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How to treat climate evolution in the assessment of the long-term safety of disposal facilities for radioactive waste: examples from Belgium

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Climate evolution in radwaste assessment

M. Van Geet et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

In order to protect man and the environment, long-lasting, passive solutions are needed for the different categories of radioactive waste. In Belgium, three main categories of conditioned radioactive waste (termed A, B and C) are defined by radiological and thermal power criteria. It is expected that Category A waste – low and intermediate level short-lived waste – will be disposed in a near-surface facility, whereas Category B and C wastes – high-level and other long-lived radioactive waste – will be disposed in 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 as the time scales of the evaluation and long term climate evolution overlap. In case of a near-surface facility (Category A waste), ON-DRAF/NIRAS is considering the conclusions of the IPCC, demonstrating that a global warming is nearly unavoidable. The consequences of such a global warming and the longer term evolutions on the evolution of the near-surface facility are considered. In case of a geological repository, in which much longer time frames are considered, even larger uncertainties exist in the various climate models. Therefore, the robustness of the geological disposal system towards the possible results of a spectrum of potential climate changes and their time of occurrence will be evaluated. The results of climate modelling and knowledge of past climate changes will merely be used as guidance of the extremes of climate changes to be considered and their consequences.

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

CPD

5, 463–494, 2009

Climate evolution in radwaste assessment

M. Van Geet et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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”. 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 safety of a disposal system, different scenario’s of possible future evolution are considered. In this frame, climate evolution and its impact on the disposal system is studied as well. In this paper we focus on how to treat the evolution of climate in the safety assessment of waste disposal facilities. First, the bases for the safety of waste disposal facilities are treated. Then, the characteristics and reference designs of the disposal facilities for category A and category B&C waste will be given. Afterwards, the process of safety assessment and scenario development will be explained. Finally, the impact of climate change and the treatment of it in safety assessment of category A and category B&C will be explored.

Climate evolution in radwaste assessment

M. Van Geet et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



2 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 the protect human health and the environment, now and in the future, without imposing undue burdens on future generations. 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. “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. In addition, it limits and spreads in time the releases of contaminants from the waste drums.
 - “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. By achieving R2, there is also a limitation of gaseous transport of radionuclides, since low water permeabilities are obtained by limiting the pore space available for water transport, which also limits transport of gaseous components because the same pore space is used for gas transport.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Climate evolution in
radwaste assessment**

M. Van Geet et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



– “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.

2. “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.

3. “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.

A number of engineered and natural barriers, fulfilling different safety functions, are placed between the contaminants and the accessible environment. Furthermore, the waste form can also fulfill one or several safety functions. The set of components and barriers contributing to the concentration and confinement strategy constitute the “disposal system”.

**Climate evolution in
radwaste assessment**

M. Van Geet et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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.

5 The processes of “dispersion and dilution” are considered a role of the environment, as opposed to a safety function, since all efforts made to maximize or optimize them would lead to a “disperse and dilute” strategy, instead of the chosen strategy to “concentrate and confine”.

10 When dealing with scenarios of climate evolution, two distinct elements have to be considered. Firstly, the influence of climate evolution on the disposal system has to be assessed. Secondly, the impact of climate evolution on the dispersion and dilution in the environment of the disposal system has to be assessed. The first element has more weight in the long-term safety of waste disposal facilities than the second element.

3 Radioactive waste: characteristics and reference design of disposal facilities

15 Based on the radioactive waste inventory 2003/2004, which assumes amongst others a 40 year operational lifetime of the commercial nuclear power plants, a volume of approximately 70 500 m³ conditioned category A waste is expected. About half of this category A waste originates from the future decommissioning of the nuclear power plants.

20 The steepest decline of radioactivity, and therefore of radiological hazard (expressed here as normalised Radiotoxicity Index, NRTI), of category A waste occurs within the first 200 to 300 years after emplacement of the waste. Beyond about 2000 years the decline in radiotoxicity is so slow that for practical purposes no further reduction of radiological hazard occurs except over very long times. At about 2000 years after waste emplacement the total radiological hazard of the emplaced waste is similar of a
25 typical coal-mining waste pile (Fig. 1).

The preliminary repository design (Fig. 2) comprises two double rows of sealed concrete disposal modules filled with concrete monoliths containing the conditioned waste.

Each double row of modules is protected against penetration of rainwater by a multi-layer cover several meters thick, which forms a tumulus. Two tumuli are foreseen, each about 15 m height.

Category B waste is mainly the outcome either of the processing/conditioning of liquid process effluent and decontamination operations, with possible pre-concentration, or, of the conditioning of solid waste that is highly contaminated by alpha and/or beta emitters. Assuming a phasing out of nuclear energy production in Belgium, a total of about 8700 m³ of category B waste is foreseen.

Most of the Category C waste comes from nuclear fuel used to generate electricity. Depending on whether the spent fuel is reprocessed or not, category C waste will mainly consist of glass, enclosing unusable material removed from the fuel, or the spent fuel itself. The option of full reprocessing would result in a total volume of about 2200 m³ vitrified waste, while a continued moratorium on reprocessing would result in about 4 700 m³ of spent fuel and vitrified waste.

The most important decline of radioactivity, and therefore of radiological hazard, of spent nuclear fuel (category C waste) occurs within the first 100 000's of years after emplacement of the waste. Beyond about 300 000 years the decline 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 (Fig. 3).

In the current ONDRAF/NIRAS reference concept (Bel et al., 2005), the repository will be constructed in the middle of an approximately 100 m thick Boom Clay layer, with the overlying sedimentary formations providing the geological coverage to isolate the waste. The concept for underground facilities is illustrated in Fig. 4, which also shows the emplacement of the B&C waste in approximately horizontal disposal galleries in spatially separated sections of the repository. Access to the disposal galleries is through a series of shafts and an access gallery. The underground facility includes engineered containment barriers that provide complete containment of heat-generating wastes and associated contaminants at least through the period when the heat output from the waste is high.

Climate evolution in radwaste assessment

M. Van Geet et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



4 Safety assessment

4.1 Aim of safety assessment

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. As stated by the International Commission on Radiological Protection (ICRP) in ICRP Publication-81 (ICRP, 2000): “The principal objective of disposal of solid radioactive waste is the protection of current and future generations from the radiological consequences of waste produced by the current generation.”

The position of the Federal Agency for Nuclear Control (FANC), consistent with the recommendations of ICRP, is that if protection is such that individual humans are protected from potential radiological hazards, then other living organisms in the environment will also be sufficiently protected. Hence, the “safety” of a radioactive waste management facility is defined by the level of protection that it provides to humans – both workers and members of the public, as well as those that may be exposed in the future.

In radioactive waste management, long-term safety assessment (generally referred to simply as safety assessment in the remaining of this text) is the means by which various lines of argument for the long-term safety of a given disposal facility are identified and critically evaluated. 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.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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.

5 These scenarios have not the intention to be predictions of the actual evolution of the disposal system, but are aimed as illustrations of potential future states. By including conservatism, the scenarios are used to assess the most stringent impacts on the disposal system, while maintaining a sound scientific basis regarding the possibility or relevance of occurrence of the scenarios.

10 4.2 Scenario development

The development of scenarios and assessment cases 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).

25 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

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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.

The text in the remainder of this section focuses onto the method currently proposed within the B&C disposal program. Although the general principles are similar within the category A disposal program, the method used there is slightly different (ONDRAF/NIRAS, 2008a).

Although different methodologies and terminologies might be used, the core of a safety assessment is based on a set of assertions regarding the safety of the disposal system, which we term here safety statements, each of which must be supported.

Safety statements generally begin as hypotheses (e.g. statements of the type “the repository and/or its components should ...”), which may initially be tentative. These are developed into increasingly well-substantiated claims (statements of the type “the repository and/or its components are expected to ...”) as the design and implementation procedures are developed and optimised, and the evidence, arguments and analyses that underpin each statement are acquired or developed, key elements of which are detailed and/or fundamental scientific evidence and arguments. The top level statements correspond with the safety functions a repository has to fulfil, namely to isolate the waste, to contain the waste during the thermal phase for heat-emitting waste (category C waste) and to delay and attenuate the releases of radionuclides to the environment.

Figure 5 shows an example of the chain of increasingly more specific statements for a B&C waste repository, underlying the statement, that:

“The disposal system delays and attenuates releases to the environment, ensuring releases remain below regulatory targets/standards and general guidance”.

It illustrates how this statement is underpinned ultimately by a range of geoscientific evidence regarding the safety-relevant properties of the geological environment.

Climate evolution in radwaste assessment

M. Van Geet et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Climate evolution in
radwaste assessment**

M. Van Geet et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Because of geoscientific and other uncertainties, not all safety statements can necessarily be said to hold true with absolute certainty. Uncertainties generally begin at the lower levels of the hierarchy of safety statements (including uncertainties in the underpinning geoscientific evidence and arguments) and propagate to higher-level statements if they cast significant doubt on their validity. The most critical uncertainties are those that cast doubt on the highest level statements and thus potentially give rise to alternative evolution scenarios. Figure 6 shows an example of how uncertainties related to climate change (specifically a change to a colder climate) could propagate through the set of safety statements introduced in Fig. 5.

Whether or not a specific uncertainty affects a particular safety statement may be assessed using scoping calculations, more qualitative arguments, or, in the cases of the highest-level safety statements, calculations of performance and safety indicators, including dose or risk. A key task of safety assessment consists essentially of evaluating, by means of suitable calculations, whether specific uncertainties cast significant doubt on the highest level safety statements, such the uncertainties must be reduced (by enhancing the assessment basis), or mitigated or avoided (e.g. by changes to the repository design).

5 Climate evolution: impact and currently available projections

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. When considering the long-term evolution of the disposal system, major climate changes (e.g. future glacial periods) should therefore be addressed; and the assessment time frame should be defined as appropriate to the hazard posed by the waste and potential changes at the site.

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 changes 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.

5.1 Example of climate change impact assessment provided by the PHYMOL project

The PHYMOL project, carried out in 1997–1999 (A Palaeohydrogeological study of the Mol site; Marivoet et al., 2000), 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 m depth, with a thickness of about 100 m at the Mol site. The project includes a palaeoreconstruction of the hydrogeological system at the Mol site, over the past 125 000 years i.e. from Eemian to present day (PD). The climate effects are then evaluated for the next 125 000 years based on the conclusions of the palaeoreconstruction and by considering a projected natural climate evolution as calculated by Berger and Loutre in 1991 (Berger et al., 1991).

Figure 7 illustrates the higher concentrations obtained in the aquifers above and below the Boom Clay when considering the climate changes. The 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 this study and the future climate evolution used in the simulation does not take CO₂ forcing scenarios into account which are now more developed (see below). 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. It stress on the influential parameters that are represented by the infiltration and river heads.

Climate evolution in radwaste assessment

M. Van Geet et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



5.2 Current short-term climate projections (up to a few thousands of years AP)

In a relatively short time frame, climate predictions from the Intergovernmental Panel on Climate Change (IPCC, 2007) provide valuable 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 (the A1B scenario¹) and then keeps atmospheric composition constant to the year 3000. By the year 2100, the projected global mean warming is between 1.2°C and 4.1°C. By the year 3000, the global warming range is 1.9°C to 5.6°C (Fig. 8).

While surface temperatures approach equilibrium relatively quickly, the sea level continues to rise for many centuries. Emissions during the 21st century continue to have an impact even at the year 3000 when both surface temperature and sea level rise due to thermal expansion are still substantially higher than pre-industrial.

For Europe, the assessments of projected climate change are such that annual mean temperatures are likely to increase more than the global mean (ICPP, 2007). The warming in Northern Europe is likely to be the largest in winter, whereby the lowest winter temperatures are likely to increase more than the average winter temperatures. Annual precipitation is very likely to increase in most of Northern Europe, while extremes of daily precipitation are very likely to increase.

Under the conditions of the A1B scenario, the simulated annual mean warming from 1980–1999 to 2080–2099 varies from 2.3°C to 5.3°C in Northern Europe. The warming in Northern Europe is likely to be largest in winter. The annual area mean precipita-

¹Four climate scenario families have been defined (a1, a2, b1, and b2). The a1 storyline assumes a world of very rapid economic growth, a global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. a1 is divided into three groups that describe alternative directions of technological change, of which a1b assumes a balance across all energy resources (i.e. similar improvement rates apply to all energy supply and end use technologies).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



tion change from 1980–1999 to 2080–2099 in the MMD (Multi-model data set)-A1B projections vary from 0 to 16% in Northern Europe.

The largest increases in precipitation for Northern and Central Europe are simulated in winter. In summer, the Northern Europe area-mean changes vary in sign between models, although most models simulate a decreased precipitation south of about 55° N. In Northern Europe, where increased precipitation competes with earlier snowmelt and increased evaporation, the mmd models disagree on whether summer soil moisture will increase or decrease.

Results further indicated that in a region comprising mainly Germany, circulation changes played a major role in all seasons. In most models, increases in winter precipitation were enhanced by increased westerlies, with decreases in summer precipitation largely due to more easterlies and anticyclonic flow. The residual precipitation change varied less with season and among models, being generally positive as expected from the increased moisture transport capacity of the warmer atmosphere.

In Northern and Central Europe in winter, where mean precipitation is simulated to increase, high extremes of precipitation are very likely to increase both in magnitude and frequency. The risk of drought is likely to increase in southern and central Europe. By contrast, major changes in dry spell length in Northern Europe are not expected.

5.3 Current long-term climate projections ($t > 10\,000$ years)

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; ANDRA, 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.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Within bioclim, several scenarios of future atmospheric CO₂ concentrations were evaluated using the In 2D nh (Louvain-la-Neuve 2D Northern Hemisphere) climate model (Berger et al., 1998). From a total of 15 CO₂ scenarios, only a few of them were proposed for further analysis.

Figure 8 shows the simulated northern hemisphere continental ice volume considering only natural CO₂ variations (scenarios A3, A4a and A4b):

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

In the natural A3 and A4 scenario, conditions as warm as the present day persist for a considerable time: for Central England and the Northeast of France warm conditions persists from today on up to about 50 000 years AP. A3 and A4b predict a glacial period at about 53 000 years AP, while this glacial period is not predicted by the A4a model. At about 100 000 years AP, a glacial period is predicted by the three models. Just after 100 000 years AP, Central England and the Northeast of France experience a brief period of polar climate and tundra. Later on, the different scenarios predict again 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. 9), and this from today on up to 600 000 years AP. These uncertainties have to be considered in the safety assessment studies.

Figure 10 shows the simulated northern hemisphere continental ice volume considering natural and anthropogenic CO₂ variations (scenarios B1, B3 and B4):

- B1: anthropogenic low CO₂ increase scenario (Burgress's regression used for the natural CO₂ variation);

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Climate evolution in radwaste assessment

M. Van Geet et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- B3: anthropogenic low CO₂ increase scenario (Pallard's threshold model a used for the natural CO₂ variation);
- B4: anthropogenic high CO₂ increase scenario (Pallard's threshold model a used for the natural CO₂ variation).

The main feature of the results of these anthropogenic scenarios is the persistence of conditions warmer than the present day temperate oceanic climate. For Central England and the Northeast of France a subtropical climate with subtropical winter rain persists within the next few hundred years:

- until 73 500 years AP for the low CO₂ scenario (B3); and
- apart from a couple of minor cooling events, until 165 500 years AP in the high CO₂ scenario (B4).

The present day temperate oceanic climate does not reappear until 93 000 years AP for the B3 and 168 500 years AP for the B4 scenario. Overall, the period from present day through to 170 000 years AP is characterised by a climate that is only moderately warmer than at present day and that is associated with a similar degree of water availability through the year, though with somewhat drier summers.

6 How to treat climate changes in the safety assessment of radioactive waste disposal facilities?

6.1 Category A

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 these elements are of lesser safety importance than the changes to the disposal system.

In contrast with the earlier evaluations of climate change in safety assessment of geological disposal of radioactive waste (i.e. phymol Project, Wemaere et al., 2000; the

**Climate evolution in
radwaste assessment**

M. Van Geet et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



6.2 Category B&C

For the longer time scales related to category B&C waste (beyond 100 000 years up to 1 000 000 years AP), it becomes very uncertain to obtain precise climate evolution predictions (see the differences between the different climate scenarios). Therefore, the option chosen is rather to evaluate the impact of global warming and cooling on the performance of the repository system components (see also Fig. 6), including, amongst others,:

- possible range of effects on hydrogeology (low infiltration, 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.

Based on the results of the BIOCLIM project, however, it seems acceptable to assume a low probability of high ice volume culmination in the next 180 000 years. Probably, the base assessment case of the reference scenario could make use of the present-day climatic conditions, whereas B3 and B4 could be additional assessment cases. Only if scenarios A3 and A4b are considered, an earlier cooling period becomes pertinent, starting from about 53 000 years AP. During such a glaciation, climatic conditions become considerably different from present day conditions, which might be incorporated in an altered evolution scenario.

An increased support from the community of experts in climate evolution on this reasoning would reinforce our case in order to diminish uncertainties or to clearly define the remaining uncertainties. For the safety assessment of B&C waste disposal, the direct effect of climate change on the repository system is somewhat lower than for the category A repository system, but the timing of 100 000 years is quite important. This is related to the fact that the most important, but still small, peak of radionuclide release

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



occurs after about 100 000 years (Fig. 11). The more precise the boundary constraints of the system are known, the better the overall safety of the system can be demonstrated. To this end, it is foreseen to have a continued interaction with experts in climate evolution, geology, hydrogeology and geography to evaluate the current reasoning and to assess more precisely the impact of possible changes in climate evolution.

7 Conclusions

- Safety is the driving force in developing repositories for radioactive waste.
- Time frames differ between cat. A (1000–100 000 years) and cat B&C (100 000–1 000 000 years).
- Climate evolution plays an important role in the definition and elaboration of scenarios used as central tool in long-term safety assessment of waste repositories.
- No full translation of phenomenology is necessary in scenarios for safety assessments:
 - scenarios are illustrative, conservative
- Models on climate evolution helps in:
 - narrowing the amount of scenarios to be considered
 - steering the research on the possible impact of future climate evolution on the repository system
- What are we expecting from the phenomenological community:
 - the spectrum of consequences of climate evolution
 - confirmation of no glaciation <100 000 years
 - data on climate records at a spatio-temporal scale commensurate with the scale(s) of safety assessment model applications.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



References

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CPD

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Climate evolution in radwaste assessment

M. Van Geet et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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CPD

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Climate evolution in radwaste assessment

M. Van Geet et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Climate evolution in
radwaste assessment

M. Van Geet et al.

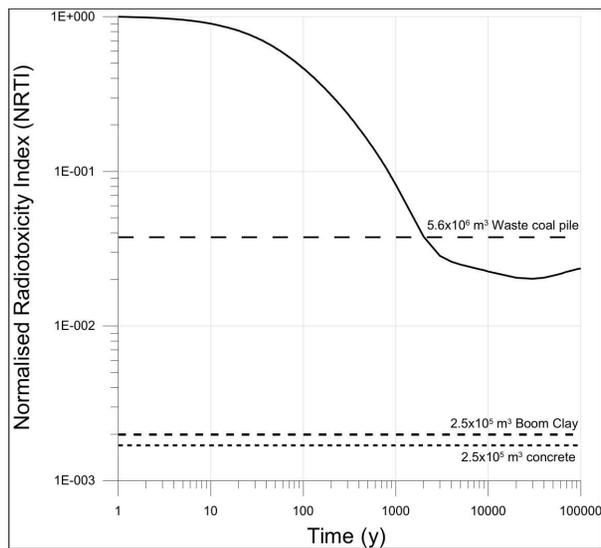


Fig. 1. Normalized radiotoxicity (NRTI) of the Belgian category waste inventory as a function of time based on 20 critical radionuclides).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

**Climate evolution in
radwaste assessment**

M. Van Geet et al.

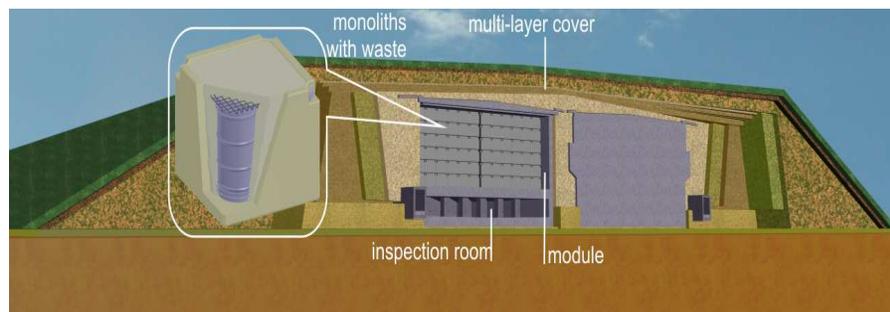


Fig. 2. Cross-sectional view of near surface disposal facility.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Climate evolution in radwaste assessment

M. Van Geet et al.

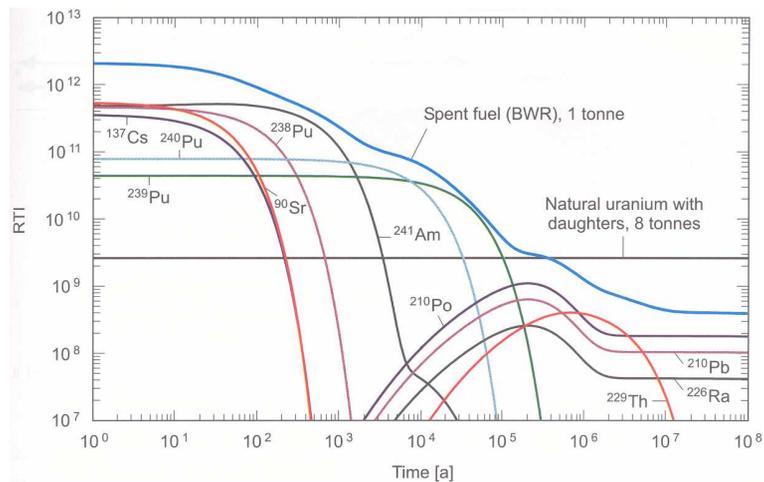


Fig. 3. An example of the radiotoxicity index (RTI) of 1 tonne of representative Swiss spent fuel and of 8 tonnes of natural uranium (picture from NAGRA, 2002).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Climate evolution in radwaste assessment

M. Van Geet et al.

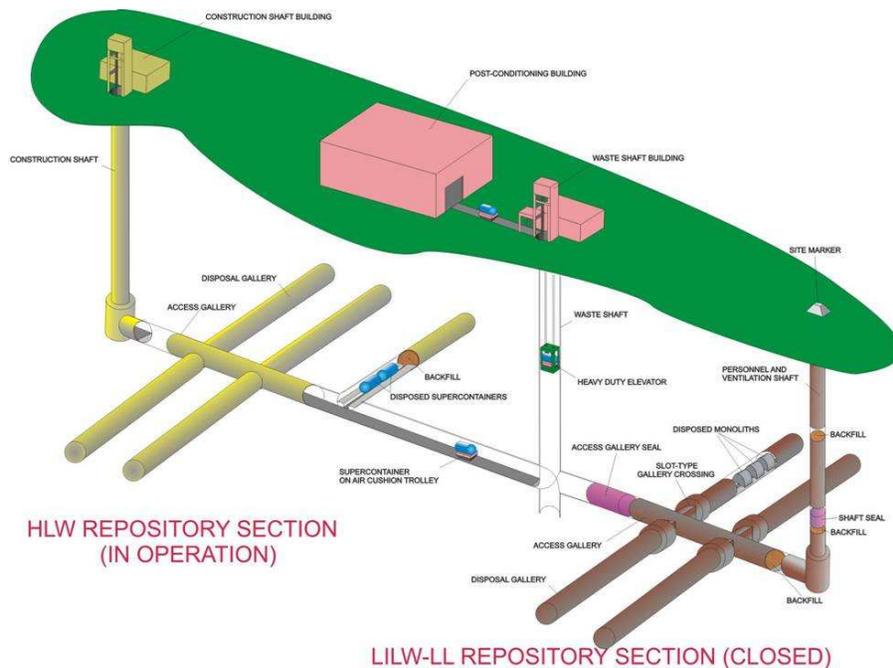


Fig. 4. Schematic lay-out of the concept of underground repository facilities and of the related surface facilities during disposal facility operation. HLW is high-level waste (category C waste) and LILW-LL is low and intermediate-level waste – long lived (category B waste).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



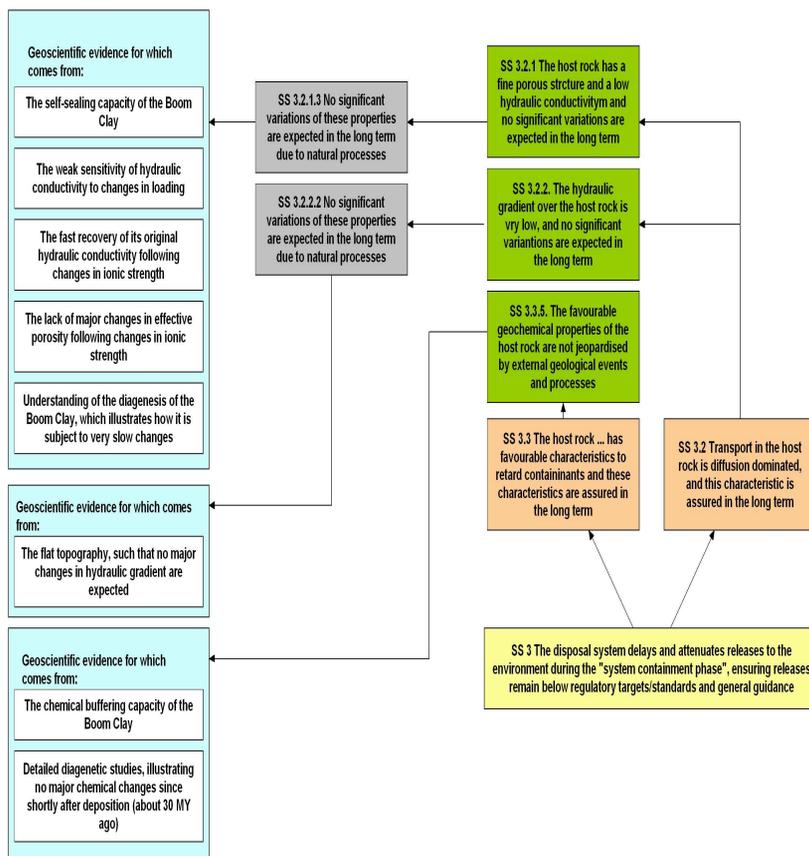


Fig. 5. Example of geoscientific evidence underpinning safety statements (SS).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



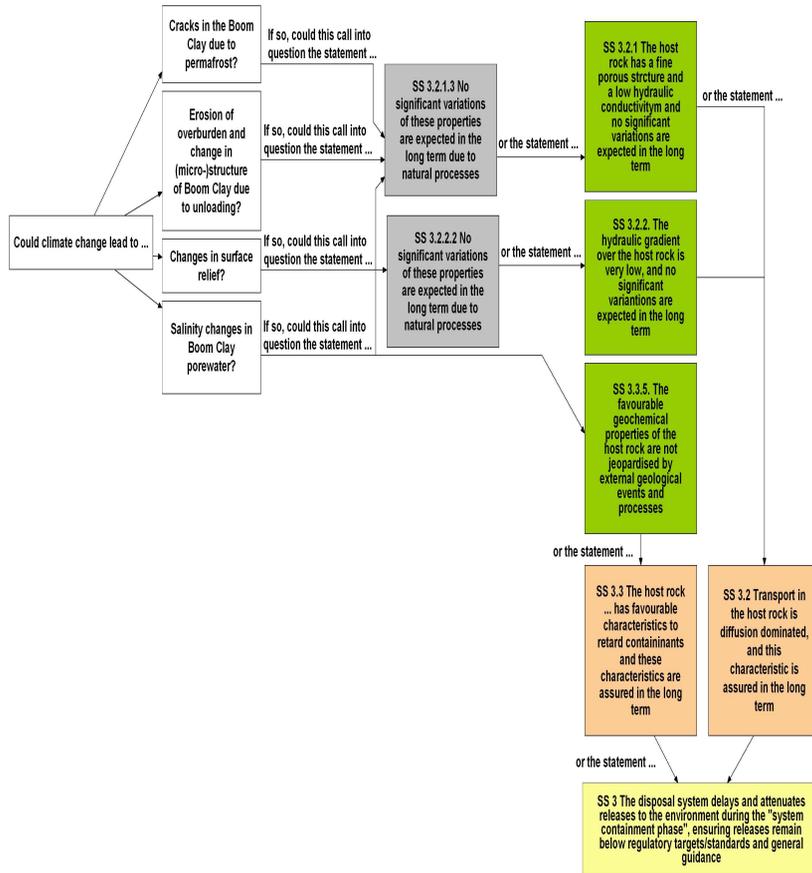


Fig. 6. Example of the propagation of uncertainties related to climate change through a hierarchy of safety statements.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



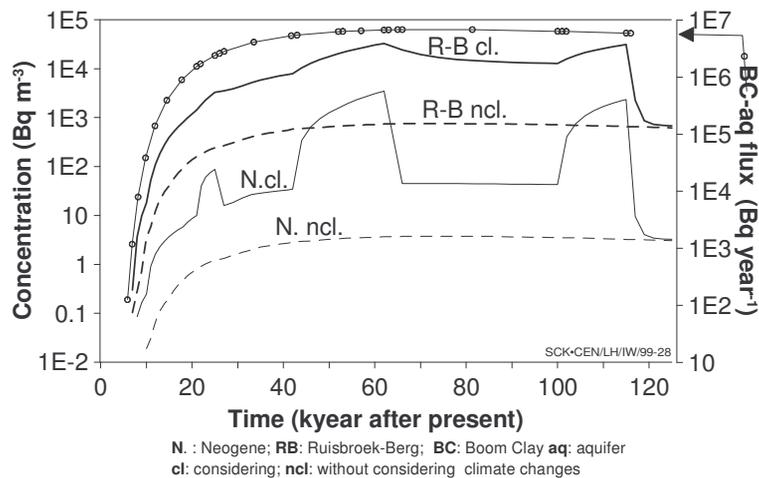


Fig. 7. Evolution of the radionuclide concentration in the aquifers.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Climate evolution in
radwaste assessment

M. Van Geet et al.

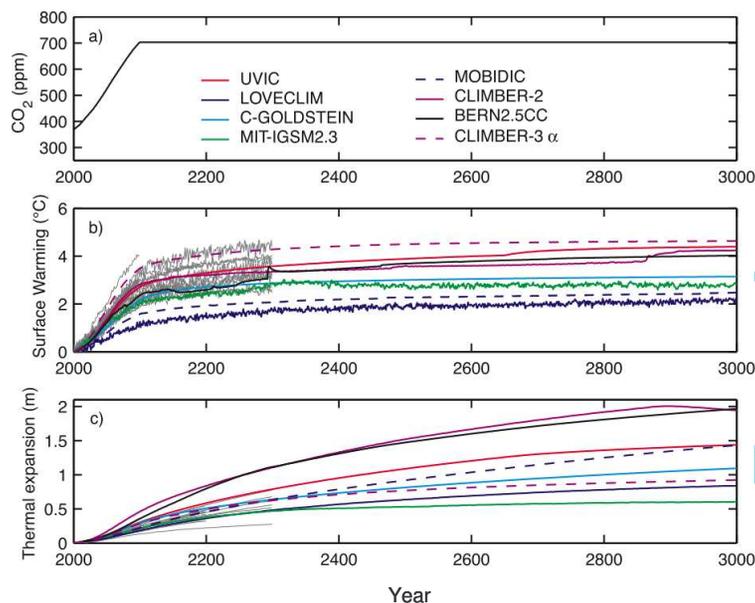


Fig. 8. (a) Atmospheric CO₂, (b) global mean surface warming and c) sea level rise from thermal expansion calculated by eight EMICs for the Special Report on Emissions Scenarios (SRES) A1B scenario and stable radiative forcing after 2100. Coloured lines are results from EMICs, grey lines indicate Atmosphere-Ocean General Circulation Models (AOGCM) results where available for comparison. Vertical bars indicate ± 2 standard deviation uncertainties due to ocean parameter perturbations in the C-Goldstein model (from IPCC, 2007).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Climate evolution in
radwaste assessment

M. Van Geet et al.

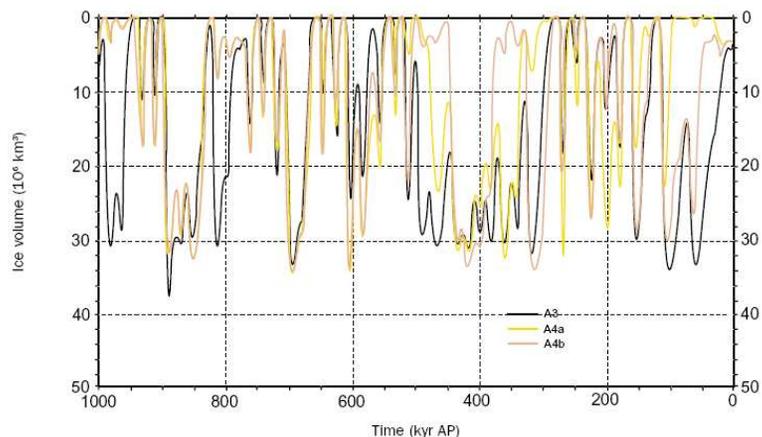


Fig. 9. The simulated northern hemisphere continental ice volume considering only natural CO_2 variation. A3: natural variations in insolation and natural atmospheric carbon dioxide concentrations (based on Burgress's regression); A4a: natural variations in insolation and natural atmospheric carbon dioxide concentrations (based on Pallard's threshold model **(a)**); A4b: natural variations in insolation and natural atmospheric carbon dioxide concentrations (based on Pallard's threshold model **(b)**) (BIOCLIM, 2003).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Climate evolution in
radwaste assessment

M. Van Geet et al.

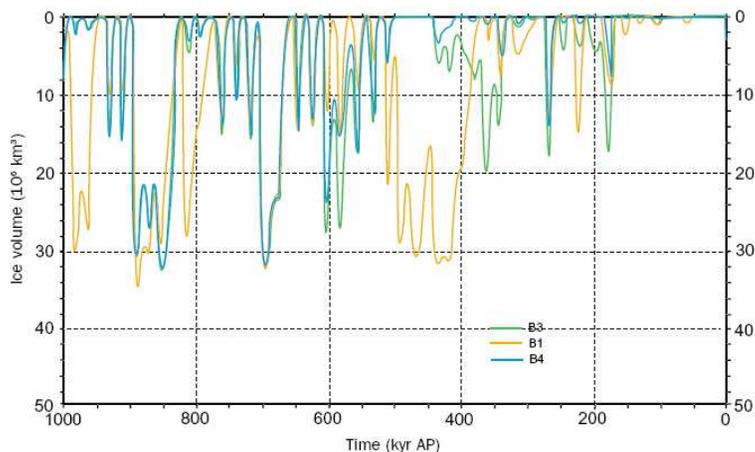


Fig. 10. The northern hemisphere continental ice volume considering natural CO₂ variation and low and high fossil fuel contributions. B3: anthropogenic low CO₂ increase scenario (Pallard's threshold model a used for the natural CO₂ variation); B1: anthropogenic low CO₂ increase scenario (Burgress's regression used for the natural CO₂ variation); B4: anthropogenic high CO₂ increase scenario (Pallard's threshold model a used for the natural CO₂ variation) (BIOCLIM, 2003).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Climate evolution in radwaste assessment

M. Van Geet et al.

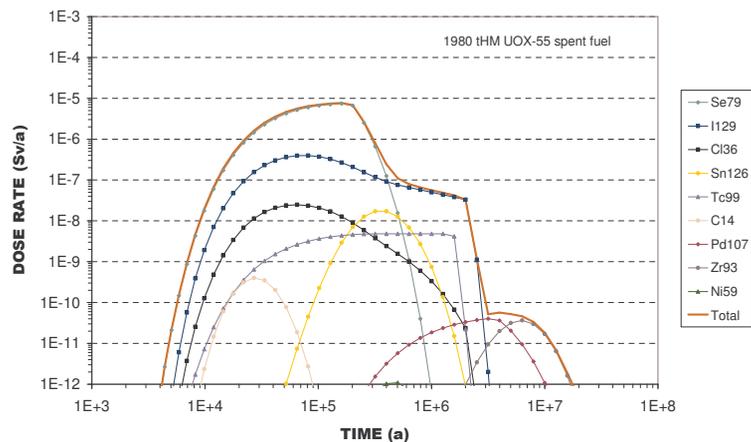


Fig. 11. Evolution of the dose rate via the well pathway for spent fuel. The mean annual natural exposure in several countries and worldwide is several 10^{-3} Sv/a. The international guide line advises a dose limit for the public of 10^{-3} Sv/a and specifically for repositories a dose limit of $1\text{--}3 \cdot 10^{-4}$ Sv/a.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

