.P. and Andersen H.L., *Seismic tracking of geological hazards related to clay tectonics in the Southern Bight of the North Sea*, Koninklijke Vlaamse Ingenieursvereniging, Proceedings of the Symposium on Engineering in Marine Environment, 1.5-1.15, 1982

(Henriet *et al.*, 1983) Henriet J.P., Schittekat J. and Heldens Ph., *Borehole seismic profiling and tube wave applications in a dam site investigation*, Geophysical Prospecting, 31, pp. 72-86, 1983

(Henriet *et al.*, 1988) Henriet J.P., De Batist M., Van Vaerenbergh W. and Verschuren M., *Seismic facies and clay tectonic features of the Ypresian clay in the southern North Sea*, Bull. Soc. Belg. Geol. 97, pp. 457-472, 1988

(Henriet and De Batist, 1989) Henriet J.P. and De Batist M., *The faulted zone of the North Hinder (Southern North Sea)*, Annales de la Société Géologique de Belgique, 112, p. 313, 1989

(Henriet *et al.*, 1989) Henriet J.P., De Batist M., D'Olier B. and Auffret J.P., *A northeast trending structural deformation zone near North Hinder*, Henriet *et al.* (Eds.), The Quaternary and Tertiary geology of the Southern Bight, North Sea. 9-15, 1989

(Henriet *et al.*, 1991) Henriet J.P., De Batist M. and Verschuren M., 1991, *Early fracturing of Palaeogene clays, southernmost North Sea: relevance to mechanisms of primary hydrocarbon migration*, Ed. A.M. Spencer, Generation, accumulation, and Production of Europe's hydrocarbons, Special publications of the European Association of Petroleum Geoscientists 1, pp. 217-227, 1991

(Henriet and De Batist, 1996), Henriet J.P. and De Batist M., *Palaeo and Present-day Fluid Flow through Eocene Clay Layers in Flanders. Fracturation and Intraformational*

*Faulting in the Ieper Clay: Evidence for a Major Palaeo-flow Event*, Fluid Flow through Faults and Fractures in Argillaceous Formations, Proceedings of a Joint NEA/EC Workshop, Berne, Switzerland, 10-12 June, 1996, Organised by NEA Working Group on Measurement and Physical Understanding of Groundwater Flow through Argillaceous Media (the "Clay Club") and NAGRA, 381-388 pp., 1996

(Hermans *et al.*, 2012) Hermans T., Vandenbohede A., Martin R., Kemna A., Beaujean J. and Nguyen F., *Imaging artificial salt water infiltration using electrical resistivity tomography constrained by geostatistical data*, Journal of Hydrogeology, in press, dx.doi.org/10.1016/j.jhydrol.2012.03.021, 2012

(Herms, 2010) Herms E., *General criteria for the selection of carbon steels to face hydrogen embrittlement in the context of deep geological disposal*, CEA Report NT DPC/SCCME 09-474-A, 2010

(Hobbs *et al.*, 2011) Hobbs P.R.N., Dobbs M.R. and Cuss R.J., *Desk based study and literature review of diapirism in plastic clays and an analysis of the critical state of Boom Clay*, Minerals and Waste, Commercial Report CR/11/012, British Geological Survey, ed. Shaw R., 2011

(Honty and De Craen, 2009) Honty M. and De Craen M., *Mineralogy of the Boom Clay in the Essen-1 borehole*, External Report of the Belgian Nuclear Research Centre; SCK•CEN ER-87, 2009

(Honty, 2010) Honty M., *CEC of the Boom Clay – a review*, External Report of the Belgian Nuclear Research Centre; SCK•CEN ER-134, 2010

(Honty *et al.*, 2010b) Honty M., De Craen M., Osacký M. and Madejová J., *Thermally induced modifications of clays, Final Activity Report for TIMODAZ WP 3.2.*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-116, 2010

(Honty *et al.*, 2010c) Honty M., De Craen M., Wang L., Madejová J., Czímerová A., Pentrák M., Stríček I. and Van Geet M., *The effect of high pH alkaline solutions on the mineral stability of the Boom Clay– Batch experiments at 60°C*, Applied Geochemistry Volume 25, Issue6, pp. 825-840, 2010

(Honty and De Craen, 2012) Honty M. and De Craen M., *Boom Clay mineralogy – qualitative and quantitative aspects, Status 2011*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-194, 2012

(Honty *et al.*, 2012b) Honty M., Wang L., Osacký M., Uhlík P., Czímerová A., Madejová J., *Experimental interactions of the Opalinus Clay and Boom Clay with various repository relevant solutions at 90 °C under closed conditions*, Applied Clay Science, Vol. 59-60, pp. 50-63, May 2012

(Horseman *et al.*, 1987) Horseman S. T., Winter M. G. and Entwistle D.C., *Geotechnical characterisation of Boom clay in relation to disposal of radioactive waste*, Publications of the European Communities, EUR 1087 EN, Luxembourg, 1987

(Hueckel and Pellegrini, 1996) Hueckel T. and Pellegrini R., *A Note on Thermomechanical Anisotropy of Clays*, Engineering Geology 41 (1-4) (January), pp. 171-180, 1996

(Hueckel *et al.*, 2009) Hueckel T., François B. and Laloui L., *Explaining Thermal Failure in Saturated Clays*, Géotechnique 59, No. 3, pp. 197-212, 2009

(Huet, 2005) Huet B., *Comportement à la corrosion des armatures dans un béton carbonaté. Influence de la chimie de la solution interstitielle et d'une barrière de transport*, Thèse doctorale, Institut national des sciences appliquées de Lyon, 2005

(Huet *et al.*, 2005b) Huet B., L'Hostis V. Miserque F and Idrissi H., *Electrochemical behavior of mild steel in concrete: influence of pH and carbonate content of concrete pore solution*, Electrochimica Acta 51, pp. 172-180, 2005

(Huybrechts, 2010) Huybrechts P., *Vulnerability of an underground radioactive waste repository in northern Belgium to glaciotectionic and glaciofluvial activity during the next 1 million years*, Departement Geografie Vrije Universiteit Brussel, Report 10/01, 2010

(Huysmans, 2006) Huysmans M., *A geostatistical methodology for modelling groundwater flow and transport in low-permeability media: application on Boom Clay, Ieper Clay and Toarcian argillites*, Ph.D. thesis, KULeuven, Belgium, 2006

(Huysmans and Dassargues, 2006) Huysmans M. and Dassargues A., *Hydrogeological modeling of radionuclide transport in low permeability media: a comparison between Boom Clay and Ypresian Clay*, Environmental Geology 50, pp. 122-131, 2006

(IAEA, 1995) IAEA, *The principles of radioactive waste management*, Safety Series No. 111-F, International Atomic Energy Agency, Vienna, 1995

(IAEA, 1997) IAEA, *Joint Convention on the Safety of Irradiated fuel Management and on the Safety of Radioactive Waste Management*, INFCIRC/546, International Atomic Energy Agency, Vienna, 1997

(IAEA, 2001) IAEA, *Monitoring of Geological Repositories for High Level Radioactive Waste*, IAEA TECDOC-1208, International Atomic Energy Agency, Vienna, 2001

(IAEA, 2003) IAEA, *"Reference Biospheres" for solid radioactive waste disposal*, Report of BIOMASS Theme 1 of the BIOSphere Modelling and ASSESSment (BIOMASS) Programme, IAEA-BIOMASS-6, International Atomic Energy Agency, Vienna, 2003

(IAEA, 2003b) IAEA, *Safety indicators for the safety assessment of radioactive waste disposal*, report TECDOC-1372, International Atomic Energy Agency, Vienna, 2003

(IAEA, 2003c) IAEA, *Radioactive Waste Management Glossary*, 2003 Edition, International Atomic Energy Agency, Vienna, 2003

(IAEA, 2004) IAEA, *Convention on nuclear safety*, International Atomic Energy Agency, Vienna, INFCIRC/449, 2004

(IAEA, 2006) IAEA, *Geological Disposal of Radioactive Waste*, IAEA Safety Standards for Protecting People and the Environment, Safety Requirements No. WS-R-4, International Atomic Energy Agency, Vienna, 2006

(IAEA, 2006b) IAEA, *Fundamental Safety Principles*, Safety Fundamentals No.°SF-1, International Atomic Energy Agency, Vienna, 2006

(IAEA, 2006c) IAEA, *The management system for facilities and activities, Safety requirements*, IAEA Safety Standards Series No. GS-R-3, International Atomic Energy Agency, Vienna, 2006

(IAEA, 2007) IAEA, *IAEA Safety Glossary, Terminology Used in Nuclear Safety and Radiation Protection 2007 Edition*, International Atomic Energy Agency, Vienna, 2007

(IAEA, 2008) IAEA, *The Management System for the Disposal of Radioactive Waste*, Safety Guide, No. GS-G-3.4, International Atomic Energy Agency, Vienna, 2008

(IAEA, 2009) IAEA, *Regulations for the Safe Transport of Radioactive Material*, IAEA Safety Standards for Protecting People and the Environment, Safety Requirements No. TS-R-1, International Atomic Energy Agency, Vienna, 2009

(IAEA, 2011) IAEA, *Geological disposal facilities for radioactive waste*, Specific safety guide, Safety Standard Series No. SSG-14, International Atomic Energy Agency, Vienna, 2011

(IAEA, 2011b) IAEA, *Disposal of radioactive waste*, Specific Safety Requirements No. SSR-5, IAEA Safety Standards, International Atomic Energy Agency, Vienna, 2011

(IAEA, 2012) IAEA, *Monitoring and Surveillance of Radioactive Waste Disposal Facilities*, Safety Standards DS357, Draft Safety Guide, International Atomic Energy Agency, Vienna, 2012

(ICRP, 2005) ICRP, *Assessing Dose of the Representative Person for the Purpose of Radiation Protection of the Public and The Optimisation of Radiological Protection: Broadening the Process*, Annals of the ICRP, ICRP Publication 101, International Commission on Radiological Protection, 2005

(ICRP, 2007) ICRP, *The 2007 Recommendations of the International Commission on Radiological Protection*, ICRP Publication 103, Elsevier, International Commission on Radiological Protection, 2007

(ICRP, 2008) ICRP, *Radiation Protection Recommendations as Applied to the Disposal of Long-lived Radioactive Waste*, Publication 81, Annals of the ICRP 28 4, International Commission on Radiological Protection, 1998

(ICRP, 2013) ICRP, *Radiological Protection in Geological Disposal of Long-Lived Solid Radioactive Waste*, ICRP Publication 122, Ann. ICRP 42(3), International Commission on Radiological Protection, 2013

(Imbert and Villar, 2006) Imbert Ch. and Villar M.V., *Hydro-mechanical response of a bentonite pellets/powder mixture upon infiltration*, Applied Clay Science Volume 32, Issues 3–4, pp. 197–209, May 2006

(I.N.I.S.Ma, 1998) I.N.I.S.Ma., *Report on physical and thermal properties (bulk and grain density, water content, porosity, specific surface, thermal conductivity and heat*



capacity) of core samples of the Doel 1 borehole, Technical Report N°74.252 by the Institut National Interuniversitaire des Silicates Sols et Matériaux a.s.b.l., Mons, commissioned by ONDRAF/NIRAS, 12p., 1998

(Ireland *et al.*, 2010) Ireland M.T., Goultly N.R. and Davies R.J., *Influence of pore water chemistry on silica diagenesis: evidence from the interaction of diagenetic reaction zones with polygonal fault systems*, Journal of the Geological Society, London, 167, pp. 273-279, 2010

(Jacobs *et al.*, 2001) Jacobs P., De Ceukelaire M. and Sevens E., *Toelichtingen bij de geologische kaart van België - Vlaams gewest - Kaartblad Proven – Ieper – Ploegsteert (27-28-36)*, Ministerie van de Vlaamse Gemeenschap, 68p., 2001

(Jacops *et al.*, 2010) Jacops E., Volckaert G., Maes N., Weetjens E. and Govaerts J., A new method to determine gas diffusion coefficients in saturated porous media: He and CH<sub>4</sub>, 4<sup>th</sup> International Meeting on Clays in Natural and Engineered Barriers for radioactive waste confinement, Nantes, France, 2010

(Jacops *et al.*, 2012) Jacops E., Maes N., Volckaert G., Govaerts J. and Maes T., *Results and interpretation of gas-driven radionuclide transport in disturbed and undisturbed Boom Clay and Boom Clay – bentonite interfaces*, External report of the Belgian Nuclear Research Centre, SCK•CEN ER-222, 2012

(Jacquemin, 2011) Jacquemin A., *Etude de faisabilité d'un système de basculement d'un Supercontainer contenant des déchets hautement radioactifs*, travail de fin d'études en vue de l'obtention du diplôme de Master en Sciences de l'Ingénieur Industriel finalité Electromécanique, ECAM Masters thesis, 2011

(Jia, 2009) Jia S., *Long term hydro-mechanical behaviour of Boom Clay*, Ph.D. thesis, Wuhan Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, P.R.China, 2009

(Johnson and McGinnes, 2002) Johnson L.H. and McGinnes D.F., *Partitioning of Radionuclides in Swiss Power Reactor Fuels*, Technical Report 02-07, Nagra, 2002

(Johnson *et al.*, 2005) Johnson L., Ferry C., Poinssot C. and Lovera P., *Irradiated fuel radionuclide source-term model for assessing irradiated fuel performance in geological disposal: Part I. Assessment of the instant release fraction*, Journal of Nuclear Materials 346, pp. 56-65, 2005

(Johnson and King, 2008) Johnson L. and King F., *The effect of the evolution of environmental conditions on the corrosion evolutionary path in a repository for irradiated fuel and high-level waste in Opalinus Clay*, Journal of Nuclear Materials, Volume 379, Issues 1-3, pp. 9-15, 2008

(Johnston, 2011) Johnston D.T., *Multiple sulphur isotopes and the evolution of the Earth's surface sulphur cycle*, Earth-Science Reviews, 106, pp. 161-183, 2011

(Kamali *et al.*, 2008) Kamali S., Moranville M. and Leclercq S., *Material and environmental parameter effects on the leaching of cement pastes: Experiments and modelling*, Cement and Concrete Research 38, pp. 575-585, 2008

(Keskin *et al.*, 2004) Keskin S.N., Tekinsoy M.A. and Uzundurukan S., *The Effects Of Over Consolidation Ratio And Effective Stresses To The Earth Pressure At Rest At Clay Soils*, IMO Digest, Technical Journal, Vol. 15, pp. 947-961, 2004

(King, 2007) King F., *Overview of a Carbon Steel Container Corrosion Model for a Deep Geological Repository in Sedimentary Rock*, NWMO TR-2007-01, Nuclear Waste Management Organisation Canada, 2007

(Knol, 2010) Knol A.B., Slottje P., van der Sluijs J.P. and Lebret E., *The use of expert elicitation in environmental health impact assessment: a seven step procedure*, Environmental Health, 9:19, 2010

(Kursten and Druyts, 2008) Kursten B. and Druyts F., *Methodology to make a robust estimation of the carbon steel overpack lifetime with respect to the Belgian Supercontainer design*, Journal of Nuclear Materials, Vol. 379, pp. 91-96, ISSN 0022-3115, 2008

(Kursten, 2009) Kursten B., *SCC susceptibility studies of C-steel in artificial concrete pore solutions, status on January 2009*, External report of the Belgian Nuclear Research Centre, SCK•CEN ER-83, 2009

(Kursten, 2010) Kursten B., *Uniform Corrosion Rate Data of Carbon Steel in Cementitious Environments relevant to the Supercontainer Design, 'best estimate' from available literature data*, Status on December 2010, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-94, 2010

(Kursten *et al.*, 2011) Kursten B., Druyts F., Macdonald D.D., Smart N.R., Gens R., Wang L., Weetjens E. and Govaerts J., *Review of corrosion studies of metallic barrier in geological disposal conditions with respect to Belgian Supercontainer concept*, Corrosion Engineering, Science and Technology, Vol. 46, No 2, pp. 91-97, 2011

(Kursten and Moors, 2011b) Kursten B. and Moors H., *Corrosion studies of structural in-situ steel tubes exposed to Boom Clay for 20 years*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-82, 2011

(Kursten *et al.*, 2011c) Kursten B., Druyts F. and Gens R., *The Belgian Supercontainer concept - corrosion issues.-*, Sulphur-assisted corrosion in nuclear disposal systems, Leeds, United Kingdom, Maney Publishing, pp. 1-18, 2011

(Labat, 2011) Labat S., *Overview and Analysis of 30 Years Piezometric Observations in North-East Belgium*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-163, 2011

(Labieuse *et al.*, 2013) Labieuse V., Sauthier C. and You S., *Hollow cylinder simulation experiments of galleries in Boom Clay formation*, Rock Mechanics and Rock Engineering, published online 15 February 2013

(Laenen, 1997) Laenen B., *The geochemical signature of relative sea-level cycles recognized in the Boom Clay*, Ph.D. thesis, KULeuven, 1997

(Laga, 1966) Laga P., *Kleidiapir in de uitgraving voor de spoorwegtunnel van de E3-weg op de rechteroever te Antwerpen*, Het ingenieursblad, 35, pp. 552-553, 1966

(Laga et al., 2001) Laga P., Louwye S. and Geets S., *Paleogene lithostratigraphic units (Belgium)*, in Bultynck and Dejonghe (eds.) Guide to a revised lithostratigraphic scale of Belgium, *Geologica Belgica*, 4(1-2), pp. 135-152, 2001

(Lance and Boulanger, 2007) Lance B. and Boulanger D., *Stratégie d'application réaliste du BUC pour le concept belge de dépôt final*, Note 0600588/740 - « B » - 1, Belgonucléaire, 2007

(Le, 2008) Le T., *Comportement thermo-hydro-mécanique de l'argile de Boom*, Thèse de doctorat, CERMES, Ecole Nationale des Ponts et Chaussées, France, 2008

(Le et al., 2012) Le T., Cui Y., Tang A., Delage P. and Li X., *The behaviour of Boom clay under triaxial compression at different temperatures*, Proceedings of the European Commission TIMODAZ THERESA International Conference Impact of thermo hydro mechanical chemical (THMC) processes on the safety of underground radioactive waste repositories, Luxembourg, 29 September–1 October 2009, EUR 25527 EN, 2012

(Legrand, 1968) Legrand R., *Le Massif du Brabant*, Mémoires pour servir à l'explication des Cartes géologiques et minières de la Belgique 9, 148p., 1968

(Lemmens, 2010) Lemmens K., *Source term and compatibility of irradiated fuel in Supercontainer disposal conditions (status 2010)*, External Report of the Belgian Nuclear Research Centre SCK•CEN ER-150, 2010

(Lemmens, 2011) Lemmens K., *Source term and compatibility of vitrified (V)HLW waste in Supercontainer disposal conditions (status mid 2011)*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-149, 2011

(Lenhardt, 2009) Lenhardt W.A., *The Impact of Earthquakes on Mining Operations*, BHM, 154, Heft 6, Springer-Verlag, 2009

(LGC, 1998) LGC (Henriet G. and Sine B.), *Report of physical and mechanical properties (Young's and Poisson's ratios, cohesion and angle of internal friction, swelling pressure, Atterberg limits and grain-size distribution) of core samples of the Doel 1 borehole*, Rapport d'essais N°254/78-98 by the Laboratoire du Génie Civil, Université Catholique de Louvain, commissioned by ONDRAF/NIRAS, Bestel Bon 9702856, 171p., 1998

(L'Hostis et al., 2011) L'Hostis V., Amblard E., Blanc C., Miserque F., Paris C. and Bellot-Gurlet L., *Passive corrosion of steel in concrete in context of nuclear waste disposal*, Corrosion Engineering, Science and Technology Vol. 46 No. 2, pp. 177-181, 2011

(Li et al., 2010) Li X., Bastiaens W., Van Marcke P., Verstricht J., Chen G., Weetjens E. and Sillen X., *Design and development of large-scale in-situ PRACLAY heater test and horizontal high-level radioactive waste disposal gallery seal test in Belgian HADES*, Journal of Rock Mechanics and Geotechnical Engineering, 2:2, pp. 103-110, 2010

(Lima, 2011) Lima A.F., *Thermohydromechanical behaviour of two deep Belgian clay formations: Boom and Ypresian clays*, doctoral thesis, Universitat Politècnica de Catalunya, 2011

(Lima et al., 2011) Lima A., Romero E. and Piña Y., *Water retention properties of two deep clay formations within the context of radioactive waste disposal*, VII Brazilian Symposium on Unsaturated Soil, Pirenópolis, Goiania, Brazil, pp. 315-321 2011

(Loida et al., 2007) Loida A, Metz V. and Kienzler B., *Alteration behaviour of high burnup irradiated fuel in salt brine under hydrogen overpressure and in presence of bromide*, Materials Research Society, Mater. Res. Soc. Symp. Proc. Vol. 985, 2007

(Loida et al., 2009) Loida A., Gens R., Metz V., Lemmens K., Cachoir C., Mennecart T. and Kienzler B., *Corrosion Behavior of High Burnup Irradiated fuel in Highly Alkaline Solutions*, Mater. Res. Soc. Symp. Proc. Vol. 1193, Materials Research Society, 2009

(Loida et al., 2009b) Loida A., Müller N., Soballa E., Schild D., Kienzler B., *Investigation of the Corrosion Behaviour of Irradiated Irradiated fuel in High pH Solutions*, Draft Final report, FZK-INE 002/09, contract No 350 150 65 with ONDRAF/NIRAS, Forschungszentrum Karlsruhe, Institut für Nukleare Entsorgung (INE), 2009

(Loida et al., 2012) Loida A., Gens R., Bube C., Lemmens K., Cachoir C., Mennecart T. and Kienzler B., *Corrosion behaviour of spent nuclear Fuel in High pH solutions – Effect of hydrogen*, Mater. Res. Soc. Symp. Proc. Vol. 1475, 2012

(Lonergan et al., 1998) Lonergan L., Cartwright J. and Jolly R., *The geometry of polygonal fault systems in the Tertiary mudrocks of the North Sea*, Journal of Structural Geology, 20, pp. 529-548, 1998

(Lonergan et al., 1998b) Lonergan L., Cartwright J., Laver R. and Staffurth J., *Polygonal faulting in the Tertiary of the central North Sea: implications for reservoir geology*, in M.P. Coward, T.S. Baltaban and H. Johnson (eds.) Structural Geology in Reservoir Characterization. Geological Society, London, Special Publications, 127, pp. 191-207, 1998

(Lorant et al., 2008) Lorant, F., Largeau, C., Behar, F. and De Cannière P., *Improved kinetic modeling of the early generation of CO<sub>2</sub> from the Boom Clay kerogen. Implications for simulation of CO<sub>2</sub> production upon disposal of high activity nuclear waste*, Organic Geochemistry 39, pp. 1294–1301, 2008

(MacDonald et al., 2011) Macdonald D.D., M. Urquidi-Macdonald M., Engelhardt G.R., Azizi O., Saleh A., Almazooqi A. and Rosas-Camacho O., *Some important issues in electrochemistry of carbon steel in simulated concrete pore water Part 1 – theoretical issues*, Corrosion Engineering, Science and Technology, Vol. 46, No. 2, 2011

(MacDonald, 2011b) MacDonald D.D., *The history of the Point Defect Model for the passive state: A brief review of film growth aspects*, Electrochimica Acta Vol.56, no.4, pp. 1761-1772, 2011

(Machel, 2001) Machel H.G., *Bacterial and thermochemical sulfate reduction in diagenetic settings – old and new insights*, Sedimentary Geology, 140, pp. 143-175, 2001

(Maes *et al.*, 2008) Maes N., Salah S., Jacques D., Aertsens M., Van Gompel M., De Cannière P., Velitchkova N., *Retention of Cs in Boom Clay: comparison of data from batch sorption tests and diffusion experiments on intact clay cores*, Phys. Chem. of the Earth, Vol. 33, pp. S149-S155, 2008

(Maes *et al.*, 2011) Maes N., Salah S., Bruggeman C., Aertsens M. and Martens E., *Caesium retention and migration behaviour in Boom Clay first draft*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-153, 2011

(Maes *et al.*, 2012) Maes N., Salah S., Bruggeman C., Aertsens M., Martens E. and Van Laer L., *Strontium retention and migration behaviour in Boom Clay Topical report - First Full Draft*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-197, 2012

(Mair *et al.*, 1992) Mair R.J., Taylor R.N. and Clarke B.G., *Repository tunnel construction in deep clay formations*, Commission of the European Communities, Nuclear science and Technology, Report EUR 13964, 1992

(Mallants *et al.*, 2001) Mallants D., Marivoet J. and Sillen X., *Performance Assessment of the disposal of vitrified high-level waste in a clay layer*, Journal of Nuclear Materials 298, pp. 125-135, 2001

(Mariën *et al.*, 2011) Mariën A., Bleyen N., Aerts S. and Valcke E., *The Study of Abiotic Reduction of Nitrate and Nitrite in Boom Clay*, Physics and Chemistry of the Earth 36, pp. 1639-1647, 2011

(Mariën *et al.*, 2012) Mariën A., Valcke E., Bleyen N., Van Geet M. and Wevers M., *The Use of  $\mu$ CT and ESEM in the Study of the Osmosis Induced Water Uptake by Eurobitum Bituminized Radioactive Waste*, Microscopy and Microanalysis 18, pp. 1-18, 2012

(Mariën *et al.*, 2012b) Mariën A., Valcke E., Bleyen N. and Smets S., *The osmosis induced swelling and  $\text{NaNO}_3$  leaching of radioactive and artificially aged Eurobitum bituminized waste*, Material Research Society, Symp. Proc. Vol. 1475, pp. 113-118, 2012

(Mariën *et al.*, 2013) Mariën A., Bleyen N. and Valcke E., *The swelling of EUROBITUM by water uptake and its geo-mechanical consequences*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-218, 2013

(Marivoet *et al.*, 2009) Marivoet J., Jacques D., Van Geet M., Bastiaens W. and Wemaere I., *Considerations on Upscaling of Hydraulic and Transport Parameters for a Plastic Clay Formation*, Report prepared in the framework of the EC funded Integrated Project FUNMIG, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-102, 2009

(Marivoet *et al.*, 2010) Marivoet J., Weetjens E., Raeymaekers F. and Seetharam S., *Testing Safety and Performance Indicators for a Geological Repository in Clay: Results*

obtained by SCK•CEN in the framework of WP3.4 of the EC PAMINA Project, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-125, 2010

(Martens *et al.*, 2010) Martens E., Maes N., Weetjens E., Van Gompel M. and Van Ravestyn L., *Modelling of a Large-scale In-situ Migration Experiment with <sup>14</sup>C-labelled Natural Organic Matter in Boom Clay*, 12<sup>th</sup> International Conference on the Chemistry and Migration Behaviour of Actinides and Fission Products in the Geosphere. Migration 2009, Kennewick, Washington, United States, 20-25 September 2009, *Radiochimica Acta*, 98:9-11, pp. 695-701, 2010

(Martens *et al.*, 2011) Martens E., Jacques D., Wang L., De Cannière P., Van Gompel M., Mariën A. and Valcke E., *Modelling of cation concentrations in the outflow of NaNO<sub>3</sub> percolation experiments through Boom Clay cores*, *Physics and Chemistry of the Earth*, 36, pp. 1693-1699, 2011

(Mathys, 2009) Mathys M., *The Quaternary geological evolution of the Belgian Continental Shelf, southern North Sea*, Ph.D thesis, UGent, 482pp., 2009

(Mazurek, *et al.*, 2008) Mazurek M., Gautschi A., Marschall P., Vigneron G., Lebon P. and Delay J., *Transferability of geoscientific information from various sources (study sites, underground laboratories, natural analogues) to support safety cases for radioactive waste repositories in argillaceous formations*, *Physics and Chemistry of the Earth*, 33, S95-S105, 2008

(Mazurek *et al.*, 2009) Mazurek M., Alt-Epping P., Bath A., Gimmi T., Waber H. N., Buschaert S., De Cannière P., De Craen M., Gautschi A., Savoye S., Vinsot A., Wemaere I., Wouters L., *Natural Tracer Profiles Across Argillaceous Formations: the CLAYTRAC project*, *Radioactive Waste Management, Nuclear Energy Agency, NEA No. 6253*, 2009

(Melkior *et al.*, 2005) Melkior T., Yahiaoui S., Motellier S., Thoby D. and Tevissen E., *Caesium sorption and diffusion in Bure mudrock samples*, *Applied Clay Science* Vol. 29 issue 3-4, pp. 172-186, June 2005

(Melkior *et al.*, 2007) Melkior T., Yahiaoui S., Thoby D., Motellier S., and Barthès V., *Diffusion coefficients of alkaline cations in Bure mudrock*, *Physics and Chemistry of the Earth* 32, pp. 453-462, 2007

(Mennecart *et al.*, 2011) Mennecart T., Cachoïr C. and Lemmens K., *The effect of cement on the UO<sub>2</sub> dissolution rate and UO<sub>2</sub> solubility*, *Programme 2004-2008, status March 2009*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-156, 2011

(Mercier-Castiaux and Dupuis, 1988) Mercier-Castiaux M. and Dupuis Ch., *Clay mineral associations in the Ypresian Formations in the NW European Basin – Time and geographical variations – Interpretations*, *Bulletin de la Société belge de Géologie*, 97(3-4), pp. 441-450, 1988

(Mertens *et al.*, 2003) Mertens J., Vandenberghe N., Wouters L. and Sintubin M., *The origin and development of joints in the Boom Clay Formation (Rupelian) in Belgium*, *Subsurface Sediment Mobilization*, Geological Society, London, Special Publications, Ed. Van Rensbergen P., Hillis R.R., Maltman A.J. and Morley C.K., 216, pp. 309-321, 2003

(Mertens *et al.*, 2004) Mertens J., Bastiaens W. and Dehandschutter B., *Characterisation of induced discontinuities in the Boom Clay around the underground excavations* (URF, Mol, Belgium), *Applied Clay Science* 26, pp. 413– 428, 2004

(Mertens, 2005) Mertens J., *Burial history of the two potential host formations (Boom Clay; Ypresian clays)*, ONDRAF/NIRAS note 2005-0062 (rev. 0), 2005

(Metz *et al.*, 2008) Metz V., Loida A., Bohnert E., Schild D. and Dardenne K., *Effects of hydrogen and bromide on the corrosion of spent nuclear fuel and  $\gamma$ -irradiated  $UO_2(s)$  in NaCl brine*, *Radiochimica Acta*, 96, pp. 637-648, 2008

(Meyus *et al.*, 2000) Meyus Y., Van Daele T., Batelaan O. and De Smedt F., *Concept Vlaams Grondwater Model (VGM): Eindrapport*, Report by Vrije Universiteit Brussel, Vakgroep Hydrogeologie en Waterbouwkunde, commissioned by Ministerie van de Vlaamse Gemeenschap, AMINAL, afdeling Water, Brussel, 90p., 2000

(Meyus *et al.*, 2004) Meyus Y., Severyns J., Batelaan O. and De Smedt F., *Ontwikkeling van regionale modellen ten behoeve van het Vlaams Grondwater Model (VGM) in GMS/MODFLOW. Perceel 1: Het Centraal Kempisch model. Deelrapport 1: Basisgegevens en conceptueel model*, Report by Vrije Universiteit Brussel, Vakgroep Hydrogeologie en Waterbouwkunde, commissioned by Ministerie van de Vlaamse Gemeenschap, AMINAL, afdeling Water, Brussel, 126p., 2004

(Meyus *et al.*, 2004b) Meyus Y., Adyns D., Woldeamlak S.T., Batelaan O., De Smedt F., *Opbouw van een Vlaams Grondwatermodel Deelrapport 2. Totaal VGM-karteergebied en Vlaanderen*, Report by Vrije Universiteit Brussel, Vakgroep Hydrogeologie en Waterbouwkunde, commissioned by Ministerie van de Vlaamse Gemeenschap, AMINAL, afdeling Water, Brussel, 70p., 2004

(MICADO, 2010) Grambow B., Bruno J., Duro L., Merino J., Tamayo A., Martin C., Pepin G., Schumacher S., Smidt O., Ferry C., Jegou C., Quiñones J., Iglesias E., Rodriguez Villagra N., Nieto J.M., Martínez-Esparza A., Loida A., Metz V., Kienzler B., Bracke G., Pellegrini D., Mathieu G., Wasselin-Trupin V., Serres C., Wegen D., Jonsson M., Johnson L., Lemmens K., Liu J., Spahiu K., Ekeroth E., Casas I., de Pablo J., Watson C., Robinson P. and Hodgkinson D., *Model Uncertainty for the Mechanism of Dissolution of Irradiated fuel in Nuclear Waste Repository, Final report*, MICADO Project, European Commission, EUR 24597 EN, 2010

(Michels *et al.*, 2010) Michels R., Faure P., Schumacher A., *Influence de l'eau et des minéraux sur la formation de  $CO_2$  pendant la pyrolyse de l'Argile de Boom : conséquences sur le bilan de masse et la cinétique de formation, Comparaison de la pyrolyse de l'argile de Boom et de son kérogène isolé*, Rapport CREGU n° 2009-31, 2010

(MODERN, 2011) MoDeRn Expert Stakeholders Workshop, Deliverable D-5.3.1, Report May 2011, EU project (FP 7), 2011

(Mohammad *et al.*, 2009) Mohammad W., Vandenberghe N. and Zeelmaekers E., *The NIRAS-ONDRAF Kallo 1&2 boreholes – The Ypresian cored section: 254-410m depth*, Report by the Laboratory for Applied Geology and Mineralogy, KULeuven, 142p., December 2009

(Mokni *et al.*, 2011) Mokni, N., Olivella S., Valcke E., Mariën A., Smets S. and Li X., *Deformation and Flow Driven by Osmotic Processes in Porous Materials: Application to Bituminised Waste Materials*, *Transport in Porous Media* 86 (2): 635–662. doi:10.1007/s11242-010-9644-2, 2011

(Moniteur belge, 1983) *Convention BENELUX en matière de conservation de la nature et de protection des paysages*, signée à Bruxelles le 8 juin 1982, Moniteur belge du 20 octobre 1983

(Moniteur belge, 1995) = (VLAREM, 1995)

(Moniteur belge, 2001) Article 17 de l'arrêté royal du 20 juillet 2001 portant règlement général de la protection de la population, des travailleurs et de l'environnement contre le danger des rayonnements ionisants, Moniteur belge du 30 août 2001

(Moniteur belge, 2003) Loi du 31 janvier 2003 sur la sortie progressive de l'énergie nucléaire à des fins de production industrielle d'électricité, Moniteur belge du 28 février 2003

(Moniteur belge, 2003b) Loi du 17 décembre 2002 portant assentiment à la Convention sur l'accès à l'information, la participation du public au processus décisionnel et l'accès à la justice en matière d'environnement, et aux Annexes I<sup>er</sup> et II, faites à Aarhus le 25 juin 1998, Moniteur belge du 24 avril 2003

(Moniteur belge, 2006) Loi du 13 février 2006 relative à l'évaluation des incidences de certains plans et programmes sur l'environnement et à la participation du public dans l'élaboration des plans et des programmes relatifs à l'environnement, Moniteur belge du 10 mars 2006

(Moniteur belge, 2008) Arrêté royal du 28 novembre 2008 instituant un groupe d'experts sur le mixte énergétique de la Belgique, Moniteur belge du 2 décembre 2008

(Moors, 2005) Moors H., *Topical report on the effect of the ionic strength on the diffusion accessible porosity of Boom Clay*, External report of the Belgian Nuclear Research Centre, SCK•CEN ER-02, 2005

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

(Nagra, 2002b) Nagra, Project Opalinus Clay, Models, Codes and Data for Safety Assessment, *Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis)*, Nagra Technical Report 02-06, December 2002

(Nagra, 2004) Nagra, *Estimates of the Instant Release Fraction for UO<sub>2</sub> and MOX Fuel at t=0*, a report of the Irradiated fuel Stability (SFS) Project of the 5<sup>th</sup> Euratom Framework Program, Nagra Technical Report 04-08, November 2004

(Nagra, 2005) Nagra, *Irradiated fuel evolution under disposal conditions, synthesis of Results from the EU Irradiated fuel Stability (SFS) Project*, a report of the Irradiated fuel



Stability (SFS) Project of the 5<sup>th</sup> Euratom Framework Program, Nagra Technical Report 04-09, March 2005

(Nagra, 2010) Nagra, *Tremblements de terre: Pas de danger pour les dépôts en milieu géologique profond*, Nagra, Cahier thématique, 2010

(Nagra, 2010b) NAGRA, *Scenario Development methodologies: Applications at Japanese and European implementers*, Outcomes of NUMO's Scenario Development Methodology Workshop at Baden, Switzerland (2-3 December 2009), Nagra Project Report NPB 10-02, 2010

(Nakayama and Akashi, 1991) Nakayama G. and Akashi M., *The critical condition for the initiation of localized corrosion of mild steel used for nuclear waste package*, Mat. Res. Soc. Symp. Proc. Vol. 212, pp. 279- 286, 1991

(National Nuclear Laboratory, 2010) National Nuclear Laboratory (Stanley S.), *Development of innovative solutions to monitor radioactive waste packages in order to validate long-term behaviour and performance*, National Nuclear Laboratory Report to the Nuclear Decommissioning Authority, NNL (09) 10730, 2010

(NEA, 2000) NEA, *Features, Events and Processes (FEPs) for Geological Disposal of Radioactive Waste – An International Database*, OECD/NEA, Paris, 2000

(NEA, 2002) NEA, *The Role of the Biosphere in a Safety Case*, Integration Group for the Safety Case (IGSC), IGSC TOPICAL SESSION at the third IGSC Meeting, 24 October 2001, NEA/RWM/NEA/RWM/IGSC(2002), OECD/NEA, Paris, 2002

(NEA, 2003) NEA, *SAFIR2: Belgian R&D Programme on the Deep Disposal of High-level and Long-lived Radioactive Waste: An International Peer Review*, OECD/NEA, 2003

(NEA, 2004) NEA, *Post-closure safety case for geological repositories: Nature and purpose*, NEA Report No. 3679, OECD/NEA, Paris, 2004

(NEA, 2005) NEA, *Clay Club Catalogue of Characteristics of Argillaceous Rocks*, Compiled by J.-Y. Boisson (IRSN, France) with the help of the Working Group on the Characterisation, the Understanding and the Performance of Argillaceous Rocks as Repository Host Formations (the "Clay Club"), OECD/NEA, 2005

(NEA, 2006) NEA, *Very high Burnups in Light Water Reactors*, NEA Report No. 6224, OECD/NEA, Paris, 2006

(NEA, 2010) NEA, *Self-sealing of Fractures in Argillaceous Formations in the Context of Geological Disposal of Radioactive Waste, Review and Synthesis*, Radioactive Waste Management, NEA Report No. 6184, OECD/NEA, Paris, 2010

(NEA, 2010b) NEA, *Towards Transparent, Proportionate and Deliverable Regulation for Geological Disposal*, Workshop Proceedings Tokyo, Japan 20-22 January 2009, Radioactive Waste Management, NEA Report No. 6825, OECD/NEA, Paris, 2010

(NEA, 2010c) NEA, *Optimisation of geological disposal of radioactive waste. National and international guidance and questions for further discussion*, NEA Report No. 6836, OECD/NEA, Paris, 2010

(NEA, 2012) NEA, *Reversibility of Decisions and Retrievability of Radioactive Waste, Considerations for National Geological Disposal Programmes*, Radioactive Waste Management, NEA Report No. 7085, OECD/NEA, Paris, 2012

(NEA, 2012b) NEA, *Thermodynamic Sorption Modelling in Support of Radioactive Waste Disposal Safety Cases, NEA Sorption Project Phase III*, NEA Report No. 6914, OECD/NEA, Paris, 2012

(NEA, 2012c) NEA, *Methods for Safety Assessment of Geological Disposal Facilities for Radioactive Waste, Outcomes of the NEA MeSA initiative*, NEA Report No. 6923, OECD/NEA, Paris, 2012

(NEA, 2013) NEA, *The nature and Purpose of the Post-closure Safety Cases for Geological Repositories – Safety Case Brochure 2012*, Integration Group for the Safety Case (IGSC), NEA/RWM/R(2013)1, OECD/NEA, Paris, 25 March 2013

(NF-PRO, 2008) Aranyossy J., Mayor J., Marschall P., Plas F., Blumling P., Van Geet M., Armand G., Techer I., Alheid A., Rejeb A., Pinettes P., Balland C., Popp T., Rothfuchs T., De Craen M., Wiczorek K., Pudewills A., Czaikowski O., Hou Z. and Fröhlich H., *EDZ Development and evolution (RTDC 4)*, Final Synthesis Report (D. 4.5.3) NF-PRO, 2008

(Nguyen, 2013) Nguyen X.P., *Etude du comportement chimico-hydro-mécanique des argiles raides dans le contexte du stockage de déchets radioactifs*, Ph.D. thesis, CERMES, Ecole Nationale des Ponts et Chaussées (ParisTech), Paris, 2013

(NIREX, 2002) NIREX, *The propagation of localised corrosion of carbon steel in cementitious environments*, AEAT/ERRA-0309, A report produced for United Kingdom NIREX Limited, 2002

(NIREX, 2002b) NIREX, *The localised corrosion of carbon steel and stainless steel in simulated repository*, AEAT/ERRA-0318, A report produced for United Kingdom NIREX Limited, 2002

(NIREX, 2004) NIREX (coordinator), *Thematic Network on the Role of Monitoring in a Phased Approach to Geological Disposal of Radioactive Waste*, European Commission Project Report EUR 21025, EC, Luxembourg, 2004

(Ollila, 2011) Ollila K., *Influence of Radiolysis on UO<sub>2</sub> Fuel Matrix Dissolution under Disposal Conditions*, Literature Study, Working Report 2011-27, Posiva OY, May 2011

(Olsthoorn, 2011) Olsthoorn T.N., *Geologische Berging Van Radioactief Afval in België: Mogelijke Gevolgen voor Nederland*, Rapport opgesteld in opdracht van Provincie Noord-Brabant, TU Delft, 2011

(Olyslaegers et al., 2009) Olyslaegers G., Sweeck L., van den Hoof C. and Vandenhove H., *Modelling approach for the assessment of radionuclide dispersion in the biosphere*,

Restricted contract report of the Belgium Nuclear Research Centre SCK•CEN R-4807, 2009

(ONDRAF/NIRAS, 1990) ONDRAF/NIRAS, *Safety Assessment and Feasibility Interim Report (SAFIR)*, Report submitted to the Secretary of state for Energy, 22 May 1990

(ONDRAF/NIRAS, 1994) ONDRAF/NIRAS, *Analogies naturelles en milieu argileux – Essai de synthèse bibliographique*, ONDRAF/NIRAS report NIROND 94-13, Octobre 1994

(ONDRAF/NIRAS, 2001) ONDRAF/NIRAS, *Technical Overview of the SAFIR2 report*, ONDRAF/NIRAS report NIROND 2001-05E, 2001

(ONDRAF/NIRAS, 2001b) ONDRAF/NIRAS, *SAFIR2 – Safety Assessment and Feasibility Interim Report 2*, ONDRAF/NIRAS report NIROND 2001-06E, 2001

(ONDRAF/NIRAS, 2003) ONDRAF/NIRAS, *3D-Model of the Boom Clay around the HADES-URF, Construction of an AUTOCAD 3D-model of the URF, together with the internal clay layering*, ONDRAF/NIRAS report NIROND 2003-02, 2003

(ONDRAF/NIRAS, 2004) ONDRAF/NIRAS, *A Review of Corrosion and Material Selection Issues Pertinent to Underground Disposal of Highly Active Nuclear Waste in Belgium*, ONDRAF/NIRAS report NIROND 2004-02, 2004

(ONDRAF/NIRAS, 2004b) ONDRAF/NIRAS, *Multi-criteria analysis on the selection of a reference EBS design for vitrified high level waste*, ONDRAF/NIRAS report NIROND 2004-03, 2004

(ONDRAF/NIRAS, 2005) ONDRAF/NIRAS, *The Ypresian clays as Possible Host Rock for Radioactive Waste Disposal: An Evaluation*, ONDRAF/NIRAS report NIROND-TR 2005-01, 2005

(ONDRAF/NIRAS, 2006) ONDRAF/NIRAS, *Overview of SFC1 quality measures and activities – V2 May 2007*, ONDRAF/NIRAS note NIROND-2006-1103, working document v 1.4, June 2006

(ONDRAF/NIRAS, 2006b) ONDRAF/NIRAS (Van Baelen H. and Sintubin M.), *Evaluation of the Tectonic Activity in the Roer Valley Graben (NE Belgium)*, ONDRAF/NIRAS report NIROND-TR 2006-01E, 2006

(ONDRAF/NIRAS, 2006c) ONDRAF/NIRAS (Wouters L., De Preter P., Lalieux Ph., Cool W., De Putter Th., Loutre M.-F., Bergen A., Camelbeeck Th., Vanneste K. and Alexandre P.), *Geoprospectives. Seismicity, Celestial Bodies, Climate and Volcanism*, ONDRAF/NIRAS report NIROND-TR 2006-02E, 2006

(ONDRAF/NIRAS, 2008) ONDRAF/NIRAS, *Rapport de gestion – Situation actuelle de la gestion des déchets radioactifs en Belgique*, ONDRAF/NIRAS report NIROND 2008-02, 2008

(ONDRAF/NIRAS, 2008b) ONDRAF/NIRAS (Wickham S.), *Evolution of the Near-field of the ONDRAF/NIRAS Repository Concept for Category C Wastes: First full draft report*, ONDRAF/NIRAS report NIROND-TR 2007-07E, 2008

(ONDRAF/NIRAS, 2008c) ONDRAF/NIRAS, *ACRIA-NGA-A38, De acceptatiecriteria voor het niet-geconditioneerd radioactief afval van de categorie A38*, ONDRAF/NIRAS 2008-0519 (herz. 0), 2008

(ONDRAF/NIRAS, 2009) ONDRAF/NIRAS, *The Long-Term Safety Strategy for the Geological Disposal of Radioactive Waste – SFC1 level 4 report: second full draft*, ONDRAF/NIRAS report NIROND-TR 2009-12E, 2009

(ONDRAF/NIRAS, 2009b) ONDRAF/NIRAS, *Tritiated water retention and migration behaviour in Boom Clay – SFC1 level 5 report: First Full Draft*, ONDRAF/NIRAS report NIROND-TR 2009-16E, 2009

(ONDRAF/NIRAS, 2009c) ONDRAF/NIRAS, *The Plan for the Safety and Feasibility Case 1 – SFC1 level 4 report: first full draft*, ONDRAF/NIRAS report NIROND-TR 2009-13E, 2009

(ONDRAF/NIRAS, 2009d) ONDRAF/NIRAS, *Cost Evaluation of Geological Disposal of Category B&C Waste for the Long Term Fund (Revision of 2009)*, ONDRAF/NIRAS report NIROND-TR 2009-15E, 2009

(ONDRAF/NIRAS, 2009e) ONDRAF/NIRAS, *The Long-Term Safety Assessment Methodology for the Geological Disposal of Radioactive Waste*, SFC1 level 4 report: second full draft, ONDRAF/NIRAS report NIROND-TR 2009-14E, 2009

(ONDRAF/NIRAS, 2009f) ONDRAF/NIRAS, *Long-Term Testing and Monitoring Strategy*, SFC1 level 5 Report: Final report, NIROND-TR 2011-29E, 2009

(ONDRAF/NIRAS, 2009g) ONDRAF/NIRAS, *Seismotectonic zones for probabilistic seismic-hazard assessment in Belgium*, ONDRAF/NIRAS report NIROND-TR 2008-31E, 2009

(ONDRAF/NIRAS, 2010a) ONDRAF/NIRAS, *Production of gas and sulphide by bacteria in Boom Clay*, ONDRAF/NIRAS report NIROND-TR 2010-16E, 2010

(ONDRAF/NIRAS, 2010b) ONDRAF/NIRAS, *Environmental non-human biota impact assessment and associated risk linked with biosphere releases from category A waste disposal*, ONDRAF/NIRAS report NIROND-TR 2010-09E, 2010

(ONDRAF/NIRAS, 2010c) ONDRAF/NIRAS, *Reference biosphere approach*, Project near surface disposal of category A waste at Dessel, Version 1, ONDRAF/NIRAS report NIROND-TR 2009-21 E Version 1, 2010

(ONDRAF/NIRAS, 2010d) ONDRAF/NIRAS, *Additional parameters for the cementitious near field and multilayer cover of the Dessel near surface repository*, Project near surface disposal of category A waste at Dessel, ONDRAF/NIRAS report NIROND-TR 2009-07 E, 2010

(ONDRAF/NIRAS, 2010e) ONDRAF/NIRAS, *Evolution of the Disturbed Zone around a Geological Repository for Nuclear Waste in Boom Clay*, ONDRAF/NIRAS report NIROND-TR 2010-20E

(ONDRAF/NIRAS, 2010f) ONDRAF/NIRAS, *Additional sorption parameters for the cementitious barriers of a near surface repository*, ONDRAF/NIRAS report NIROND-TR 2010-06 E, 147p., 2010

(ONDRAF/NIRAS, 2011) ONDRAF/NIRAS, *Biosphere model report*, Project near surface disposal of category A waste at Dessel, ONDRAF/NIRAS report NIROND-TR 2008-19 E V2, 2011

(ONDRAF/NIRAS, 2011b) ONDRAF/NIRAS, *The wastes of categories B&C – General overview*, note 2010-0998 (rev. 1), 2011

(ONDRAF/NIRAS, 2011c) ONDRAF/NIRAS, *Waste Plan for the long-term management of conditioned high-level and/or long-lived radioactive waste and overview of related issues*, ONDRAF/NIRAS report NIROND 2011-02E, September 2011

(ONDRAF/NIRAS, 2011d) ONDRAF/NIRAS, *Category A detailed design monolith*, ONDRAF/NIRAS report NIROND-TR 2011-63 E, 2011

(ONDRAF/NIRAS, 2011e) ONDRAF/NIRAS, *Feasibility Strategy and Feasibility Assessment Methodology for the Geological Disposal of Radioactive Waste*, ONDRAF/NIRAS report NIROND-TR 2010-19 E, 2011

(ONDRAF/NIRAS, 2011f) ONDRAF/NIRAS, *Long-term climate change and effects on disposal facility, geosphere and biosphere*, Project near surface disposal of category A waste at Dessel, ONDRAF/NIRAS report NIROND-TR 2009-07E Version 1, 2011

(ONDRAF/NIRAS, 2012) ONDRAF/NIRAS, *IRA3 Inventory 2012 report*, 2012

(ONDRAF/NIRAS, 2012b) ONDRAF/NIRAS, *Boom Clay: Integrating data and upscaling using geostatistical techniques. Transferability of regionalized variables*, ONDRAF/NIRAS report NIROND-TR 2012-01, 2012

(ONDRAF/NIRAS, 2013) ONDRAF/NIRAS, *The Category B Waste Monolith Design Basis Report*, SFC1 level 5 report: first full draft, ONDRAF/NIRAS report NIROND-TR 2013-03E, 2013

(ONDRAF/NIRAS, to be published) ONDRAF/NIRAS, *ONDRAF/NIRAS Management Strategy and Management System for SFC1*, SFC1 Level 4 Report: first draft – VS4, ONDRAF/NIRAS report NIROND-TR 2012-24, to be published

(Ortiz *et al.*, 1996) Ortiz L., Put M., De Bruyn D., Moerkens K., Bernier F., *Geological disposal of conditioned high-level and long lived radioactive waste – Task 4.4: Large scale measurement of the hydraulic conductivity of the Boom Clay*, SCK•CEN, Restricted contract report R-3095, 1996

(Ortiz *et al.*, 2002) Ortiz L., Volckaert G. and Mallants D., *Gas generation and migration in Boom Clay, a potential host formation formation for nuclear waste storage*, Engineering Geology, Volume 64, Issues 2–3, May 2002, pp. 287–296, 2002

(Ortiz, 2005) Ortiz L., *Influence of a NaNO<sub>3</sub> plume: microbial denitrification study (NRM039A and NRM039B experiments)*, SCK•CEN, Restricted Contract Report R-4263, 2005

(Pabalan *et al.*, 2009) Pabalan R.T., Glasser F.P., Pickett D.A., Walter G.R., Biswas S., Juckett M.R., Sabido L.M. and Myers J.L., *Review of literature and assessment of factors relevant to performance of grouted systems for radioactive waste disposal*, Center for Nuclear Waste Regulatory analyses, San Antonio, Texas, Report CNWRA 2009-001 (Contract NRC NRC-02-07-006), April 2009

(Panet, 1995) Panet, M., *Calcul Des Tunnels Par La Méthode Convergence-confinement*, Presses de l'École nationale des ponts et chaussées, ISBN 2859782303, 1995

(Passagez, 2011) Passagez A.E., *Effects of earthquakes on underground structures*, Work placement report, Université Libre de Bruxelles (ULB), Juillet 2011

(Petley, 1999) Petley D.N., *Failure envelopes of mudrocks at high effective stresses*, In A. C. Aplin, A. J. Fleet and J. H. S. Macquaker (eds) *Physical Properties of Muds and Mudstones, Special Publication of the Geological Society of London* 158, pp. 61-71, 1999

(Peuget *et al.*, 2007) Peuget S, Broudic V., Je'gou C., Frugier P., Roudil D., Deschanel X., Rabiller H. and Noel P.Y., *Effect of alpha radiation on the leaching behavior of nuclear glass*, Journal of Nuclear Materials 362, pp. 474-479, 2007

(Pfungsten, 2001) Pfungsten W., *Indications for self-sealing of a cementitious repository for low and intermediate-level waste*, Nagra Technical report NTB-01-05, 2001

(PHYMOL, 2000) Marivoet J., Van Keer I., Wemaere I., Hardy L., Pitsch H., Beaucaire C., Michelot J.L., Marlin C., Philippot A.C., Hassanizadeh M. and van Weert F., *A PalaeoHYdrogeological study of the MOL site (PHYMOL project)*, Final report, EUR 19146 EN, Nuclear science and technology, European Commission, 2000

(Piessens *et al.*, 2005) Piessens K., De Vos W., Beckers R., Vancampenhout P. and De Ceukelaire M., *Opmaak van de pre-Krijt subcropkaart van het Massief van Brabant voor invoering in de Databank Ondergrond Vlaanderen – Eindverslag*, Project VLA03-1.1 carried out by Koninklijk Belgisch Instituut voor Natuurwetenschappen and Belgische Geologische Dienst, commissioned by Ministerie van de Vlaamse Gemeenschap, Afdeling Natuurlijk Rijkdommen en Energie, 90p., 2005

(Piña, 2011) Piña Y., *Thermo-hydro-mechanical behaviour of Ypresian clay*, Master's Thesis in Geotechnical Engineering, Universitat Politècnica de Catalunya, Spain, 92p., 2011

(Poinssot *et al.*, 2006) Poinssot P., Ferry C., Grambow B., Kelm M., Spahiu K., Martinez A., Johnson L., Cera E., de Pablo J., Quinones J., Wegen D., Lemmens K. and McMenamin T., *Mechanisms governing the release of radionuclides from spent nuclear fuel in geological repository: major outcomes of the European Project SFS*, Mat. Res. Soc. Symp. Proc. Vol. 932, pp. 421-432, 2006

(Poinssot and Gin, 2012) Poinssot C and Gin S., *Long-term Behavior Science: the cornerstone approach for reliably assessing the long-term performance of nuclear waste*, Journal of Nuclear Materials, 420, pp. 182-192, 2012

(Posiva, 2006) Posiva, (Kukkola, T.), *Encapsulation Plant Preliminary Design, Phase 2: Repository Connected Facility*, Working Report, 2006-95, 2006

(Post *et al.*, 2003) Post V.E.A., Van der Plicht H. and Meijer H.A.J., *The origin of brackish and saline groundwater in the coastal area of the Netherlands*, Netherlands Journal of Geosciences/Geologie en Mijnbouw, 82(2), pp. 133-147, 2003

(Post, 2004) Post V.E.A., *Groundwater salinization process in the coastal area of the Netherlands due to transgressions during the Holocene*, Ph.D thesis, Vrije Universiteit Amsterdam, 138p., 2004

(Pourbaix, 1974) Pourbaix M., *Atlas of Electrochemical Equilibria in Aqueous Solutions* (second edition), National Association of Corrosion Engineers, Houston, Texas, USA, 1974

(Pourbaix and L'Hostis, 2006) Pourbaix A. and L'Hostis V., *Passivation, localised corrosion and general corrosion of steel in concrete and bentonite – Theory and experimental*, The international workshop NUCPERF 2006, Corrosion and long term performance of concrete in NPP and waste facilities, Journal de Physique IV, Vol. 136, EDP Sciences, 2006

(Poursaei and Hansson, 2007) Poursaei A. and Hansson C.M., *Reinforcing steel passivation in mortar and pore solutions*, Cement and Concrete Research 37, pp. 1127-1133, 2007

(Poyet, 2005) Poyet S., *Conception du Superconteneur Ondraf-Niras phase 2: simulation du comportement thermo-hydrrique du tampon en béton en service*, CEA, France, report RT DPC/SCCME 04-690-A, 2005

(Poyet, 2007) Poyet S., *Design of the ONDRAF supercontainer concept for vitrified HLW disposal in Belgium: Study of the thermo-hydric behaviour of the concrete buffer*, CEA 2007

(Pröpper and Steenbeeck, 1999) Pröpper I. and Steenbeeck D., *De aanpak van interactief beleid: elke situatie is anders*, Bussum: Coutinho, 1999

(Pusch *et al.*, 2010) Pusch R., Kasbohm J. and Thao H.T.M., *Chemical stability of montmorillonite buffer clay under repository-like conditions—A synthesis of relevant experimental data*, Applied Clay Science 47, pp. 113–119, 2010

(RESEAL II, 2009) Van Geet M., Bastiaens W., Volckaert G., Weetjens E., Sillen X., Maes N., Imbert Ch., Billaud P., Touzé G., Filippi M., Plas F., Villar M.V., García-Gutiérrez M., Mingarro M., Gens A. and Vallejan B., *RESEAL II A large-scale in-situ demonstration test for repository sealing in an argillaceous host formation – Phase II*, Final report, EUR 24161 EN, 2009

(Richet *et al.*, 2004) Richet C., Galle C., Le Bescop P., Peycelon H., Bejaoui S., Tovena I., Pointeau I., L'Hostis V. and Lovera P., *Synthèse des connaissances sur le comportement à long terme des bétons – Application aux colis cimentés*, CEA, rapport CEA-R-6050, ISSN 0429-3460, 2004

(Robinet and Pasquiou, 1998) Robinet J.C. and Pasquiou A., *Etudes des transferts hydriques entre le massif argileux et les excavations dans un laboratoire souterrain pour le stockage de déchets radioactifs – essai PHEBUS*, Rapport final, Commission Européenne EUR 17792 FR, Luxembourg, 1998

(Romero, 1999) Romero E., *Characterisation and thermo-hydro-mechanical behaviour of unsaturated Boom clay: an experimental study*, Ph.D. Thesis, Universitat Politècnica de Catalunya, Barcelona, Spain, 1999

(Rousset, 1988) Rousset G., *Comportement mécanique des argiles profondes, application au stockage de déchets radioactifs*, Ph.D. thesis, Ecole Nationale des Ponts et Chaussées, 1988

(Roux *et al.*, 2006) Roux S., Feugeas F and Cornet A., *Bioréceptivité et dégradation des bétons en eau douce*, Matériaux 2006 13-17 Novembre – Dijon, France, 2006

(Rueedi *et al.*, 2011) Rueedi J., Marschall P. and Teodori S., *Demonstration of gas permeable seals for radioactive waste repositories – laboratory and in-situ experiments*, 14<sup>th</sup> International Conference on Environmental Remediation and Radioactive Waste Management ICEM'11, Reims, France, 25-29 September 2011

(Salager *et al.*, 2011) Salager S, Rizzi M and Laloui L., *An innovative device for determining the soil water retention curve under high suction at different temperatures*, Acta Geotechnica 6(3): pp. 135-142, 2011

(Salah *et al.*, 2008) Salah S., Maes N. and Van Gompel M., *Diffusion and retention processes in a bentonite Near-Field: Thorium Sorption onto MX-80 (Volclay KWK)*, NF-PRO Final activity report for SCK•CEN (RTDC2-WP2.5), 2008

(Salah and Wang, 2012) Salah S. and Wang L., *Speciation and solubility calculations for waste relevant radionuclides in Boom Clay*, First Full Draft, External report of the Belgian Nuclear Research Centre, SCK•CEN ER-198, 2012

(Saleh *et al.*, 2011) Saleh A., Azizi O., Rosas-Camacho O., Al-Marzooqi A. and MacDonald D.D., *Some important issues in electrochemistry of carbon steel in simulated concrete pore water Part 2 – Experimental*, Corrosion Engineering, Science and Technology, Vol. 46, No. 2, pp. 104-110, 2011

(Schenck-Wenderoth and Lamarche, 2005) Schenck-Wenderoth M. and Lamarche J., *Crustal memory and basin evolution in the Central European Basin System – new insights from a 3D structural model*, Tectonophysics, 397, pp. 143-165, 2005

(Schittekat *et al.*, 1983) Schittekat J., Henriët J.P. and Vandenberghe N., *Geology and geotechnique of the Scheldt surge barrier characteristics of an overconsolidated clay*, Proc. 8<sup>th</sup> Harbour Congress, Antwerp, Vol. 2, pp. 121-135, 1983



(Secretary of State for Energy, 1990) Secretary of State for Energy, SAFIR Evaluation Commission, Final report, Report finalised in February 1990

(SEIFRAC, 2007) Bernier F., Li X.L., Bastiaens W., Ortiz L., Van Geet M., Wouters L., Frieg B., Blümling P., Desrues J., Viaggiani G., Coll C., Chanchole S., De Greef V., Hamza R., Malinsky L., Vervoort A., Vanbrabant Y., Debecker B., Verstraelen J., Govaerts A., Wevers M., Labiouse V., Escoffier S., Mathier J.F., Gastaldo L. and Bühler Ch., SEIFRAC, *Fractures and self-healing within the Excavation Disturbed Zone in Clays (SEIFRAC)*, Final report EUR 22585, EC project, 2007

(Sillen and Marivoet, 2007) Sillen X. and Marivoet J., *Thermal impact of a HLW repository in clay – Deep disposal of vitrified high-level waste and irradiated fuel*, External Report of the Belgian Nuclear Research Centre, SCK•CEN ER-38, 2007

(Sillen, 2012) Sillen X., *Keynote on repository-induced perturbations of the host formation, in the context of the safety case for the geological disposal of VHLW and SF in clay formations*, Proceedings of the European Commission Timodaz-Theresa International Conference Impact of thermo hydro mechanical chemical (THMC) processes on the safety of underground radioactive waste repositories, Luxembourg, 29 September-1 October 2009, EUR 25527 EN, 2012

(SKB, 2005) SKB (Carbol P., Cobos-Sabate J., Glatz J-P, Ronchi C., Rondinella V., Wegen D.H., Wiss T., Loida A., Metz V., Kienzler B., Spahiu K., Grambow B., Quiñones J. and Martinez Esparza Valiente A.), *The effect of dissolved hydrogen on the dissolution of <sup>233</sup>U doped UO<sub>2</sub> (s), high burnup irradiated fuel and MOX fuel*, Technical Report TR-05-09, SKB, 2005

(Smart *et al.*, 2004) Smart N.R., Blackwood D.J., Marsh G.P., Naish C.C., O'Brien T.M., Rance A.P. and Thomas M.I., *The Anaerobic Corrosion of Carbon and Stainless Steels in Simulated Cementitious Repository Environments: A Summary review of NIREX research*, Report No. AEAT/ERRA-0313, AEA Technology, Harwell, United Kingdom, 2004

(Smart *et al.*, 2009) Smart N.R., Rance A.P., Winsley R.J., Fennell P.A.H., Reddy B. and Kursten B., *The effect of irradiation on the corrosion of carbon steel in alkaline media*, RILEM Workshop on long-term performance of cementitious barriers and reinforced concrete in nuclear power plants – NUCPERF 2009, Cadarache, France, 30 March – 2 April 2009

(Smith, 1985) Smith A.J., *A catastrophic origin for the palaeovalley system of the eastern English Channel*, Marine geology, 64, pp. 65-75, 1985

(Sneyers *et al.*, 2001) Sneyers A., Paul M., Tyrer M., Glasser F.P., Fays J. and Van Iseghem P., *In-situ Interaction between Cement and Clay: Implications for Geological Disposal*, Mat. Res. Soc. Symp. Proc. Vol. 663 Materials Research Society, 2001

(Soetaert and Herman, 1995) Soetaert K. and Herman P.M., *Estimating estuarine residence times in the Westerschelde (The Netherlands) using a box model with dispersion coefficients*, Hydrobiologia, 311, pp. 215-224, 1995

(Soler, 2001) Soler J.M., *The effect of coupled transport phenomena in the Opalinus Clay and implications for radionuclide transport*, Journal of Contaminant Hydrology, 53, pp. 63-84, 2001

(SPIN, 2002) Becker D.A., Buhmann D., Storck R., Alonso J., Cormenzana J.L., Hugi M., van Gemert F., O'Sullivan P., Laciok A., Marivoet J., Sillen X., Nordman H., Vieno T. and Niemeyer M., *Testing of safety and performance indicators (SPIN)*, EC, Luxembourg, Final report EUR 19965 EN, 2002

(Steurbaut and Nolf, 1986) Steurbaut E. and Nolf D., *Revision of Ypresian stratigraphy of Belgium and northwestern France*, Contributions to Tertiary and Quaternary Geology, 23 (4), pp. 115-172, 1986

(Steurbaut, 1998) Steurbaut E., *High-resolution holostatigraphy of Middle Paleocene to Early Eocene strata in Belgium and adjacent areas*, Palaeontographica Abteilung A, 247, pp. 91-156, 1998

(Steurbaut, 2006) Steurbaut E., *Ypresian*, in Dejonghe, L. ed., Current status of chronostratigraphic units named from Belgium and adjacent areas, Geologica Belgica, Brussels, p/1-2: 73-93, 2006

(Sultan, 1997) Sultan N., *Etude du comportement thermo-mécanique de l'argile de Boom: expériences et modélisation*, Thèse de doctorat, Ecole Nationale des Ponts et Chaussées, France, 1997

(Sweeck et al., 2011) Sweeck L., Olyslaegers G and Van den Hoof C., *Evaluation of some relevant features of the biosphere assessment approach*, SCK•CEN, External Restricted report R-5152, 2011

(Tesauro et al., 2006) Tesauro M., Hollenstein C., Egli R., Geiger A. and Kahle H.-G., *Analysis of central western Europe deformation using GPS and seismic data*, Journal of Geodynamics, 42, pp. 194-209, 2006

(Tesauro et al., 2007) Tesauro M., Kaban M.K., Cloetingh S.A.P.L., Hardebol N.J. and Beekman F., *3D strength and gravity anomalies of the European lithosphere*, Earth and Planetary Science Letters, 263, pp. 56-73, 2007

(Tesauro et al., 2009) Tesauro M., Kaban M.K. and Cloetingh S.A.P.L., *A new thermal and rheological model of the European lithosphere*, Tectonophysics, 476, pp. 478-495, 2009

(TIMODAZ, 2011) Li X.L. (editor), *Thermal Impact on the Damaged Zone Around a Radioactive Waste Disposal in Clay Host formations, TIMODAZ final activity report*, EC project (FI6W-CT-2007-036449), 2011

(Tractebel, 2007) Tractebel Engineering GDF Suez, *Category B&C Disposal Facility Design – Stage 2, performed in the context of the 2007 Cost Evaluation*, Report to ONDRAF/NIRAS, 2007

(Tractebel, 2010) Tractebel Engineering GDF Suez, *Basculeur de container*, Projet Etudes dépôt déchets catégorie B&C, rev. 00., 2010

(TRANCOM-CLAY, 2000) Dierckx A., Put M., De Cannière P., Wang L., Maes N., Aertsens M., Maes A., Vancluysen J., Verdickt W., Gielen R., Christiaens M., Warwick P., Hall A. and van der Lee J., *TRANCOM-CLAY: Transport of radionuclides due to complexation with organic matter in clay formations*, Final report, European Commission Nuclear Science and Technology, EUR-19135, Contract no. FI4W-CT95-0013, 2000

(TRANCOM-II, 2004) Maes N., Wang L., Delécaut G., Beauwens T., Van Geet M., Put M., Weetjens E., Marivoet J., van der Lee J., Warwick P., Hall A., Walker G., Maes A., Bruggeman C., Bennett D., Hicks T., Higgo J. and Galson D., *Migration Case Study: Transport of radionuclides in a reducing Clay Sediment (TRANCOM-II)*, European Commission Nuclear Science and Technology, Final report EUR 21022 EN, EC, Luxembourg, 2004

(TRUCKII, 2000) Barnichon J.D., *Cora project TRUCKII (FAS 63561)*, Restricted report of the Belgian Nuclear Research Centre, SCK•CEN R-3409, 2000

(Tsang *et al.*, 2005) Tsang C., Bernier F. and Davies, *Geohydromechanical processes in the excavation damaged zone in crystalline rock, rock salt, and indurated and plastic clays*, International Journal of Rock Mechanics and Mining Science, Vol. 42, Elsevier Science B.V., Amsterdam, pp. 109-125. ISSN 1365-1609, 2005

(Tsang *et al.*, 2011) Tsang C., Barnichon J., Birkholzer J., Li X., Liu H. and Sillen X., *Coupled thermo hydro mechanical processes in the near field of a high level radioactive waste repository in clay formations*, International Journal of Rock Mechanics and Mining Sciences 49, Elsevier, 2011, pp. 31-44, 2011

(Turnbull, 2009) Turnbull A., *A Review of the Possible Effects of Hydrogen on Lifetime of Carbon Steel Nuclear Waste Canisters*, Nagra Technical Report NTB-09-04, 2009

(Umicore, 2011) Umicore, *Common understanding of process and framework to develop a long term solution for the radioactive materials in Olen*, Workshop OLERA between Umicore, TVH MWH-ARCADIS and Kamakta, FANC, ONDRAF/NIRAS and OVAM, with external experts, Brussels 2nd and 3rd March 2011, slides from the presentation, 2011

(Valcke *et al.*, 2003) Valcke E., Sneyers A. and Van Iseghem P., *Geological disposal of conditioned high-level and long-lived radioactive waste – Chemical Degradation of Cellulose-based Waste*, Final report, Restricted contract report SCK•CEN R-3785, 2003

(Valcke *et al.*, 2009) Valcke E., Mariën A. and Van Geet M., *The methodology followed in Belgium to investigate the compatibility with geological disposal of EUROBITUM bituminized intermediate-level radioactive waste*, Scientific Basis for Nuclear Waste Management XXXIII. Symposium Proceedings, Volume 1193, St. Petersburg, Russian Federation, 25-29 May 2009 / V.G. Khlopin Radium Institute, Warrendale, PA, United States, Materials Research Society, pp. 105-116, 2009

(Valcke *et al.*, 2010) Valcke E., Mariën A., Smets S., Li X., Mokni N., Olivella S. and Sillen X., *Osmosis-induced Swelling of Eurobitum Bituminized Radioactive Waste in Constant Total Stress Conditions*, Journal of Nuclear Materials 406 (3) (30 November): 304–316. doi:10.1016/j.jnucmat.2010.08.060, 2010

(Valcke *et al.*, 2013) Valcke E., Mariën A. and Bleyen N., *The long-term behaviour of EUROBITUM bituminised radioactive waste in geological disposal conditions*, Integration report in preparation of the safety and feasibility case 1 of ONDRAF/NIRAS, External report of the Belgian Nuclear Research Centre, SCK•CEN ER-216, 2013

(Van Cauteren, 1994) Van Cauteren L., *Evaluatie van de warmtegeleidbaarheid en de warmtecapaciteit van de Boomse klei*, Nota 94-0605, ONDRAF/NIRAS, 1994

(Van Cotthem *et al.*, 2012) Van Cotthem A., Van Humbeek H. and Biurrun E., *Underground Architecture and Layout for the Belgian High-Level and Long-Lived Intermediate-Level Radioactive Waste Disposal Facility*, WM2012 Conference, Phoenix, Arizona, USA, February 26 – March 1, 2012

(Vandenberghé, 1978) Vandenberghé N., *Sedimentology of the Boom Clay (Rupelian) in Belgium*, Verhandeling Koninklijke Academie voor Wetenschappen, Letteren en Schone Kunsten van België, Klasse Wetenschappen, XL/147, 1978

(Vandenberghé *et al.*, 1988) Vandenberghé N., Laga, P., Vandormael, C. and Elewaut, E., *The geophysical log correlations in the Ieper Clay sections in Belgium*, Bulletin Société belge Géologie, 97 (3-4), pp. 437-440, 1988

(Vandenberghé *et al.*, 1997) Vandenberghé N., Laenen B., Van Echelpoel E., Lagrou D., *Cyclostratigraphy and climate eustasy, Example of the Rupelian stratotype*, in Sciences de la Terre et des Planètes (Earth and Planetary Sciences), Paris, Académie des Sciences, Elsevier, Vol. 325, pp. 305-315, 1997

(Vandenberghé *et al.*, 1998) Vandenberghé N., Laga P., Steurbaut E., Hardenbol J. and Vail P.R., *Tertiary sequence stratigraphy at the southern border of the North Sea Basin in Belgium*, in: de Graciansky, P.-C., Hardenbol, J. Jacquin, T and Vail, P.R. (eds): Mesozoic and Cenozoic Sequence Stratigraphy of European Basins, Society for Sedimentary Geology (SEPM), Special Publication 60, pp. 119-154, 1998

(Vandenberghé *et al.*, 2003) Vandenberghé N., Van Simaëys S. and Steurbaut E., *The stratigraphic architecture of the Paleogene sedimentary filling of the southern border of the North Sea Basin in Belgium*, Abstract from a poster presentation at the Symposium on the Paleogene, Preparing for Modern Life and Climate, held on 25-30 August 2003 at Leuven, Belgium, International Subcommission on Paleogene Stratigraphy, poster -78, 2003

(Vandenberghé *et al.*, 2004) Vandenberghé N., Van Simaëys S., Steurbaut E., Jagt J.W.M. and Felder P.J., *Stratigraphic architecture of the Upper Cretaceous and Cenozoic along the southern border of the North Sea Basin in Belgium*, Netherlands Journal of Geosciences, 83 (3), pp. 155-171, 2004

(Vandenberghé *et al.*, to be published) Vandenberghé N., De Craen M. and Wouters L., *The Boom Clay geology, from sedimentation to present-day occurrence, A review*, Memoirs of the Geological Survey of Belgium, 60, to be published

(Vandenbohede and Lebbe, 2006) Vandenbohede A. and Lebbe L., *Occurrence of salt water above fresh water in dynamic equilibrium in a coastal groundwater flow system near De Panne*, Belgium, Hydrogeology Journal, 14, pp. 462-472, 2006

(Vandenbohede *et al.*, 2010) Vandenbohede A., Lebbe L and Courtens C., *Een hydrogeologisch model in de streek rond Doel (Beveren)*, Reported by Onderzoekseenheid Grondwatermodellering, Universiteit Gent, commissioned by ONDRAF/NIRAS, 164pp., 2010

(Vandenbohede *et al.*, 2010b) Vandenbohede A., Courtens C., Lebbe L. and De Breuck W., *Fresh-salt water distribution in the Central Belgian Coastal Plain: an update*, *Geologica Belgica*, 11(3), pp. 163-169, 2010

(van der Kemp *et al.*, 2000) van der Kemp W.J.M., Appelo C.A.J and Walraevens K., *Inverse chemical modeling and radiocarbon dating of palaeogroundwaters: The Tertiary Ledo-Paniselian aquifer in Flanders, Belgium*, *Water Resources Research*, 36(5), pp. 1277-1287, 2000

(van der Meer and Verstricht, 2008) van der Meer K. and Verstricht J., *State-of-the-art of safeguards of a geological repository*, Internal report of the Belgian Nuclear Research Centre, SCK•CEN R-4481, 2008

(van der Meer and Turcanu, 2012) van der Meer K. and Turcanu C., *Developments in safeguards of a geological repository in the period 2009-2011*, Internal report of the Belgian Nuclear Research Centre, SCK•CEN R-5382, 2012

(Vandersteen *et al.*, 2012) Vandersteen K., Gedeon M. and Rogiers B., *Transient model of the confined aquifers below the Boom Clay: 2011 update – Regional Hydrogeological Modelling of the Mol Site*, External report of the Belgian Nuclear Research Centre, SCK•CEN ER-199, 2012

(Van Echelpoel, 1991) Van Echelpoel E., *Kwantitatieve cyclostratigrafie van de formatie van Boom (Rupeliaan, België), De methodologie van het onderzoek van sedimentaire cycli via walshanalyse*, verhandeling voorgedragen tot het bekomen van de graad van Doctor in de Wetenschappen groep Aard- en Delfstofkunde, KULeuven, 1991

(Van Geet *et al.*, 2003) Van Geet M., Maes N. and Dierckx A., *Characteristics of the Boom Clay organic matter, a review*, Geological survey of Belgium, Professional paper 2003/1 N. 298, Royal Belgian Institute of Natural Sciences, ISSN 0378-0902, 2003

(Van Geet, 2003b) Van Geet, M., *Oxidation phenomena in Boom Clay: case study from the Northern Starting Chamber in the second Shaft*, in: Bastiaens *et al.* (Eds.), *The Connecting Gallery*, EURIDICE Internal Report 03-293 and related Compact Discs, 2003

(Van Geet *et al.*, 2003c) Van Geet M., Bastiaens W., Volckaert G., Vallejan B. and Gens A., *Reconnaissance Study of EDZ around a Large Scale Shaft Sealing Demonstration Test (RESEAL)*, A European Commission CLUSTER Conference and Workshop on EDZ in Radioactive Waste Geological Repositories, 3-5 November 2003, Luxembourg, EUR21028 EN, 2003

(Van Geet *et al.*, 2005) M. Van Geet, G. Volckaert and Roels S., *The use of microfocuss X-ray computed tomography in characterising the hydration of a clay pellet/powder mixture*, *Applied Clay Science*, Volume 29, issue 2, pp. 73-87, April 2005

(Van Geet *et al.*, 2006) Van Geet M., Wang L., De Boever P. and De Craen M., *Geochemical boundary conditions relevant for assessing corrosion processes for the Supercontainer design*, External report of the Belgian Nuclear Research Centre, SCK•CEN ER-14, SCK•CEN, Mol, Belgium, 2006

(Van Geet *et al.*, 2006b) Van Geet M., De Craen M., Weetjens E. and Sillen X., *Extent of oxidising conditions in the host formation*, External report of the Belgian Nuclear Research Centre SCK•CEN ER-5, 2006

(Van Geet, 2008) Van Geet M., *A definition of thermal phase: proposal and suggested use*, ONDRAF/NIRAS ref. 2008-0911 (rev. 0), 2008

(Van Geet *et al.*, 2008b) Van Geet M., Bernier, F., Sillen, X. and Li, X., *(Excavation) Damaged and disturbed zone*, ONDRAF/NIRAS ref. 2007-2229 (rev. 0), 2008

(Van Geet *et al.*, 2008c) Van Geet M., Bastiaens W. and Ortiz L., *Self-sealing capacity of argillaceous rocks: Review of laboratory results obtained from the SELFRAC project*, Physics and Chemistry of the Earth, Parts A/B/C Volume 33, Supplement 1, 2008, pp. S396–S406, Clays in Natural and Engineered Barriers for Radioactive Waste Confinement, 2008

(Van Geet *et al.*, 2008d) Van Geet M., Bastiaens W., Volckaert G., Weetjens E., Sillen X., Gens A., Villar M.V., Imbert Ch., Filippi M. and Plas F., *Installation and evaluation of a large-scale in-situ shaft seal experiment in Boom Clay*, Science and Technology Series n°334, Andra, pp. 95-109, 2008

(Van Geet *et al.*, 2012) Van Geet M., De Craen M., Beerten K., Leterme B., Mallants D., Wouters L., Cool W. and Brassinnes S., *Climate evolution in the long-term safety assessment of surface and geological disposal facilities for radioactive waste in Belgium*, Geologica Belgica 15/1-2: 8-15, 2012

(Van Geet and Weetjens, 2012b) Van Geet M. and Weetjens E., *Strategic choices in the Belgian supercontainer design and its treatment in a safety case*, NEA workshop 2009 Cementitious materials in Safety Cases for Geological Repositories for Radioactive Waste: Role, Evolution and Interactions, Workshop of the NEA IGSC, 17-20 November 2009, Brussels, Belgium, NEA/RWM/R(2012)3/REV, 2012

(Van Humbeeck *et al.*, 2007) Van Humbeeck H., De Bock C. And Bastiaens W., *Demonstrating the construction and backfilling feasibility of the Supercontainer design for HLW*, International Conference on Radioactive Waste Disposal in Geological Formations, Braunschweig, 6-9 November 2007

(Van Humbeeck *et al.*, 2008) Van Humbeeck H., Bastiaens W., De Bock C. and Van Cotthem A., *Experimental Programme to Demonstrate the Viability of the Supercontainer Concept for HLW*, International Conference on Underground Disposal Unit Design and Emplacement Processes for a Deep Geological Repository, 16-18 June 2008, Prague, 2008

(Van Humbeeck *et al.*, 2009) Van Humbeeck H., Verstricht J., Li X.L., De Cannière P., Bernier F and Kursten B., *The OPHELIE mock-up*, ESV EURIDICE GIE, EURIDICE Report 09-134, January 2009

(Van Impe, 1993) Van Impe W.F., *Boom clay for storage of nuclear waste (discussion session 2b)*, Geotechnical Engineering of Hard Soils-Soft Rocks, Athen, Al. A. E. (eds), Balkema, Rotterdam, 3, pp. 1885-1895, 1993

(Van Loon *et al.*, 2004) Van Loon L.R., Wersin P., Soler J.M., Eikenberg J., Gimmi T., Hernan P., Dewonck S. and Savoye S., *In-situ diffusion of HTO,  $^{22}\text{Na}^+$ ,  $\text{Cs}^+$  and  $\text{I}^-$  in Opalinus Clay at the Mont Terri underground rock laboratory*, Radiochimica Acta 92, pp. 757-763, 2004

(Van Loon *et al.*, 2005) Van Loon L.R., Baeyens B., Bradbury M.H., *Diffusion and retention of sodium and strontium in Opalinus Clay: Comparison of sorption data from batch sorption and diffusion measurements and geochemical calculations*, Applied Geochemistry 20, pp. 2351-2363, 2005

(Van Marcke *et al.*, 2009) Van Marcke P, Chen G., Li X., Verstricht J. and Bastiaens W., *Excavating in a deep plastic clay layer: observations at the HADES URF (Mol, Belgium)*, EURO:TUN 2009, 2<sup>nd</sup> International Conference on Computational Methods in Tunnelling, Ruhr University Bochum, 9-11 September 2009, Aidificatio Publishers, 1-4, 2009

(Van Marcke and Bastiaens, 2010) Van Marcke P. and Bastiaens W., *Excavation induced fractures in a plastic clay formation, Observations at the HADES URF*, Journal of Structural Geology, 32, 11, pp. 1677-1684, 2010

(Van Marcke and Bastiaens, 2012) Van Marcke P. and Bastiaens W. *Construction of the PRACLAY Experimental Gallery at the HADES URF*, Clays in Natural and Engineered Barriers for Radioactive Waste Confinement, Nantes, France, 29 March - 1 April 2010, Andra, pp. 7-18, 2012

(Van Marcke *et al.*, 2012b) Van Marcke P., Van Humbeek H. and Van Cotthem A., *The Belgian Research and Development feasibility programme for the geological disposal of high-level and long-lived radioactive waste*, WM2012 Conference, Phoenix, Arizona, USA, February 26 - March 1, 2012

(Van Marcke *et al.*, 2013) Van Marcke P., Li X.L., Bastiaens W., Verstricht J., Chen G., Leysen J. and Rypens J., *The design and installation of the PRACLAY In-situ Experiment*, EURIDICE Report 13-129, 2013

(van Vliet-Lanoë *et al.*, 2002) van Vliet-Lanoë B., Vandenberghe N., Laurent M., Laignel B., Lauriat-Rage A., Louwye S., Mansy J.-L., Mercier D., Hallégouet B., Laga P., Laquement F., Meilliez F., Michel Y., Moguedet G. and Vidier J.-P., *Palaeogeographic evolution of northwestern Europe during the Upper Cenozoic*, Geodiversitas, 24(3), pp. 511-541, 2002

(Verlaan *et al.*, 1998) Verlaan P.A.J., Donze M. and Kuik P., *Marine vs Fluvial Suspended Matter in the Scheldt Estuary*, Estuarine, Coastal and Shelf Science, 46, pp. 873-883, 1998

(Verschuren, 2001) Verschuren M, *An integrated approach to clay tectonic deformation and Field Guide to its Belgian Outcrops*, in: Verschuren, M. and Van Rensbergen, P. (eds.): Origin, process and effects of subsurface sediment mobilisation on reservoir to

regional scale, Pre-meeting field trip to the clay pit in Marke (W-Belgium) held on 10 September 2001, Symposium held on the 10-13th September, 2001, Ghent, 2001

(VLAREM, 1995) Titel II van het VLAREM besluit van de Vlaamse Regering van 1 Juni 1995 houdende algemene en sectorale bepalingen inzake milieuhygiëne / Arrêté du Gouvernement flamand du 1<sup>er</sup> juin 1995 fixant les dispositions générales et sectorielles en matière d'hygiène de l'environnement, Moniteur belge du 31 juillet 1995

(VMM, 2008) VMM, *Grondwater in Vlaanderen: Centraal Vlaams Systeem*, Vlaamse Milieumaatschappij, Aalst, 111p., 2008

(Volckaert *et al.*, 1995) Volckaert G., Bernier F., Alonso E., Gens A. Samper J. and Villar M., *Model development and validation of the thermal-hydraulic- mechanical and geochemical behaviour of the clay barrier*, Final report, CEC contract N° FI2W-CT91-0102 and FI2W-CT90-0033, Restricted contract report of the Belgian Nuclear Research Centre, SCK•CEN R-3084, 1995

(Wacquier and Van Humbeeck, 2009) Wacquier W. and Van Humbeeck H., *B&C Concept and Open Questions*, ONDRAF/NIRAS ref. 2009-0146 (rev. 0), 2009

(Wacquier and Boulanger, 2010) Wacquier W. and Boulanger D., *Plan déchets – Etude de trois solutions d'entreposage*, ONDRAF/NIRAS Report, 2010-0014 FR (Rev. 2), 2010

(Wacquier *et al.*, 2011) Wacquier W., Van Humbeeck H., Wickham S.M. and Harvey E.J., *Belgian Feasibility Strategy and Assessment Methodology for Geological Disposal*, Proceedings of the 13<sup>th</sup> International High-Level Radioactive Waste Management Conference, Albuquerque, New Mexico, USA, American Nuclear Society, 10-14 April 2011

(Wacquier *et al.*, 2011b) Wacquier W., Van Humbeeck H., Gens R., Wickham S., Harvey L., Areias L., Van Cotthem A. and Villers L., *Feasibility assessment of the Belgian supercontainer disposal concept*, Proceedings of the 13<sup>th</sup> International High-Level Radioactive Waste Management Conference, Albuquerque, New Mexico, USA, American Nuclear Society, 10-14 April 2011

(Walraevens *et al.*, 1996) Walraevens K., Cardenals J., De Smet D. and De Breuck W., *Hydrogeological and Hydrogeochemical Evidence for the Present-day Existence of Preferential Pathways in the Bartonian Clay*, Fluid Flow through Faults and Fractures in Argillaceous Formations, Proceedings of a Joint NEA/EC Workshop, Berne, Switzerland, 10-12 June, 1996, Organised by NEA Working Group on Measurement and Physical Understanding of Groundwater Flow through Argillaceous Media (the "Clay Club") and NAGRA, 369-380pp., 1996

(Walraevens and Mahauden, 1999) Walraevens K. and Mahauden M., *Mineralogische, geochemische en chemische analyses van de Ieperiaan-kleien uit boring DOEL1*, Project nummer TGO 97/05, Universiteit Gent, report in four parts (1998-1999), 1999

(Walraevens *et al.*, 2001) Walraevens K., Van Camp M., Lermytte J., vander Kemp W.J.M. and Loosli H.H., *Pleistocene and Holocene groundwaters in the freshening Ledo-Paniselian aquifer in Flanders, Belgium*, in: Palaeowaters in Coastal Europe: Evolution of



Groundwater since the Late Pleistocene, Edited by Edmunds W.M. and Milne C.J., Geological Society of London, Special Publications 189, pp. 49-70, 2001

(Walraevens *et al.*, 2001b) Walraevens K., Coetsiers M., De Smet D., Martens K. and Van Camp M., *Hydrogeological aspects of Eocene clay layers in Flanders : Ypresian clay and Bartonian clay*, Editors Verschuren M. and Van Rensbergen P. in Origin, process and effects of subsurface sediment mobilisation on reservoir to regional scale, Pre-meeting field trip to the clay pit in Marke (W-Belgium) held on 10 September, 2001, Symposium held on 10-13 September 2001, Ghent, 2001

(Walraevens *et al.*, 2007) Walraevens K., Cardenal-Escarcena J. and Van Camp M., *Reaction transport modelling of a freshening aquifer (Tertiary Ledo-Paniselian Aquifer, Flanders-Belgium)*, Applied Geochemistry 22, pp. 289-305, 2007

(Wang, 2009) Wang L., *Near-field chemistry of a HLW/SF repository in Boom Clay - scoping calculations relevant to the supercontainer design*, External report of the Belgian nuclear research centre, SCK•CEN ER-17, 2009

(Wang *et al.*, 2010) Wang L., Jacques D. and De Cannière P., *Effects of an alkaline plume on the Boom Clay as a potential host formation for geological disposal of radioactive waste*, External report of the Belgian nuclear research centre, SCK•CEN ER-28, 2010

(Wang *et al.*, 2011) Wang L., Salah S. and De Soete H., *MOLDATA: A thermochemical data base for phenomenological and safety assessment studies for disposal of radioactive waste in Belgium – Data compilation strategy*, External report of the Belgian nuclear research centre, SCK•CEN ER-121, 2011

(Wantz, 2005) Wantz O., *A study of In-Package Nuclear Criticality in Possible Belgian Spent Nuclear Fuel Repository Designs*, Ph.D. thesis, Service de Métrologie Nucléaire, Faculté des Sciences Appliquées, Université libre de Bruxelles, 2005

(Wartel, 1980) Wartel S., *The Tertiary and Quaternary subbottom of the Schelde estuary near Antwerpen (Belgium)*, Geologie en Mijnbouw 59, pp. 233-240, 1980

(Weetjens and Sillen, 2005) Weetjens, E. and Sillen, X., *Thermal analysis of the Supercontainer concept – 2D axisymmetric heat transport calculations*, Restricted report of the Belgian nuclear research centre, SCK•CEN R-4277, 2005

(Weetjens, 2009) Weetjens E., *Update of the near field temperature evolution calculations for disposal of UNE-55, MOX-50 and vitrified HLW in a supercontainer-based geological repository*, External report of the Belgian nuclear research centre, SCK•CEN ER-86, 2009

(Weetjens *et al.*, 2009b) Weetjens E., Perko J. and Yu L., *Final report on calculations on gas production and transport*, Milestone M 3.2.16 from the PAMINA Project, report in the framework of the 6<sup>th</sup> EU Framework Programme, 2009

(Weetjens *et al.*, 2010) Weetjens E., Valcke E. and Mariën A., *Sodium nitrate release from EUROBITUM bituminised radioactive waste, Scoping calculations*, External report of the Belgian nuclear research centre, SCK•CEN ER-146, 2010

(Weetjens *et al.*, 2011) Weetjens E., Govaerts J. and Aertsens M., *Model and parameter validation based on in-situ experiments in Boom Clay*, External report of the Belgian nuclear research centre, SCK•CEN ER-171, 2011

(Weetjens *et al.*, 2012) Weetjens E., Marivoet J. and Govaerts J., *Preparatory Safety Assessment – Conceptual model description of the reference case*, External report of the Belgian nuclear research centre SCK•CEN ER-215, 2012

(Welkenhuysen and De Ceukelaire, 2009) Welkenhuysen K. and De Ceukelaire M., *Tertiair lithostratigrafische interpretatie op basis van geofysische boorgatmetingen van de boringen van meetnet 1 VMM – Afdeling Water, uitgevoerd in 2005-2006*, Geological Survey of Belgium, Professional Paper 2009/2 N°306, 77p., 2009

(Wemaere *et al.*, 2002) Wemaere I., Marivoet J., Beaufays R., Maes T. and Labat S., *Core manipulations and determination of hydraulic conductivities in the laboratory for the Mol-1 borehole (April-May 1997)*, Restricted report of the Belgian nuclear research centre, SCK•CEN R-3590A, 2002

(Wemaere *et al.*, 2008) Wemaere I., Marivoet J. and Labat S., *Hydraulic conductivity variability of the Boom Clay in north-east Belgium based on four core drilled boreholes*, Physics and Chemistry of the Earth 33, S24–S36, 2008

(Wersin *et al.*, 2007) Wersin P., Johnson L.H. and McKinley I.G., *Performance of the bentonite barrier at temperatures beyond 100°C: A critical review*, Physics and Chemistry of the Earth 32, 780–788, 2007

(West *et al.*, 2002) West J., McKinley I. and Stroes-Gascoyne S., *Microbial effects on waste repository materials, Interactions of Microorganisms with radionuclides*, Chapter 9, pp. 255-277, ed. Keith-Roach M.J. and Livens F.R., Radioactivity in the environment – Vol. 2, Elsevier, 2002

(Wickham *et al.*, 2005) Wickham S., Crawford M.B. and Bennett D.G., *Belgian Supercontainer Design for HLW and Irradiated fuel Disposal – Evaluation of the Reference Design*, Galson sciences LTD Report 0460-5, 2005

(Wileveau and Bernier, 2008) Wileveau Y. and Bernier F., *Similarities in the hydromechanical response of Callovo-Oxfordian clay and Boom Clay during gallery excavation*, Physics and Chemistry of the Earth 33, S343–S349, 2008

(Williamson *et al.*, 2004) Williamson J.P., Chacksfield B.C., Pharaoh T.C., McEvroy F.M., Franceschi G., De Vos W. and Van Orsmael J., *Reinterpretation of gravity data over northern Belgium*, Abstract of a poster presentation on the Avalonia-Moesia Symposium and Workshop on the Early Palaeozoic orogens of the Trans-European Suture Zone, Ghent/Ronse 9- 12 October 2004

(Winsley *et al.*, 2011) Winsley R.J., Smart N.R., Rance A.P., Fennell P.A.H., Reddy B., Scott D. and Kursten B., *Further studies on the effect of irradiation on the corrosion of carbon steel in alkaline media*, Corros. Eng. Sci. Technol., Vol. 46, pp. 148–152, 2011

(Yu and Weetjens, 2009) Yu L. and Weetjens E., *Summary of Gas Generation and Migration: Current state-of-the-art*, European Commission FP7 FORGE Fate of Repository Gases, External report of the Belgian nuclear research centre, SCK•CEN ER-106, 2009

(Yu *et al.*, 2011) Yu L., Weetjens E. and Vietor T., *Integration of TIMODAZ results within the Safety Case and Recommendations for Repository Design*, External report of the Belgian nuclear research centre, SCK•CEN ER-188, 2011

(Yu *et al.*, 2011b) Yu L., Gedeon M., Wemaere I., Marivoet J. and De Craen M., *Boom Clay Hydraulic Conductivity, A synthesis of 30 years of research*, External report of the Belgian nuclear research centre, SCK•CEN ER-122, 2011

(Yu *et al.*, 2012) Yu L., Weetjens E., Valcke E. and Mariën A., *Evaluation of the gas source term for EUROBITUM, Gas source term and scoping calculations*, External report of the Belgian nuclear research centre, SCK•CEN ER-211, 2012

(Yu and Weetjens, 2012b) Yu L. and Weetjens E., *Evaluation of the gas source term for SF, VHLW, compacted waste and MOSAIK: gas source term and scoping calculations*, External report of the Belgian nuclear research centre, SCK•CEN ER-162, 2012

(Yu H.D., 2010) Yu. H.D., *Study on long term hydro-mechanical coupled behavior of Belgium Boom Clay*, Ph.D. Thesis, Wuhan Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Beijing, China, 2010

(Yu H.D. *et al.*, 2012) Yu H., Chen W., Jia S., Cao J. and Li X., *Experimental study on the hydro mechanical behavior of Boom clay*, International Journal of Rock Mechanics and Mining Sciences 53, Elsevier, pp. 159-165, 2012

(Yu H.D. *et al.*, 2013) Yu H.D., Chen W.Z., Li X.L. and Sillen X., *A transversely isotropic damage model for Boom clay*, *Rock Mechanics and Rock Engineering*, published online 16 January 2013

(Zeelmaekers, 2011) Zeelmaekers E., *Computerized qualitative and quantitative clay mineralogy, Introduction and application to known geological cases*, Dissertation presented in partial fulfilment of the requirements for the degree of Doctor of Science, KULeuven, April 2011

(Zeelmaekers *et al.*, 2012) Zeelmaekers E., Vandenberghe N. and Srodon J., *Presence of bentonite beds in the earliest Eocene Tienen Formation in Belgium as evidenced by clay mineralogical analyses*, Austrian Journal of Earth Sciences, 105(1), pp. 110-116, 2012

(Ziegler, 1992) Ziegler P.A., *European Cenozoic rift system*, in: P.A. Ziegler (Editor), *Geodynamics of Rifting, Volume I, Case History Studies on Rifts: Europe and Asia*, Tectonophysics 208, pp. 91-111, 1992

(Ziegler and Dèzes, 2007) Ziegler P.A. and Dèzes P., *Cenozoic uplift of Variscan Massifs in the Alpine foreland: Timing and controlling mechanisms*, Global and Planetary Change 58, pp. 327-269, 2007

(Zheng and Samper, 2008) Zheng L. and Samper J., *Coupled THMC model of Febex Mock-up test*, Physics and Chemistry of the Earth 33, S486-S498, 2008

(Zheng *et al.*, 2008b) Zheng J.H., Perdieus F. and Bogaerts W., *Potential risk of SCC, Contained Environment Concept (CEC) – Initial survey of corrosion engineering data concerning caustic cracking and related phenomena*, report for ONDRAF/NIRAS, MTM, KULeuven, 2008



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