GEOLOGICA BELGICA (2012) 15/1-2: 8-15

Climate evolution in the long-term safety assessment of surface and geological disposal facilities for radioactive waste in Belgium

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ABSTRACT. In order to protect man and the environment, long-lasting, passive solutions are needed for the different categories of radioactive waste. In Belgium, it has been decided that Category A waste (low and intermediate level short-lived waste) will be disposed in a near-surface facility. The reference solution for the disposal of Category B and C wastes (high-level and other long-lived radioactive waste) is a deep geological repository. In both cases, the long-term safety of a given disposal facility is evaluated. Different scenarios and assessment cases are developed illustrating the range of possibilities for the evolution and performance of a disposal system without trying to predict its precise behaviour. Within these scenarios, the evolution of the climate will play a major role. This paper describes the fundamentals of the long-term safety assessment of waste disposal facilities in Belgium. It furthermore describes future climate evolution based on a literature review, and evaluates how climate predictions can be treated in safety assessment studies for the long-term safety of disposal facilities.

KEYWORDS: Radioactive waste disposal, safety assessment, climate evolution, Boom Clay

1. Introduction

Since its start in the 1970's, the Belgian nuclear electricity generating programme, containing 7 power reactors and totalling 5640 MWe of installed capacity, supplies more than half of the total Belgian energy production. This, together with other activities such as research facilities, some industrial applications and medical infrastructures and practices, inevitably leads to different types of radioactive waste.

Consistent with its mission, ONDRAF/NIRAS must bring forward projects for the long-term management of all Belgian radioactive waste. Disposal is the final step in the management of solid radioactive waste, and defined as 'the emplacement of radioactive waste or spent fuel in an appropriate facility without the intention of retrieval'. The latter is freely taken from the Belgian law defining the objectives and mission of NIRAS/ONDRAF. This, however, does not mean that a period of retrievability of the waste from the repository cannot be foreseen during some reasonable time if deemed desirable.

In Belgium, three main categories of conditioned radioactive waste (termed A, B and C) are defined by radiological and thermal power criteria. It is envisaged that two types of disposal facilities will be required to deal with all Belgian radioactive waste from the operation and decommissioning of past and current nuclear facilities, and also from industrial, medical and research sources:

- *A near surface type disposal facility* – designed to accept short-lived low and intermediate level radioactive waste (category A waste);
- *A geological type disposal facility* (located in a suitable geological formation at depth) – designed to accept all other radioactive waste including long-lived low and intermediate level waste (category B waste) and high level radioactive waste and spent nuclear fuel that is treated as waste (category C waste).

This allocation is consistent with international guidance on radioactive waste classification and international guidance on disposal options for radioactive waste.

In order to study the long-term safety of a disposal system, different scenarios of the possible future evolution should be considered. In this frame, climate evolution and its impact on the disposal system should be taken into account in the long-term safety assessment studies.

In the first part of this paper, the fundamentals of the long-term safety assessment of waste disposal facilities are discussed. In the next part, we will focus on climate evolution, and evaluate the existing literature on the modelling of future climate changes. Finally, we will discuss how climate evolution will be treated in the long-term safety assessment studies of radioactive waste disposal in Belgium.

2. Long-term safety assessment of radioactive waste disposal facilities

In this part the fundamentals of safe radioactive waste disposal and the long-term safety assessment of waste disposal facilities are discussed.

2.1 Passive safety of waste disposal facilities based upon the concentration and confinement strategy

The general safety objective of disposal as the final step of radioactive waste management is to protect human health and the environment, now and in the future, without imposing undue burdens on future generations. In this respect, solutions are developed that are based on passive safety. This means that no future interaction or maintenance by humans is required. However, it does not exclude a continued control as long as deemed necessary and feasible. The generally adopted strategy for disposal to achieve this objective is to concentrate and confine the waste and to isolate it from man and the environment. The safety objective and the strategy for disposal are implemented through different safety functions, i.e. functions that the disposal system should fulfill to achieve its general safety objective of providing long-term safety through concentration and confinement strategy. ONDRAF/NIRAS considers three safety functions:

1. Engineered containment (C) consists of preventing as long as required the dispersion of contaminants from the waste form and the escape of gaseous substances, by using one or several impermeable barriers.

2. Delay and attenuation of the releases (R) in order to retain the contaminants for as long as required within the facility. 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 forms.
- *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 forms and from the waste containers.
- *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 forms and from the waste containers.

3. Isolation (I) of the waste from humans and the biosphere for as long as required, by preventing direct access to the waste and by protecting the disposal facility from the potentially detrimental processes occurring in the environment of the disposal facility. 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 biosphere.
- *ensuring stable conditions for the disposed waste and the system components (I2)* – The I2-function consists of protecting the waste and the engineered barrier components of the disposal system from changes and perturbations occurring in the environment of the facility, such as climatic variations (i.e., freeze-thaw phenomena and drying-wetting cycles), erosion, uplifting, seismic events or relatively rapid changes in chemical and physical conditions.

A number of engineered and natural barriers, fulfilling different safety functions, are placed between the contaminants and the accessible environment. In this way the humans are shielded and have no direct access to the waste. 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. The set of components and barriers contributing to the concentration and confinement strategy constitute the "disposal system".

The environment of a disposal system may disperse and dilute the contaminants released from the disposal system, and as such contributes to long-term safety, because the impact of the disposal system on man and the environment is inversely proportional to the reduction in contaminant concentrations.

However the processes of ***"dispersion and dilution"*** in the environment are not considered to be part of the adopted safety strategy to "concentrate and confine" and on which the optimization of the safety would focus. They are in consequence assigned a safety role as opposed to a safety function."

When dealing with scenarios of climate evolution, safety assessment studies have to assess (1) the influence of climate evolution on the disposal system itself, and (2) the impact of climate evolution on the geological environment surrounding the disposal system (e.g. dispersion and dilution in the geological environment).

2.2 Characteristics and reference design of disposal facilities for radioactive waste

Category A waste is short-lived low and intermediate level radioactive waste, i.e. waste with only trace amounts of long-lived radioactivity. The steepest decline of radioactivity, and therefore of radiological hazard occurs within the first 100's of years after emplacement of the waste. Beyond some 1000's of years the radiological hazard reaches a residual level due to the trace amounts of long-lived radioactivity. In the current concept, waste is encapsulated in concrete boxes. These boxes are emplaced in concrete modules placed upon a sand-cement embankment (ONDRAF/NIRAS, 2010). After waste emplacement, the modules are overlain by a multi-layer cover to form a mound. The repository design that will be implemented on the Dessel-site is shown in Fig. 1.

Category B waste is long-lived low and intermediate level waste, whereas Category C waste is high level radioactive waste and spent nuclear fuel. The most important decline of radioactivity, and therefore of radiological hazard, of spent nuclear fuel occurs within the first 100 ka after emplacement of the waste. Beyond about 300 ka the decline

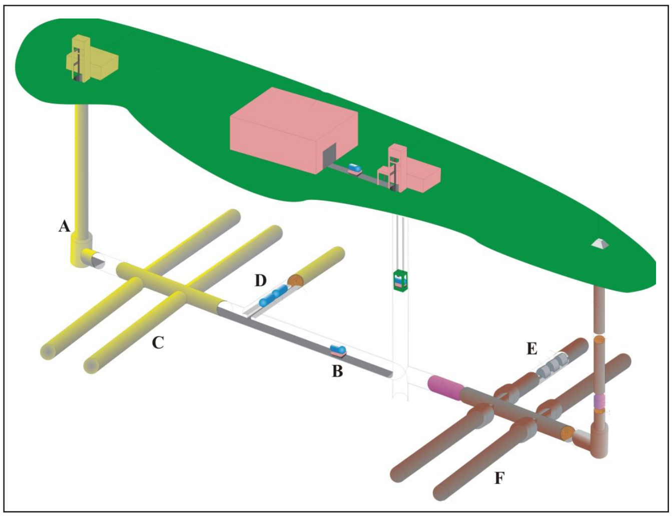

Figure 2: Schematic lay-out of the concept of underground repository facilities and of the related surface facilities during disposal facility operation. Zone for high-level waste (category C waste) is indicated in yellow and the zone for low and intermediate-level waste long lived (category B waste) is indicated in brown. A: Shaft; B: Transfer of waste package through access gallery; C: Disposal gallery for category C waste; D: Emplacement of category C waste package in disposal gallery; E: Category B waste package emplaced in disposal gallery; F: Disposal gallery for category B waste.

of the total radiological hazard of the spent nuclear fuel is similar to an equivalent amount of U ore that is used to produce such fuel. For the Category B&C waste, a geological type disposal facility is proposed. In the current ONDRAF/NIRAS concept (Bel et al., 2005), the repository will be constructed in the middle of an approximately 100 m thick clay layer, with the overlying sedimentary formations providing the geological coverage to isolate the waste. The concept for underground facilities is illustrated in Fig. 2, which also shows the emplacement of the B&C waste in approximately horizontal disposal galleries in spatially separated sections of the repository.

2.3 General aim of safety assessment and scenario development

According to the International Atomic Energy Agency (IAEA), the fundamental safety objective of all radioactive waste management activities is "to protect people and the environment from harmful effects of ionizing radiation" (IAEA, 2006). Disposal is carried out to implement that protection for present and future generations in such a way that the need for further action is minimized (= passive safety).

In radioactive waste management, long-term safety assessment is the identification and critical evaluation of various lines of arguments for the long-term safety of a given disposal facility. A safety assessment will typically consider several different scenarios, and many different assessment cases. For each scenario, a 'reference' or 'base case' is defined, together with a number of alternative cases that adopt different assumptions where there is model or parameter uncertainty. The purpose of each alternative case may be defined in terms of the uncertainties addressed. By comparing the results of these alternative cases with those of the reference case, the impact of these various uncertainties can be assessed.

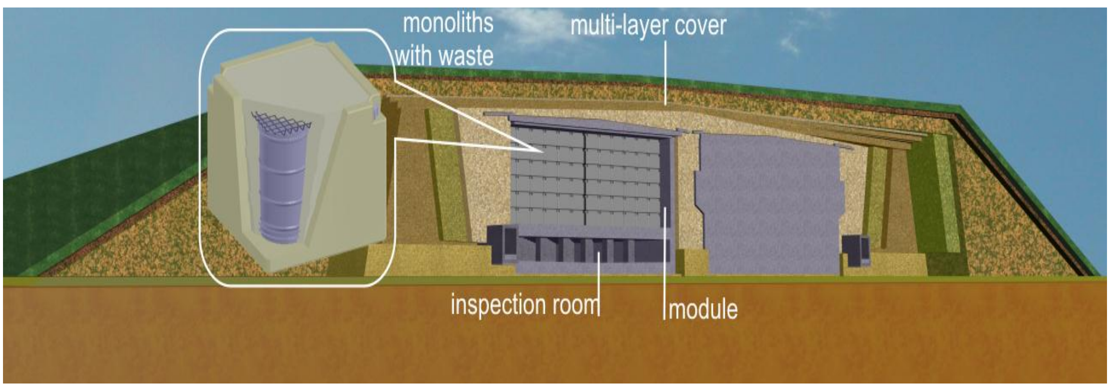

Figure 1: Cross-sectional view of near surface disposal facility.

Consequently, safety assessment requires a good knowledge of the expected evolution of a repository system, but also a clear indication of the remaining uncertainties. This will lead during an interaction of safety assessment people and scientific experts to define justified scenarios and assessment cases. These scenarios have not the intention to be predictions of the actual evolution of the disposal system, but are aimed as illustrations of the range of plausible evolutions.

The development of scenarios starts with a good knowledge of the expected evolution of the disposal system and its environment, and the possible disruptions to this evolution. It is, however, virtually impossible to predict exactly what will be the evolution of the disposal system over time. Scenarios are a basic tool aiding a systematic safety assessment, in which many different factors (e.g. conceptual model and parameter uncertainty, long time frames, human behaviour,…) need to be taken into account and evaluated in a consistent way, while accounting for large uncertainties. They provide a basic tool for structuring all these factors and, as such, a mechanism for defining the initial and boundary conditions for assessment calculations, and the way in which these conditions evolve. They handle uncertainty directly by describing alternative futures and allow for a mixture of quantitative analysis (i.e. what is the impact of a particular scenario?) and qualitative judgement (i.e. which scenarios to consider in safety assessment).

The goal of scenario development is to define a limited set of scenarios that can reasonably be analysed while still maintaining a sufficiently comprehensive coverage of possible future states of the system, identifying the important scenarios that must be considered in quantitative analyses of the system performance.

Different methods for scenario development exist and are used, depending on the national contexts and on the stage and nature of the disposal programs. For disposal programs in a research and development stage dealing with very long time frames such as the categories B&C disposal program in Belgium, the methods can be more detailed and focused onto research and development uncertainties than *e.g.* disposal programs near to an implementation stage and dealing with shorter time frames such as the category A disposal program in Belgium.

For a detailed description of the safety assessment methodology within the Belgian category A and the category B&C waste disposal programmes, we refer to the ONDRAF/NIRAS reports (ONDRAF/NIRAS, 2008, 2009).

3. Future climate evolution

In this chapter, future climate evolution is briefly described. It is based on a literature review: for the near future (the next century to millennium), the results of the Intergovernmental Panel on Climate Change – IPCC (IPCC, 2007), and the MILMO project (Fichefet et al., 2007) are used, for longer time frames up to 1 million year, the results of the BIOCLIM project (BIOCLIM, 2001, 2004) are described.

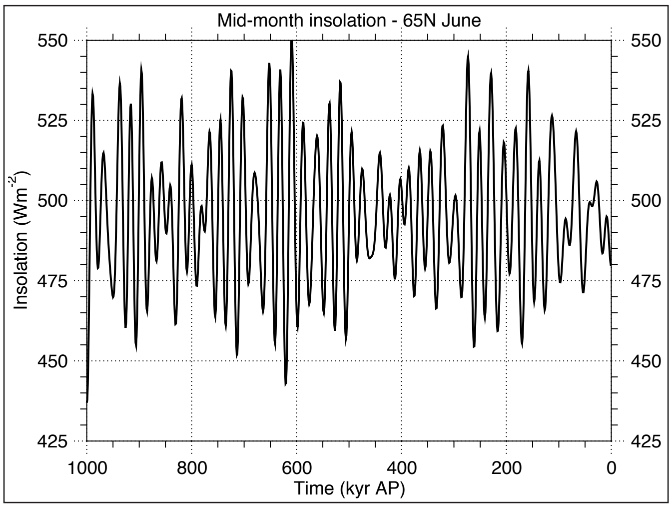

Figure 3: June Solstice insolation at 65N. (Figure from BIOCLIM, 2001).

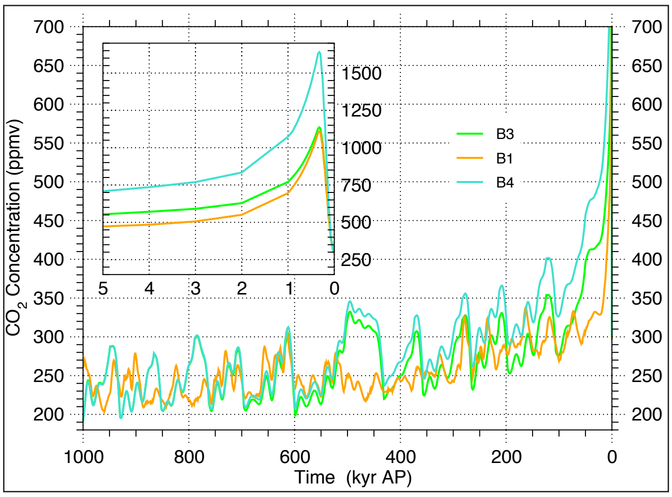

Figure 4: The natural atmospheric CO_2 scenarios from Burgess's regression (B1) and from Paillard's model (B3, B4), are combined (sum) with the fossil fuel contribution (human activity) over the next 10^3 ka. The inset panel is a blow-up of these combined scenarios for the next 5 ka. (Figure from BIOCLIM, 2001).

3.1 The driving forces of climate change

The Earth's climate has changed throughout history, from glacial periods where ice covered significant portions of the Earth to interglacial periods where ice retreated to the poles or melted entirely. Similarly, the climate will continue to change in the future.

The driving forces causing climate change are mainly related to changes in insolation and variations in the amount of greenhouse gases (mainly CO_2) and aerosols present in the atmosphere. The correlation with changes in insolation is clearly demonstrated, especially for the Late Tertiary and Quaternary (Hays et al., 1976; Berger, 1977, 1992; Berger and Loutre, 1991, 1996; Berger et al., 1991; Imbrie et al., 1984, 1993; Williams et al., 1993; Lowe & Walker, 1997; Bradley, 1999; and many others). The link with changes in CO_2 concentrations in the atmosphere is also demonstrated (Saltzman et al., 1993; Gallée et al., 1992; Loutre, 1995; Texier et al., 2003; and others), although natural variations in CO_2 concentrations are still poorly understood.

Insolation

During the next one million year, the insolation generally varies with large amplitudes (BIOCLIM project (BIOCLIM, 2001). Two periods can be identified that show much smaller amplitude of insolation variability (Fig. 3). These periods (the next 50 ka and around 400 ka AP) coincide with periods of small variations in the eccentricity, *i.e.* minima in the 400 ka period of the eccentricity change.

CO_2 concentration

During the next one million year, the natural CO_2 concentration in the atmosphere will continue to change. Unfortunately, the natural CO_2 cycle processes are poorly understood, especially in the considered time frame of 1 million year. Hence, various CO_2 scenarios are developed, in which a number of hypotheses are involved (e.g. Earth surface carbon residence time). In addition, CO_2 is added to the atmosphere from human activities. Also for this part, various amounts of fossil fuel contributions may be considered.

In the BIOCLIM project (BIOCLIM, 2001), 15 CO_2 scenarios were evaluated. Some scenarios only consider a constant CO_2 concentration (210 or 280 ppmv), while other scenarios consider natural variations in CO_2 concentration. Furthermore, these may be combined with various amounts of fossil fuel contribution, according to various computational models, giving rise to even more scenarios. A combination of natural CO_2 variations and fossil fuel contribution (as in the B1, B3 and B4 scenarios, see BIOCLIM - BIOCLIM, 2001) is considered to be the most representative. Therefore, these three scenarios were used for further modeling experiments (see Fig. 4).

3.2 Future climate models

Climate projections – although rarely found in literature – usually only cover the near future, i.e. several centuries. Climate projections for a period up to 1 Ma in the future are very scarce. In the next paragraphs, some important conclusions on future climate evolution, as reported in literature, are drawn for the various periods of time considered in the safety assessment of radioactive waste disposal.

Current short-term climate projections (up to a few ka AP)

In a relatively short time frame, climate projections reported in the IPCC report (IPCC, 2007) provide input to model boundary conditions for near field, geosphere and biosphere for surface disposal facilities. So-called Earth System Models of Intermediate Complexity (EMICs) were used to calculate climate change under a scenario of increased greenhouse gasses until 2100 and then of constant atmospheric composition until the year 3000.

The global temperature rise expected to occur by the end of the 21st century ranges between 1.1°C and 6.4°C (Meehl et al., 2007; IPCC, 2007), depending on models, demographic evolution, and on projections of politic and economic choices. Among the range of available scenarios, some of them assume a reduction of the carbon emissions after 2050. However, owing to the residence time of CO_2 in the atmosphere, the human activities will affect the climate for many centuries and millennia. One of the main consequences would be a continued rise of sea-level that could greatly exceed that projected for the next hundred years (Alley et al., 2005; Gregory & Huybrechts, 2006; Fichefet et al., 2007; Charbit et al., 2008; Naish et al., 2009; Paillard, 2006 and 2009; Solomon et al., 2009; and others).

In a recent study, Fichefet et al. (2007) modeled the evolution of the climate and sea level during the third millennium (the MILMO project). The authors showed that, for a wide range of greenhouse-gas-stabilisation profiles, it is very likely that the volume of the Greenland Ice Sheet will largely decrease in the future. In the most extreme case considered in their study, Greenland becomes ice-free in about 2 000 years AP. The ice-sheet disintegration might be even more rapid if processes responsible for the widespread glacier acceleration currently observed in Greenland (e.g. Rignot & Kanagaratnam, 2006) were taken into account in the model.

Simulations with the LOVECLIM Earth System Model for the period 2000-4000 years AP (Fichefet et al., 2007) have indicated that, for the A2 scenario (fixed CO_2 of 280 ppmv combined with high fossil fuel contribution, constant after 2100 years), with a temperature increase of 3-4°C, ice caps start to melt and they keep melting. The global sea level rises by 14 m and no steady state is reached yet by 4000 years AP (Fichefet et al., 2007). Extrapolation of the results in Fichefet et al. (2007) suggests that a sea-level rise of 20-25 m could be reached after 6 ka AP, or at least within the next 10 ka AP. Charbit et al. (2008) and Solomon et al. (2009) also demonstrated that the fossil-fuel emissions of the next century will have dramatic consequences on the climate and sea-level rise for several millennia. According to these authors, the present-day CO_2 emissions have already caused irreversible changes to the climate, and to the Greenland Ice Sheet in particular.

Note however that, although there are indications that continued sea-level rise will amount to 20-25 m within the next 10 ka, there are still considerable uncertainties associated with this scenario (e.g., the assumed greenhouse gas emissions scenario, the feedback mechanisms, and the assumed melting rates of ice in response to CO_2 rise). Over the period of 10 ka AP, north-eastern Belgium is considered to be characterised by a climate that is moderately warmer than at present, with a similar degree of water availability through the year, but with drier summers (Leterme et al., 2011). This is consistent with the development of a Cs climate (subtropical climate with winter rain) that is indicated by BIOCLIM for the regions of Central England and north-eastern France over the next 60 ka (BIOCLIM, 2004; see below).

Current long-term climate projections (up to 1 Ma AP)

A useful source of information on future climates in relation to radioactive waste disposal in longer time frames is available through the BIOCLIM project (Modelling sequential BIOsphere systems under CLIMate change for radioactive waste disposal; BIOCLIM, 2001, 2004; Texier et al., 2003). The BIOCLIM project had as its main objective to provide a scientific basis and practical methodology for assessing the possible long term impacts on the safety of radioactive waste disposal facilities due to climate and environmental change. Future climates were calculated for several typical regions in Europe. BIOCLIM data for the Northeast of France and Central England are considered useful to bound the future climate in northern Belgium.

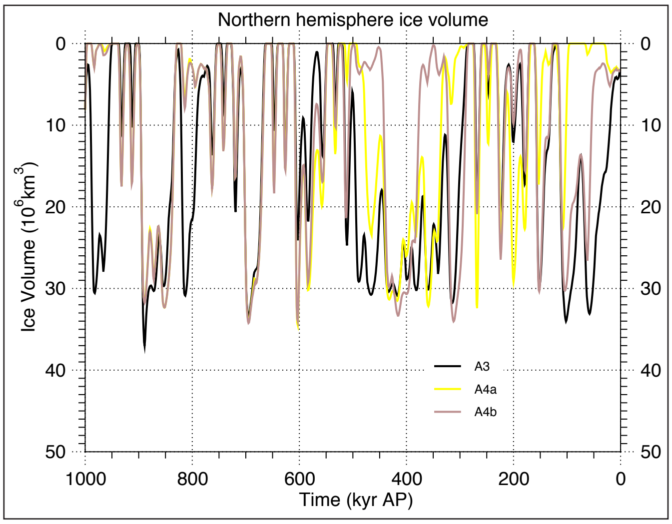

Figure 5: The simulated northern hemisphere continental ice volume considering only natural CO_2 variation. A3: natural variations in insulation and natural atmospheric carbon dioxide concentrations (based on Burgess's regression); A4a: natural variations in insulation and natural atmospheric carbon dioxide concentrations (based on Paillard's threshold model a); A4b: natural variations in insulation and natural atmospheric carbon dioxide concentrations (based on Paillard's threshold model b) (BIOCLIM, 2001).

The CO_2 scenarios used in the BIOCLIM project are based on Burgess' regression (a regression between insolation variables and the Vostok record of atmospheric CO_2 concentrations; Burgess, 1998) and Paillard's model a and b (computed from a simple threshold model, but with two values of a critical threshold, leading to similar simulated CO_2 concentrations in the past, but different ones in the future; Paillard, 1998). A detailed description of Burgess' regression and Paillard's models can be found in Burgess (1998) and Paillard (1998) respectively. A summary is given in BIOCLIM (BIOCLIM, 2001, deliverable 3). In the BIOCLIM project, these CO_2 scenarios were evaluated using the LLN 2D NH (Louvain-la-Neuve 2D Northern Hemisphere) climate model (Berger et al., 1998).

Fig. 5 shows the simulated northern hemisphere continental ice volume considering only natural CO_2 variations (scenarios A3, A4a and A4b):

- A3: natural variations in insulation and natural atmospheric carbon dioxide concentrations (based on Burgess's regression);
- A4a: natural variations in insulation and natural atmospheric carbon dioxide concentrations (based on Paillard's threshold model a);
- A4b: natural variations in insulation and natural atmospheric carbon dioxide concentrations (based on Paillard's threshold model b).

In the natural A3 and A4 scenarios, conditions as warm as the present day persist for a considerable time (up to about 50 ka AP) in Central England and the Northeast of France . A3 and A4b predict a glacial period at about 53 ka AP, while this glacial period is not projected by the A4a model. At about 100 ka AP, a glacial period is predicted by the three models. So, these climate simulations, using both insolation and natural CO_2 variations, predict an exceptionally long interglacial, lasting about 55 ka (from 5 ka BP to 50 ka AP) or even longer (Texier et al., 2003). A large number of sensitivity experiments have confirmed the likelihood of such a long interglacial period (Loutre & Berger, 2000). Just after 100 ka AP, Central England and the Northeast of France experience a brief period of polar climate and tundra. Later on, the different scenarios predict a repetition of glacial and interglacial periods.

Important to note is that the exact timing or extent might change drastically from one scenario to the other (see Fig. 5). These uncertainties have to be considered in the safety assessment studies.

However, future climate projections should also take into account the increase in atmospheric greenhouse gasses due to human activities. Fig. 6 shows the simulated northern hemisphere continental ice volume considering natural and anthropogenic CO_2 variations (scenarios B1, B3 and B4):

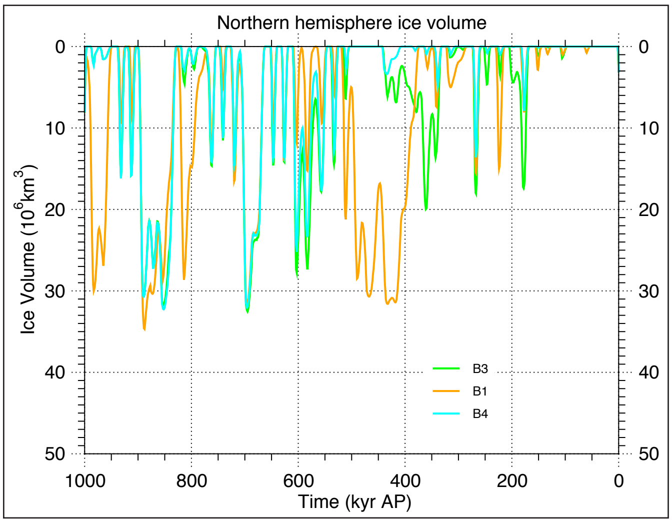

Figure 6: The northern hemisphere continental ice volume considering natural CO_2 variation and low and high fossil fuel contributions. B3: anthropogenic low CO_2 increase scenario (Paillard's threshold model a used for the natural CO_2 variation); B1: anthropogenic low CO_2 increase scenario (Burgess's regression used for the natural CO_2 variation); B4: anthropogenic high CO_2 increase scenario (Pallard's threshold model a used for the natural CO_2 variation) (BIOCLIM, 2001).

- B1: anthropogenic low CO_2 increase scenario (Burgess's regression used for the natural CO_2 variation);
- B3: anthropogenic low CO_2 increase scenario (Paillard's threshold model a used for the natural CO_2 variation);
- B4: anthropogenic high CO_2 increase scenario (Paillard's threshold model a used for the natural CO_2 variation).

The most striking result of the climate predictions taking into account the anthropogenic scenarios as well, is that the next glaciation will be delayed and less severe (see Fig. 6). The first glacial period is simulated to appear at 178 ka AP for the three scenarios, with much smaller ice caps than in the previous simulations: about 17 × 10^6 km^3 in case of scenario B3 and only 8 × 10^6 km^3 in case of scenarios B1 and B4.

The fossil fuel contribution will have an impact on the future climate for at least the next 400 ka (see Fig. 6). Thereby, the simulated ice volumes remain small (less than 3 × 10^6 km^3 on average) over most of the next 400 ka, except for some small cooler excursions at 178, 267 and 361 ka AP in B3, 224 and 267 ka AP in B1, and 267 ka AP in B4. The first important glacial period with ice caps > 30 × 10^6 km^3 appears after 400 ka AP in case of scenario B1, but not in case of the B3 and B4 scenarios. After 500 ka AP, the impact of the fossil fuel contribution becomes smaller in favour of natural variations.

Critical consideration

As mentioned several times, the natural CO_2 cycle processes are poorly understood, and hence, various CO_2 scenarios are developed, in which a number of hypotheses are involved. Future climatic scenarios are computed from the CO_2 scenarios and are thus extremely dependent on them.

The current CO_2 concentrationin the atmosphere will already have a long impact on climate evolution (see references above), but it is not known how human activity will evolve and how it will further influence the climate. Furthermore, there is a large uncertainty on the exact timing and degree of climate changes on the long-term, as various simulations may give different results. This will have implications for the evaluation of climate changes in the long-term safety assessment of radioactive waste disposal, as will be discussed below.

4. How to treat climate evolution in the long-term safety assessment of radioactive waste disposal ?

In response to climate change, the landscape and hydro(geo)logical regime at and around a disposal facility may change, as may the biosphere receptors, and the animal and human habits. Climate change can affect the groundwater flow regime. Changes in boundary conditions due to climatic variations may cause changes in infiltration, recharge to the aquifer and discharge to surface locations. Climate change can also affect the water flow in the near field of a surface disposal system. For geological disposal systems, the impact of climate change on the properties of the host rock needs to be addressed as well. Climate is also one of the major controls on the geochemistry of natural water systems, as it affects the chemical and physical processes controlling rock weathering, which in turn controls the pH, oxygen content and redox potential (E_h) of the water environment.

The design of the disposal facilities, as well as the time frames to be considered in safety assessment studies are markedly different for category A and category B&C wastes. Considering the decay of radioactivity, a near-surface disposal facility is proposed for the disposal of category A waste, and typical time frames of several centuries to millennia are evaluated. In contrast, for category B&C, a deep geological disposal facility is proposed, and time frames of several hundred thousands to one million years need to be considered. Because of these differences, both waste types are treated separately in safety assessment studies.

4.1 Climate evolution & safety assessment related to category A waste

Climate change can influence the disposal system, through the changing water infiltration through the multi-layer cover. Furthermore, the influence on the dispersion and dilution in groundwater and the biosphere have to be considered, although the adopted safety strategy does not rely on it.

In safety assessment studies related to category A waste, typical time frames of several centuries to millennia are evaluated. Also, longer time scales up to 200 ka will be considered for assessing the very low long-term impact of individual radionuclides (category A waste contains trace quantities of very long-lived radionuclides such as ^{238}U and ^{129}I).

For the next few thousands of years, it is projected that north-eastern Belgium will be characterised by a climate that is moderately warmer than at present, with a similar degree of water availability through the year, but with drier summers. In the safety assessment studies, these conditions will be evaluated as the reference case in the expected evolution scenario for the next millennia.

Available estimates of future temperature and precipitation often extend until AD 2100 only (e.g. IPCC scenarios of climate change). In absence of regional climate modeling data (RCM) for a sufficiently far future, we use climatic analogues and 1-D modelling of the soil-plant-atmosphere system to quantify infiltration for a sequence of future climate states. The following contrasting climate states are considered (based on Köppen-Trewartha classification; Trewarta, 1968): DO (maritime temperate - the present-day climate in Dessel, Belgium), Cs/Cr (subtropical with dry summers/no rainfall seasonality), EO (boreal, cold without permafrost) and FT (tundra, cold with permafrost). These possible sequences of future climate states have previously been defined to be applicable to the study area (BIOCLIM, 2004). Using criteria including altitude, distance to moisture source, and atmospheric circulation system, potential analogue stations were collected for each climate state Cs/Cr and EO/FT. Among these, the two stations displaying the least deviation from median statistics of temperature and precipitation were chosen, while the two stations having the lowest and highest precipitation record were also included to account for variability within a climate class. For the Cs/Cr climate, Gijon (Spain) was selected as analogue station, because its precipitation amount and seasonality are more in accordance with the predictions of the IPCC for the near future applied to Belgium. Gijon has a mean annual temperature that is 3.4°C warmer than Dessel, while mean annual precipitation is 48 mm higher (~5%).

Global warming will be associated with continued rise of sea-level and changes in hydrology. A sea-level rise of 20-25 m within the next 10 ka may be possible (Fichefet et al., 2007), but there are still considerable uncertainties associated with this scenario. It is not clear whether in such conditions, the Dessel-site – presently located at 25 m above sea level – will be flooded. Therefore, in safety assessment studies, the marine inundation scenario is sufficiently probable to be taken into consideration, but only as an extreme event outside the expected evolution scenario (Leterme et al., 2011).

For the longer term (up to 200 ka AP), simulations of future climate project at least one cold period with growing ice caps within the next 200 ka, although these cold climate conditions are half as severe as in the past (see Fig. 6 and the discussion above). Ice caps will develop but will most probably not reach the area of north-eastern Belgium within the considered time frame. Permafrost conditions may occur in the Dessel area. Furthermore, sea-level drop, glacio-isostatic tilting of the landmass, erosion, changes in the river system, and water balance changes should be considered. A cold climate with permafrost development at around 100 ka AP is considered as an alternative case to the expected evolution scenario, while an earlier occurrence of this climate state (around 53 ka AP) is considered only as an extreme event outside the expected evolution scenario.

Assessment of future climate changes through assessment cases of the expected evolution scenario is considered both for the near field (increased or reduced infiltration into the facility due to changing precipitation, impact on chemical evolution of the concrete, see Jacques & Mallants, 2011), and the geosphere (possible impact on groundwater heads and thus dilution).

4.2 Climate evolution & safety assessment related to category B&C waste

In safety assessment studies for category B&C waste, time frames of several hundred thousands to one million years need to be considered.

Within the time frame of 1 Ma, climate evolution will change the geosphere, and thus also the geological and hydrogeological environment of a geological disposal system. Climate changes are the driving force behind eustatic sea-level changes and landscape development via fluvial processes (incision/aggradation) and denudation processes. As a result, topography will change, as well as the entire hydro(geo)logical system through changes in fluvial style and dynamics and recharge/discharge conditions.

An example of climate change impact assessment for a geological repository system (the PHYMOL project, Marivoet et al., 2000) is illustrated below. The current approach of the climate issue in the long-term safety assessment studies for category B&C waste is furthermore discussed.

4.2.1 Example of climate change impact assessment for a geological repository system (the PHYMOL project)

The PHYMOL project (A **P**alaeo**hy**drogeological study of the **Mol** site; Marivoet et al., 2000), carried out in 1997-1999,provides an analysis of a methodology taking climatic effects into account in the performance assessment of an argillaceous repository system. The considered host formation is the Boom Clay, situated at about 190 metres depth, with a thickness of about 100 metres at the Mol site (this is the reference site for RD&D purposes). The project includes a palaeo-reconstruction of the hydrogeological system at the Mol site, over the past 125 ka *i.e.* from Eemian to present day. The climate effects are then evaluated for the next 125 ka years based on the conclusions of the palaeo-reconstruction and by considering a projected natural climate evolution as calculated by Berger and Loutre in 1991 (Berger et al., 1991).

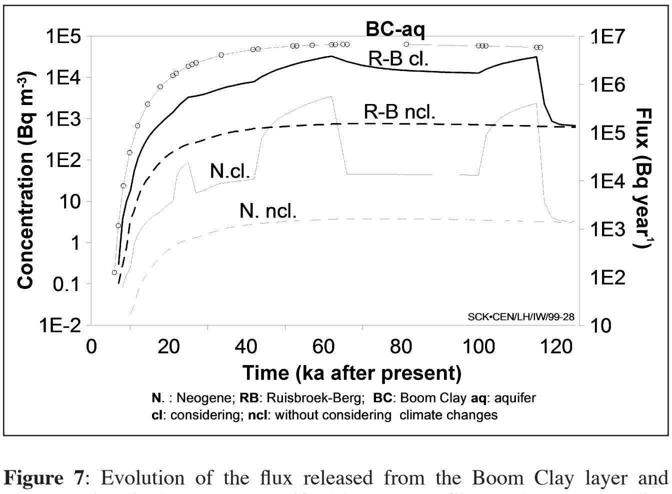

Figure 7: Evolution of the flux released from the Boom Clay layer and concentrations in the Neogene aquifer (above Boom Clay) and Lower-Rupelian aquifer (below Boom Clay) with and without considering climate changes (PHYMOL project, after Marivoet et al., 2000). The 'bumps' in the concentration profiles considering climate change are related to the decreasing water flow in the aquifers during cold climate conditions.

Fig. 7 illustrates the higher radionuclide concentrations obtained in the aquifers above the Boom Clay (Neogene aquifer system) and below the Boom Clay (Lower Rupelian or Ruisbroek-Berg aquifer) when considering the climate changes (i.e. colder periods). This climate effect on the radionuclide flux released from the Boom Clay is in contrast strongly limited since the transport in the clay layer is essentially diffusive.

Many uncertainties were encountered during the PHYMOL study. The study provides however an interesting method of evaluation as well as an estimated outcome of some colder and glacial climatic periods that possibly could occur in some of the many possible future evolution scenarios. The study furthermore illustrated the importance of parameters that are represented by the infiltration and river heads.

The climate models used in the PHYMOL project were based on astronomical and solar forcings (insolation) only. In more recent studies, however, climate projections are based on both astronomical and solar forcings, and natural and anthropogenic CO_2 forcings (BIOCLIM, 2001; Texier et al, 2003 and references therein). Therefore, it was decided to re-consider the climate issue.

4.2.2 Recent approach of the climate issue in the long-term safety assessment studies for category B&C waste

For the long time scales related to category B&C waste (beyond 100 ka up to 1 Ma AP), it becomes very uncertain to obtain precise climate evolution predictions. Various climate models, or the use of various CO_2 scenarios may give very different results. So, there is a large uncertainty on the precise timing of glacial/interglacial periods and the volume of ice caps, which may be considerably different for various climate simulations (BIOCLIM, 2001).

Consequently, the projections of future climate at such time scales are considered to be inadequate for our purposes as it is impossible to predict the timing and degree of glacials/interglacials and hence build confidence into expected climate evolution.

Therefore, safety assessment studies will not be based on the climate projection models as such. Instead, the option chosen is rather to evaluate the impact of global warming and cooling on the performance of the repository system components, including, amongst others:

- possible range of effects on hydrogeology (low infiltration, permafrost conditions, salt water intrusion, etc…);
- possible range of effects on clay properties (creation of fractures due to permafrost, salt water intrusion, etc…);
- possible range of effects on waste isolation due to host formation erosion, etc.;
- possible range of effects on overburden.

Based on the results of the BIOCLIM project (BIOCLIM, 2001, and discussion above), the following considerations are made for the long-term safety assessment of deep geological repositories within the next 1 Ma:

Similar to the past, the next 1 Ma will be characterised by a succession of several warm and cold climate conditions. So both climate conditions should be evaluated in the normally expected evolution scenarios. Several assessment cases can be evaluated: global warming with or without marine incursion, or a cold climate condition with or without permafrost in our regions. The future presence of ice caps in our regions has been a topic of debate and is therefore briefly discussed hereafter.

Future climate simulations predict at least one cold period with ice caps within the next 200 ka AP, although these cold climate conditions are half as severe as in the past (see Fig. 6 and the discussion above). The first important glacial period with ice caps similar to the one during the LGM (Last Glacial Maximum) will appear after 400 ka AP in case of scenario B1, or after about 600 ka AP in case of the B3 and B4 scenarios.

A northern hemisphere ice sheet model (Zweck & Huybrechts, 2005) is used to predict the likelihood of ice sheets in the Mol-Dessel region during the next 1 Ma (see Huybrechts, 2010 and references therein). The model predicts the 3-dimensional geometry of ice sheets in response to changes in surface temperature, precipitation and eustatic sea level. Furthermore, the model is thermo-mechanically coupled and includes marine ice dynamics. The model was extensively validated for the last glacial cycle and the LGM, showing good agreement between model results and geomorphological reconstructions, with a few exceptions. A normalised glacial index varying between 0 (present-day) and 1 (LGM) was used to force the

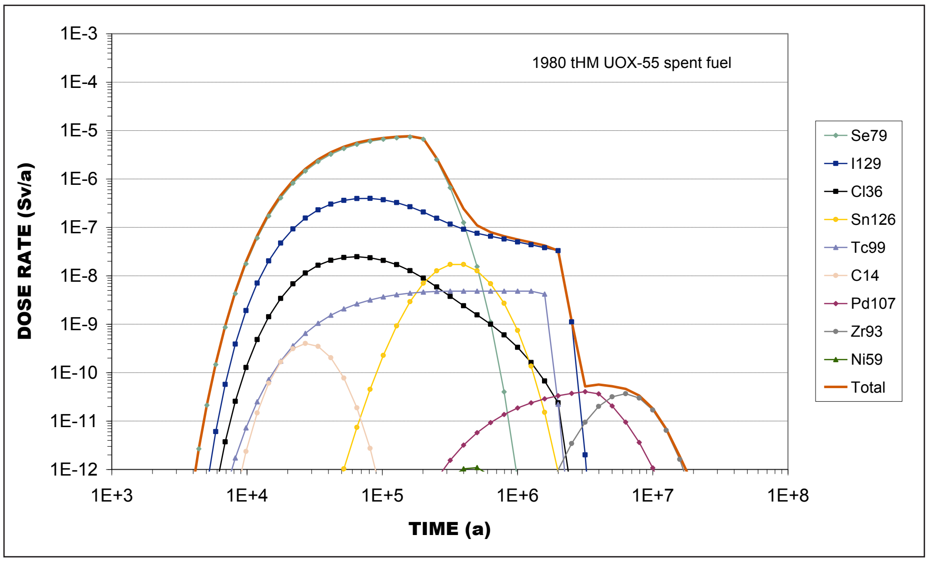

Figure 8: Evolution of the dose rate of various radioactive elements via the well pathway for spent nuclear fuel. The well pathway considers the pumping of aquifer water at a very conservative location, i.e. just above the downstream border of the repository. The mean annual natural exposure in several countries and worldwide is several 10^{-3} Sv/a. The international guide line advises a dose limit for the public of 10^{-3} Sv/a and specifically for repositories a dose limit of 1-3 10^{-4} Sv/a.

model in the time range between 120 ka BP and 1 Ma AP. The temporal evolution of the glacial index is taken from the BIOCLIM project using the LLN 2-D NH climate model that is especially designed to simulate long-term climate variations in response to Milankovitch forcing and natural CO^2 variations (Huybrechts, 2010 and references therein). The coldest BIOCLIM scenario A3 was used because of the interest in glacial maxima and its conservatism with respect to the performance of the repository system.

The main conclusion from the modelling experiment is that none of the projected future glacial maxima produces an ice sheet advancing over Belgium at any time during the next 1 Ma. Since it did not occur during the Quaternary either, even during colder glacial maxima than those projected for the next 1 Ma, the probability of such an event appears very low. So, future ice caps will probably never reach our regions, but can, however, not be excluded because of the uncertainties in the model.

Clearly, the advance of an ice sheet over Belgium is of very low probability but would be a very high impact event. Therefore, the presence of an ice sheet in our regions will be considered in safety assessment studies, albeit outside the expected evolution scenario, i.e. as an altered evolution scenario.

The consequences of future climate change are mostly derived from the study of identifiable climatic traces in the geological archive. Some of these archives contain very detailed traces of past climate states (e.g., pollen and periglacial phenomena for temperature reconstruction) that allow to classify a certain past climate, but they do not necessarily show the effect of such a past climate state or transition (e.g., river incision during a warm-cold transition). Therefore, the argumentation is done according to climate states and their most important envisageable effect (e.g., permafrost, marine inundation or river incision), rather than giving the argumentation according to well-specified climate classes (e.g., arctic, boreal, temperate, subtropical, etc.). Furthermore, the transition from one climate condition to another is evaluated as well in the safety assessment studies, as this may account for important changes in the geosphere.

Finally, it is important to mention that it is of utmost importance to reduce uncertainties or to clearly define the remaining uncertainties. For the safety assessment of geological disposal, the direct effect of climate change on the repository system is somewhat lower than for the category A surface repository system, but the timing of 100 ka is quite important. This is related to the fact that the most important, but still small, peak of radionuclide release occurs after about 100 ka. This is illustrated in Fig. 8, in which the evolution of the dose rate is shown after human intrusion through a drilling-well (well pathway scenario). The more precise the boundary constraints of the system are known, the better the overall safety of the system can be demonstrated.

5. Conclusions

The main objective when building a radioactive waste repository is to guarantee long-term safety to man and the environment. The time frames considered in the frame of category A waste and category B&C are different: the first ranging from 100 up to several 100 ka whereas the second focus on the range 100 ka to 1 Ma. The climate issue is essential in the elaboration of scenarios as these are used as central tools in the long-term safety of waste repositories. A full translation of the phenomenology is not necessary in the scenarios used for safety assessment calculations because they are illustrative and conservative. But the phenomenological models used to mimic the climate evolution help in narrowing (or enlarging) the amount of scenarios to be considered, and in steering the research on the possible impact of future climate evolution on the repository system. ONDRAF/NIRAS expects the scientific community to publish new outcomes on the spectrum of consequences of climate evolution, a better understanding of the CO_2 cycle (and the related Earth surface carbon residence time) and data on climate records at a spatio-temporal scale commensurate with the scale(s) of safety assessment model applications.

6. Acknowledgements

The authors are very grateful to André Berger, Marie-France Loutre, Michel Crucifix and Philippe Huybrechts for the interesting discussions, their expert judgment and their help in how to deal with climate evolution in the long-term safety assessment of disposal facilities for radioactive waste. Special thank is addressed to Marie-France Loutre for the permission of using the figures of the BIOCLIM project. We thank M. Thorne, D. Paillard, J. Naslund, N. Vandenberghe, R. Swennen and J.-C. Duchesne for their interest and the critical review of this document. Their comments and suggestions were very helpful to improve this document.

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Manuscript received 22.10.2010, accepted in revised form 28.06.2011, available on line 20.07.2011