ONDRAF/NIRAS

Belgian agency for radioactive waste
and enriched fissile materials

Technical overview of the SAFIR 2 report

Safety Assessment and Feasibility Interim Report 2

NIROND 2001–05 E December 2001

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Foreword and acknowledgements

This document is the technical overview of the SAFIR 2 report that synthesises all of the technical and scientific knowledge available at the end of the second phase (1990–2000) of the ONDRAF/NIRAS programme of methodological research and development on the final disposal of category B and C waste in a poorly-indurated clay formation. The SAFIR 2 report will be handed over by ONDRAF/NIRAS to its supervisory Minister at the beginning of 2002, after publication approval by its Board of Directors. It aims to inform the Minister of the progress made regarding the technical feasibility of this solution and the assessment of its long-term radiological safety.

This technical overview integrates the many aspects of the Belgian programme as thoroughly as possible, emphasising its key elements and the qualitative arguments underlying the assessments of the long-term radiological safety and of the feasibility of the solution under study. Its structure has, however, been adapted with respect to that of the SAFIR 2 report, which is available in full on the enclosed CD-ROM, with a view to facilitating its reading. For the same reason, it generally does not mention the subcontractors of ONDRAF/NIRAS, with the exception of the Belgian Nuclear Research Centre (SCK•CEN) in Mol, the main partner of ONDRAF/NIRAS for the research and development work.

However, ONDRAF/NIRAS wishes to thank, without being able to mention them all separately for they are so numerous, all its partners and subcontractors, Belgian and foreign, for their collaboration on its work programme on the final disposal of category B and C waste: SCK•CEN, various universities, consulting engineers, other waste management agencies, private companies, and public services. ONDRAF/NIRAS also expresses its special thanks to the European Commission for the financial support it has always benefited from through its participation in European research and development programmes. Moreover, it could not stress enough the benefits of participating in various international forums (IAEA, NEA, etc.): these reflexion and benchmark platforms gathering experts from many different countries are indeed a major tool for the continuous improvement of the quality of its own work. ONDRAF/NIRAS also thanks the members of the committee of Belgian experts created on the initiative of its Board of Directors to accompany the finalisation of the SAFIR 2 report and to make recommendations for its future work programme. Finally, ONDRAF/NIRAS would like to thank Brigitte Cornélis for her synthesising effort in writing the present document.

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1 Introduction

The management of radioactive waste, whether generated by nuclear power plants, industrial applications using ionising radiation, medical activities, or research, has long been the subject of in-depth study in Belgium. As early as 1974, the Belgian Nuclear Research Centre (*Studiecentrum voor Kernenergie / Centre d'Etude de l'Energie Nucléaire* or SCK•CEN) at Mol embarked upon a research and development programme designed to study the long-term management of high-level and/or long-lived waste, i.e., waste belonging to categories B and C. SCK•CEN quickly directed its attention to the solution recommended at an international level for isolating this type of waste from humans and the environment, namely, to dispose of it in a stable geological formation with appropriate characteristics. It then chose to concentrate its efforts on investigating the Boom Clay layer beneath its own site as a potential host formation. Given the lack of experience, both nationally and internationally, in the excavation of underground facilities at a depth of some 200 metres in a clay of this type, i.e., one that is poorly consolidated or 'poorly indurated', one of the main objectives of the SCK•CEN initial research and development programme was to assess and demonstrate the feasibility of such an operation. This is why the HADES (High-Activity Disposal Experimental Site) underground research facility was constructed at a very early stage in the Belgian programme.

Category B and C waste Category C waste, which is moderately to highly heat emitting, is highly radioactive and mostly long lived. Category B waste has a low heat output and is long lived. Both categories of waste are intended for deep disposal (see also Section 3.1).

The Belgian Agency for Radioactive Waste and Fissile Materials (*Organisme National des Déchets Radioactifs et des Matières Fissiles / Nationale Instelling voor Radioactief Afval en Splijtstoffen* or ONDRAF/NIRAS), was created by the law of 8th August 1980. The Belgian authorities, thus, took the decision to entrust the management of radioactive waste to a *single body under public control to ensure that the public interest prevails in all the decisions taken in this field*. The mission and functioning of ONDRAF/NIRAS were first laid down by the Royal Decree of 30th March 1981. This has been amended and supplemented by the Royal Decree of 16th October 1991 passed in execution of the law of 11th January 1991, itself amended and supplemented by the law of 12th December 1997. The 1991 law also amended the name of ONDRAF/NIRAS to '*Organisme National des Déchets Radioactifs et des Matières Fissiles* Enrichies */ Nationale Instelling voor Radioactief Afval en* Verrijkte *Splijtstoffen*' (Belgian Agency for Radioactive Waste and *Enriched* Fissile Materials).

Practically, ONDRAF/NIRAS is entrusted with developing a coherent and safe management policy for all of the radioactive waste that exists on Belgian territory. This management includes the quantitative and qualitative inventory of radioactive waste, its removal and transport, its processing and conditioning, and its interim storage and long-term management. As well as this principal mission, there are other missions relating in particular to the decommissioning of closed nuclear facilities, the management of historical waste, and the management of enriched fissile material. Finally, ONDRAF/NIRAS is required to ensure the long-term financing of its work. The costs of all of its services, including the costs of short-term and long-term management, are paid for at cost price by the waste producers.

In this document, the term 'waste' is used to refer to conditioned radioactive waste. The expression 'spent fuel' describes all types of spent fuel produced by Belgian commercial nuclear power plants (ZAGALS waste) and 'vitrified waste' is the vitrified waste from the reprocessing of that fuel (ZAGALC waste) (see also Section 3.1).

Shortly after it was created, ONDRAF/NIRAS set about establishing the bases for the coordinated management of radioactive waste and gradually assuming responsibility for managing the tasks undertaken by SCK•CEN to define solutions for the long-term management of this waste that would be both safe and feasible in technical and financial terms. Currently, the day-to-day management of radioactive waste has been fully mastered, while its long-term management is still in the research and development stage. (Research and development for category A waste seems nevertheless relatively well advanced. This is the subject of a separate programme in which the choice of the type of repository—at the surface or in the underground—is open.)

The solution that ONDRAF/NIRAS is examining for the long-term management of category B and C radioactive waste is its disposal in a suitable geological formation. This solution is based on the principle of concentrating and containing the radionuclides present in the waste. It therefore involves placing a series of barriers between the waste and the biosphere, in order to protect humans and the environment for as long as necessary from the hazards that this waste presents.

The design and methods of construction, operation, and closure of a deep repository must of course conform to the national and international legislative and regulatory framework governing this type of installation, which is both an underground facility and a nuclear facility. These regulations can basically be divided into five types of requirement:

- requirements for radiological safety in the short and long term;
- requirements associated with the non-radiological protection of humans and the environment;
- requirements for nuclear safety;
- requirements for conventional safety, including requirements associated with the construction and operation of underground facilities;
- requirements relating to civil liability.

The research and development programme has so far concentrated mainly on long-term radiological safety.

Under Belgian legislation, a deep repository is treated as a conventional nuclear facility.

This introductory chapter outlines the ONDRAF/NIRAS programme of methodological research and development on the long-term management of category B and C waste, and places the SAFIR 2 report and its *technical overview* within this framework. More precisely, the SAFIR 2 report marks the end of the second phase of the ONDRAF/NIRAS work programme, which was fixed quite arbitrarily at the end of the year 2000. It follows on from the SAFIR report (1989), which concluded the first phase of this programme (1974–1989).

1.1 The first phase of methodological R&D and the SAFIR report (1974–1989)

Eager to take advantage of the experience and the promising results already obtained by SCK•CEN in the long-term management of category B and C waste, ONDRAF/NIRAS decided in the early 1980s to intensify the studies that were then in progress, and made SCK•CEN its partner of choice in all aspects of research and development which would henceforth support its work programme in this field. This decision was reinforced by the fact that SCK•CEN possessed a research tool that was unique in the world: the HADES underground research facility.

In 1984, ONDRAF/NIRAS decided to prepare a report that would systematically present and analyse the results of all of the studies carried out into deep disposal between 1974 and 1989 in Belgium, including the results of assessments of long-term radiological safety. This was in line with recommendations made by the Evaluation Commission for Nuclear Energy (*Commission d'Evaluation en Matière d'Energie Nucléaire / Evaluatiecommissie voor Kernenergie*) created in 1975 by the Minister André Oleffe. The recommendations stated that *the high-level waste must remain accessible and under control until such time as a final solution or a solution that is sufficiently safe is found. A ten-year assessment of this risk should be conducted before continuing down the nuclear route.* The Commission also felt that nuclear energy could be used under certain conditions: *On the basis of current knowledge, it is important to undertake a ten-year reassessment of the problems linked to the use of nuclear energy before proceeding down this route, particularly since a solution that is final or at least sufficiently safe has not actually been implemented for the high-level waste or for the control of tritium, inert gases, carbon 14, and iodine 129.*

Known as the *SAFIR report* (Safety Assessment and Feasibility Interim Report), the safety and feasibility report prepared jointly with SCK•CEN and Belgatom was submitted by ONDRAF/NIRAS to its supervising minister, the Secretary of State for Energy, in May 1989. It aimed to enable the authorities of the day to express an initial opinion on the qualities of the Boom Clay layer beneath the Mol–Dessel nuclear zone as a potential host formation for the disposal of category B and C waste, and to approve the continuation of the research and development programme as they deemed appropriate.

The commission of Belgian and foreign experts set up in 1989 by the Secretary of State for Energy to evaluate the SAFIR report confirmed the conclusions of the report. These were that the poorly-indurated clays, and in particular the Boom Clay under the Mol–Dessel nuclear zone, could be considered for the disposal of category B and C waste since they are able to offer effective protection in the very long term. This poorly-indurated clay was indeed found to have a very low hydraulic conductivity, a plastic character that gives it good self-healing properties, and a high capacity to fix radionuclides and hence to delay their migration towards the biosphere. The SAFIR Evaluation Commission (*Commission d'Evaluation SAFIR / Evaluatiecommissie-SAFIR*) also expressed the view that, subject to certain changes, the research and development programme proposed by ONDRAF/NIRAS in conjunction with SCK•CEN for the period 1989–1994 was coherent and represented a logical follow-up to the work done since 1974. Finally, it recommended that work on certain aspects of the long-term safety and geology of the host formation should be expanded. It

Final disposal Disposal of radioactive waste with no intention of retrieving it.

Disposal facility or repository A facility designed to receive radioactive waste for long-term passive management.

Disposal system A system comprising the disposal facility and the host formation. It exists within an environment which is itself formed by aquifers on either side of the host formation and by the biosphere (see also Section 2.2.1).

recommended, specifically, that the research programme should include other host formations and locations, with particular attention being given to a study of the Ypresian Clays beneath the Doel nuclear zone as an alternative.

1.2 The second phase of methodological R&D and the SAFIR 2 report (1990–2000)

Having received approval to continue its work on the deep disposal of category B and C waste, in 1990, ONDRAF/NIRAS reassessed its research and development programme to bring it into line with the recommendations of the SAFIR Evaluation Commission. The programme was, and still is, a programme of *methodological research*. Its prime aim was to establish if it is feasible, both technically and financially, to design and build on Belgian territory a deep disposal solution for category B and C waste that is safe, while not prejudging the site where such a solution would actually be implemented. This programme is multi-disciplinary and, also, highly iterative (Fig. 1.1).

Given its methodological nature, the ONDRAF/NIRAS work programme has been built around the characterisation of argillaceous formations and *work sites*. More specifically, the status of the two formations and the two sites that were studied was—and still is—as follows:

- *Boom Clay and the Mol–Dessel nuclear zone*: reference host formation and reference site;
- *Ypresian Clays and the Doel nuclear zone*: alternative host formation and alternative site.

(Belgium has yet to select a disposal site, so the word ‘site’ does not imply any idea of implementation.) The ONDRAF/NIRAS programme, which is thus focused on a study of the Boom Clay beneath the Mol–Dessel nuclear zone, also gave priority to investigating solutions for waste classes seen as being the most demanding ones in terms of radiation and heat emission.

Practically, the ONDRAF/NIRAS methodological research and development programme was intended to develop all of the methods and to gather all of the knowledge needed to undertake an in-depth assessment of the safety and feasibility of the deep disposal of category B and C waste in a poorly-indurated clay. It included characterising the waste to be disposed of, characterising and assessing host formations and their environment, developing a repository design, understanding interactions within the disposal facility, developing a methodology for assessing the long-term performance and radiological safety of such a facility, developing a methodology for assessing the cost of its implementation, and preparing a full-scale demonstration experiment of its feasibility. The programme has, however, only touched upon the study of waste disposal operations proper and the study of operational safety, since such studies require a relatively accurate definition of the characteristics of the facilities which they investigate. (See the box below for a fuller description of the principal objectives of the ONDRAF/NIRAS methodological research and development programme.)

Repository design
A term used to describe the geometry of a disposal facility and the materials used in its construction. It replaces the term ‘concept’, which was used previously.

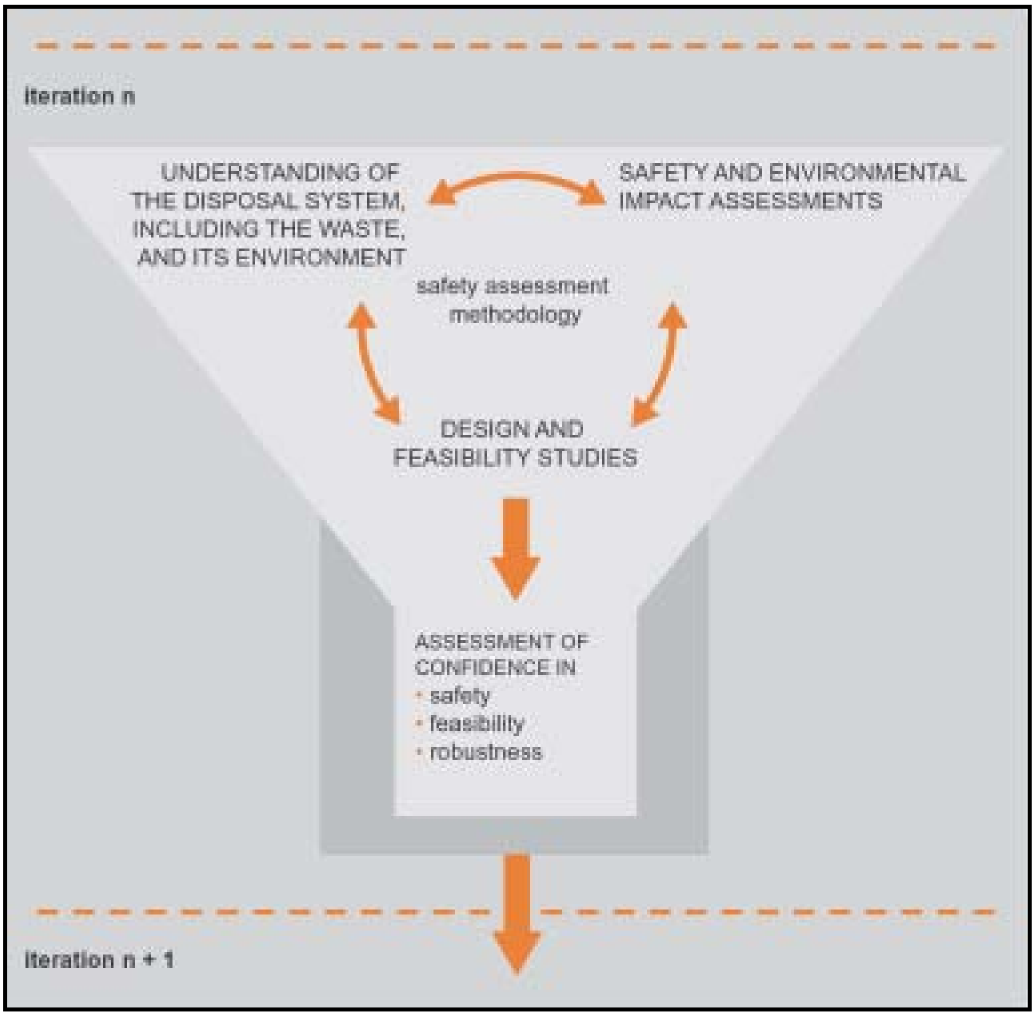


Figure 1.1 General approach taken by the Belgian methodological research and development programme into deep disposal (see also Fig. 2.2).

The publication by ONDRAF/NIRAS of the *SAFIR 2 report* in December 2001 concluded the second phase of its methodological research and development programme (1990–2000) without, however, marking the end of this programme. The SAFIR 2 report is limited to the technical and scientific advances (societal aspects are excluded), and assesses the confidence in the safety, feasibility, and robustness of the studied system. It also outlines the technical and scientific follow up proposed by ONDRAF/NIRAS. It has been evaluated by a committee of Belgian experts (Reading Committee) set up by the Board of Directors of ONDRAF/NIRAS to accompany its finalisation and to make recommendations for the future of the work programme to be conducted by ONDRAF/NIRAS on deep disposal. In 2002, it will be reviewed at international level under the ægis of the Nuclear Energy Agency (NEA) of the Organisation for Economic Cooperation and Development (OECD).

Principal objectives of the second phase of the ONDRAF/NIRAS methodological research and development programme (1990–2000), which take account of the main recommendations of the SAFIR Evaluation Commission (1990)

On the characterisation of the waste to be disposed of:

- to specify the qualitative and quantitative inventory of the waste to be emplaced in the repository and to take into account the option of non-reprocessing of the spent fuel as well as the full reprocessing option already being studied;
- to establish acceptance criteria for the waste intended for deep disposal on the basis of general rules for waste acceptance approved by the responsible authority.

On the assessment of the host formations and their environment:

- to identify and characterise the structural discontinuities (faults, etc.) and lithological heterogeneities of the Boom Clay and to study their impact on the migration of radionuclides;
- to study the thermo-hydro-mechanical behaviour of the Boom Clay;
- to refine the understanding and modelling of the regional and local hydrogeology around the Mol–Dessel nuclear zone;
- to provide a preliminary characterisation of the Ypresian Clays beneath the Doel nuclear zone.

On the development of a repository design:

- to design the disposal facility in a way that maximises the thickness of the undisturbed clay and physically separates the different classes of waste from one another;
- to go deeper into the design of that part of the disposal facility intended to receive the highly heat-emitting waste and to assess the performance of its components;
- to demonstrate the possibility of excavating galleries of appropriate dimensions in the Boom Clay using proven industrial techniques;
- to investigate ways of sealing deep repositories;
- to prepare a full-scale demonstration of the possibility of implementing the developed repository design and of emplacing highly heat-emitting vitrified waste (the PRACLAY experiment).

On the understanding of interactions within the repository:

- to understand and quantify the consequences of the generation, accumulation, and migration of gas within the repository;
- to study the behaviour under repository conditions of the different waste matrices and of the additional packaging foreseen around the highly heat-emitting waste and their compatibility with the Boom Clay.

On the assessment of long-term safety:

- to analyse the consequences of the migration of certain non-retarded radionuclides through the clay;
- to pursue the study of the behaviour of critical radionuclides in the Boom Clay and, specifically, to investigate the influence of organic matter present in the clay and of chemical fronts generated by the engineered barriers;
- to update the assessments of the radiological impact of a repository for category B and C waste and to carry out the first estimate of the impact of a repository for spent fuel;
- to define and use long-term safety indicators other than dose and risk;
- to conduct an initial study into the chemotoxicity of the waste.

On the assessment of costs:

- to develop a method for assessing the costs of disposal.

The SAFIR 2 report has three objectives:

- to provide the authorities, and all the other parties concerned, with a structured synthesis of the available technical and scientific information relevant to the disposal of category B and C waste into a poorly-indurated argillaceous formation, in order to enable them to assess the progress made in terms of technical feasibility and assessment of long-term radiological safety;
- to promote interaction with the nuclear safety authority (*Agence Fédérale de Contrôle Nucléaire / Federaal Agentschap voor Nucleaire Controle* or *AFCN/FANC*—Federal Nuclear Control Agency) so as to reach closer agreement on the research efforts still required and on the principles of safety assessments, and to specify the modes of enforcement of the regulations that are applicable to the specific case of a deep repository;
- to be one of the technical and scientific bases for a broad dialogue with all of the parties concerned by the long-term management of radioactive waste.

The SAFIR 2 report is not a safety report in the strict sense, as it does not support any licence application. It is rather a report devoted to the state of the art in Belgium.

Three important documents come with the SAFIR 2 report:

- the *present document,* which constitutes a *technical overview of the SAFIR 2 report* and which also contains, in annex, the final opinion of the Reading Committee charged with reviewing the SAFIR 2 report;
- a *brochure* summarising the key messages of the SAFIR 2 report for information to the wider public;
- the document entitled *Towards a Sustainable Management of Radioactive Waste*, which discusses the integration of the technical and societal dimensions of the long-term management of radioactive waste.

1.3 The technical overview of the SAFIR 2 report

The present document is the technical overview of the SAFIR 2 report, the full version of which is available on the enclosed CD-ROM. Its objectives and scope are therefore the same as those of the SAFIR 2 report. However, its structure has been modified to make it easier to read and it focuses on the key elements of the Belgian programme, on its specific achievements, and on the qualitative arguments underlying the assessments of the long-term radiological safety. Chapters 2 and 3 aim to answer the question of *how to isolate the radioactive waste from the biosphere in a way that is practicable and safe*. Chapter 2 deals mainly with all of the requirements on which the design of a deep repository must be based, and which ultimately come down to a requirement for safety, a requirement for feasibility, and a requirement for robustness. After surveying the waste that must be disposed of, Chapter 3 reviews all of the scientific and methodological achievements of the programme centred on the study of the Boom Clay beneath the Mol–Dessel nuclear zone, but excluding information relating to safety assessments. It summarises the current knowledge of the behaviour of the waste under disposal conditions and of the characterisation and behaviour of the reference host formation and the environment of the disposal system. It also describes the reference design currently being studied by ONDRAF/NIRAS for the underground facility and the way in which it would be constructed and operated. Finally, it very briefly presents the current knowledge of the Ypresian Clays, which are being studied as an alternative host formation. Chapter 4 is devoted entirely to long-term radiological safety assessments. While it is not possible to prove the long-term radiological safety of a repository by direct industrial experience, it is possible to *assess* indirectly *whether the proposed mode of isolation and containment of the radioactive waste is safe* in the long term. Chapter 5 discusses very briefly the assessment of the cost of implementing a deep repository. The concluding chapter, Chapter 6, surveys the key results acquired to date, proposes the main themes of a future programme, and assesses the present level of confidence in the disposal solution under study. The technical overview of the SAFIR 2 report ends with a postscript. It also has five annexes: a list of figures, tables, and boxes; a list of the most common abbreviations and acronyms; a list of further reading; a detailed cross-reference table designed to help the reader locate any additional information he/she may require in the SAFIR 2 report; and the final opinion of the Reading Committee of the SAFIR 2 report. It has no bibliography, as it would have been difficult to select references from the very large number of available references. However, the reader will find a bibliography by chapter on the enclosed CD-ROM.

2 Ensuring safety and feasibility: guiding principles of the development of a deep repository

Two options may be envisaged at first sight to ensure the management of radioactive waste in the long term: first, the *dilution and* immediate *dispersion* into the biosphere of the radioactivity contained in the waste, which is commonly used—albeit within strict regulatory limits—for liquid and gaseous discharges; second, the option of *concentration and containment*, which involves isolating the waste from the biosphere for a period of time that is long enough to allow a sufficient decrease in the activity of the radionuclides present before their inevitable release into the biosphere in the long term, where they will be gradually diluted and dispersed (Fig. 2.1).

For the category B and C waste, only the option of concentration and containment is regarded as being responsible at international level. This option may be implemented by storing the waste in specially designed buildings on the surface, or by disposing of it in an appropriate underground facility. While the former solution would require future generations to conduct active maintenance and monitoring operations for a very long period of time, the latter may be designed from the outset so as to be passively safe and require no intervention to maintain safety in either the short or the long term. This is the solution to which ONDRAF/NIRAS has always given research priority as the reference solution. This is also the solution under investigation in most countries faced with the task of managing category B and C waste.

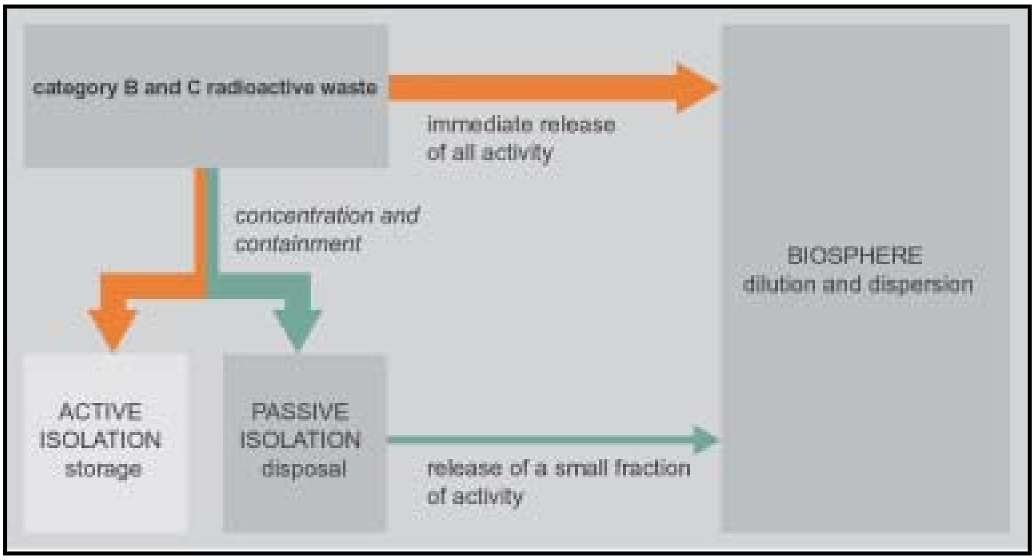


Figure 2.1 The potential options for the long-term management of radioactive waste. The option studied by ONDRAF/NIRAS for the management of category B and C waste is the concentration and containment of the waste by disposal.

Safety assessment A detailed examination of the consequences and risks associated with a possible new practice. This assessment is based on comparisons between results obtained and nationally and internationally accepted criteria and limits, as well as on qualitative arguments. It is an iterative process conducted in parallel with the research and development work.

The conception and implementation of a deep disposal solution for the long-term management of category B and C waste is a lengthy and complex process. The general objective may be easy to state: to protect humans and the environment from the potential harmful effects of radioactive waste in the short and in the long term. The actual solution is far less easy to design, as it will be required to remain safe over timescales far beyond those normally comprehended by our society. It cannot, therefore, be based on experience acquired from other similar projects. It also involves a large number of scientific and technical disciplines, including geology and hydrogeology, civil and mining engineering, geochemistry, the chemistry of radionuclides, material science, as well as statistics and numerical analysis. Its implementation, from the start of the phase of methodological research and development to the closure of the repository and the subsequent period of institutional control, will take several decades and will necessarily be conducted stepwise.

The method used to arrive at a disposal solution that is both safe and technically and financially feasible involves *working iteratively* within the framework of a *stepwise and flexible process* (Fig. 2.2). This process aims to make a coherent synthesis of the results of research and development work undertaken in all of the technical and scientific disciplines that are involved, and of the changes in the legislative and regulatory framework and, thus, to continuously improve the knowledge and design of the disposal system and refine the safety assessments. The process therefore incorporates aspects of system understanding, design, construction, operation, and closure in a global approach, with a view to identifying the areas requiring further investigation at the appropriate time. For example, the design of the repository has a direct impact on the waste emplacement system, and vice versa. The conclusions of the safety assessments—which determine when one implementation phase will move on to the next—and the evolution of the repository design raise issues for further investigation in their turn, and so on. The reference repository design and the safety assessments will, thus, gradually evolve towards their final form.

After stating the objectives of a deep repository, this second chapter describes the two categories of requirement that flow from the objectives and which the design of a repository must satisfy. First are the general requirements: primarily, a requirement for safety both during the operation of the repository and after its closure, a requirement for robustness so that its long-term radiological safety can be credibly assessed, and a requirement for feasibility. Second are the requirements that are specific to a repository in the Boom Clay. Their task is to prevent the intrinsic characteristics of the waste, the materials used to construct the repository, and the actual construction of the repository from unacceptably compromising the safety of the solution under study. This chapter concludes with a discussion of the aspects of quality management and quality assurance that will ultimately affect all phases of the implementation of the disposal system.

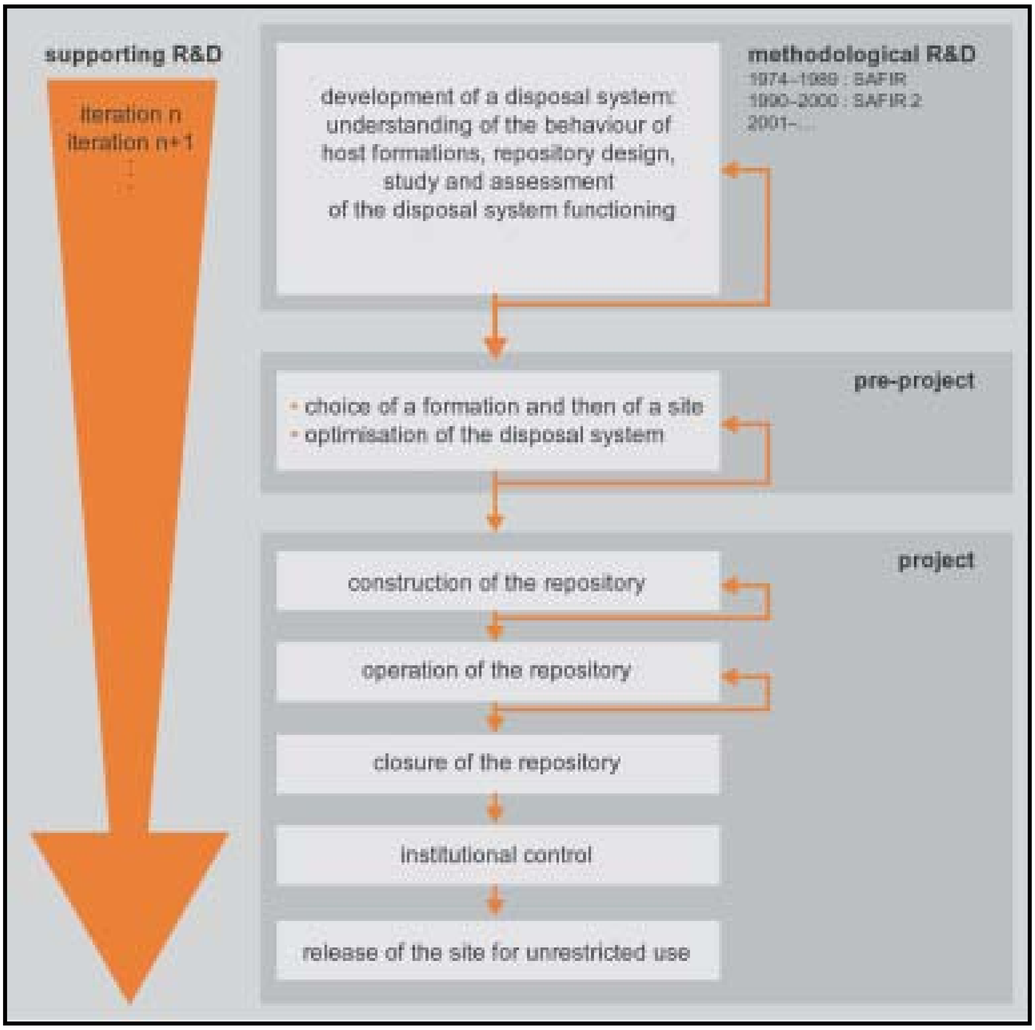


Figure 2.2 The main phases of the stepwise implementation of a disposal system. The approach is flexible and iterative, with the iterations involving making adjustments and, if necessary, looking back within the same phase or to a prior phase (see also Fig. 1.1). Successive safety assessments also contribute to understand how the disposal system functions and help gradually build the confidence that is necessary to progress from one phase of the programme to the next.

2.1 The objectives of deep disposal

The studies into the long-term management of radioactive waste conducted in Belgium lie within a *radiological safety framework* built around two sets of fundamental principles. The first set, concerning the management of radioactive waste, was drawn up by the International Atomic Energy Agency (IAEA); the second, relating to radiological protection (see box on the following page), was drawn up by the International Commission on Radiological Protection (ICRP). These principles must form the main thread running through the implementation of the disposal solution, from the conception of the repository via its construction and operation through to its closure. The first of the three principles of radiological protection, however, the principle of the justification of practices, is instantly fulfilled. The management of radioactive waste, and its disposal in particular, can, indeed, not be seen as practices as such, requiring separate justification. Rather, they should be seen as being part of much broader practices, such as energy generation or medical diagnosis, which are deemed to be justified.

The principles of radioactive waste management established by the IAEA are translated by a dual objective regarding disposal.

- *To protect humans and the environment* The repository must protect humans and the environment from the risks that the radioactive waste may pose by concentrating it and containing it for as long as necessary.
- *To limit the transfer of burdens to future generations* The repository must provide passive protection, i.e., protection that ultimately will require no actions by future generations.

The first objective, that of protection, comprises an aspect of radiological protection and an aspect of non-radiological protection for humans and the environment, both of which fall within a national and international legislative and regulatory framework. Belgian radiological protection regulations are based on the three fundamental principles of radiological protection and conform to the relevant European directives, which are also based on these principles. The European Directive 96/29/EUR lays down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionising radiation; the European Directive 97/43/EUR relates to the health protection of individuals against the dangers of ionising radiation in relation to medical exposure. The limits of the effective dose laid down by Directive 96/29/EUR govern the total exposure resulting from all of the controllable practices and sources with which a given individual is faced. The limit is 1 mSv per year for members of the public. The ICRP recommends moreover that the maximum permitted dose for a deep repository, i.e., the dose constraint for the repository, should not exceed 0.3 mSv per year (see also Section 4.3.1). By comparison, the mean exposure to ionising radiation in Belgium represents a dose of 3.6 mSv per year, which is mainly due to natural sources (Fig. 2.3). As regards the non-radiological protection of the environment, an important directive applicable in Belgium is European Directive 97/11/EC, which relates to the assessment of the impact of certain public and private projects on the environment.

Effective dose
The sum of the equivalent doses for all of the organs and tissues in the human body multiplied by a factor expressing sensitivity to radiation. The unit of effective dose is the sievert (Sv). The word ‘dose’ is often used loosely to mean ‘effective dose’.

Equivalent dose
The product of the absorbed dose with a weighting factor characteristic of the radiation and that expresses its biological impact on the tissue. The unit of equivalent dose is the sievert (Sv).

Absorbed dose
The amount of radiation energy deposited per unit of mass. The unit of absorbed dose is the gray (Gy).

Dose limit The maximum value of the dose that workers exposed occupationally or members of the public may receive in a given period. This limit does not apply to either natural sources or medical exposure. There is one dose limit for workers and another for members of the public (see also Fig. 2.3).

Dose constraint A restriction imposed on the dose, which a given source, practice, or task may deliver to individuals, in order to ensure that the dose limit is not exceeded. The dose constraint is used to optimise protection against ionising radiation.

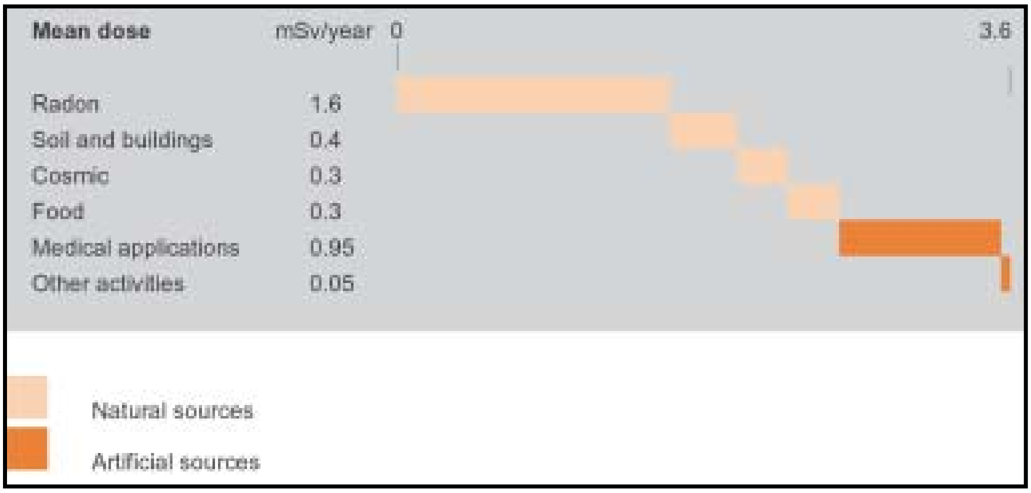


Figure 2.3 Mean annual exposure to ionising radiation in Belgium. 72 % of the mean exposure of 3.6 mSv per year is due to natural sources and 26 % to artificial medical sources.

The three fundamental principles of radiological protection

Principle of justification of practices: any practice that involves exposure to ionising radiation must offer more advantages than disadvantages, without those advantages necessarily having to benefit those who suffer the disadvantages.

Principle of optimisation of protection, also referred to as the ALARA principle (As Low As Reasonably Achievable): the means of protection must be chosen in such a way that the individual doses and the number of people exposed are kept at as low a level as is reasonably possible, taking account of economic and social factors.

Principle of limitation of individual doses: the radiation dose received by workers exposed occupationally and by members of the public must be within the prescribed limits.

2.2 General requirements

The dual objective of deep disposal can be translated into a set of specific requirements. More precisely, a disposal system must be designed so that

- it is not only safe during operation and after closure,

but also that

- it is robust enough for its long-term radiological safety to be convincingly assessed,
- it takes account of risks of criticality,
- its non-radiological impact on the environment conforms to the standards in force,
- it is developed and implemented flexibly,
- it is feasible,
- the waste can be retrieved from it over a certain period of time, if necessary.

Until now, it is the requirement for long-term radiological safety that has been studied most intensively in the Belgian programme.

2.2.1 Long-term radiological safety

Any system of deep disposal must perform *four functions of long-term safety*, which together determine its level of long-term radiological safety (see also Chapter 4). These are the functions of

- physical containment;
- delaying and spreading the releases;
- dilution and dispersion;
- limitation of access.

Presented here as basic principles in the conception of a disposal facility, these functions have in fact emerged as an important tool for understanding and communicating how the disposal system works, and for assessing its safety. This is because the methodological research and development work conducted between 1990 and 2000 has made it possible to structure the knowledge of the disposal system and its environment by creating accurate links between their different components, the successive phases in the evolution of the system, and the safety functions.

With the exception of the third safety function, which is performed by the environment of the disposal system, each function is fulfilled by one or more components of the system, which are then called *barriers* (Figs. 2.4 and 3.23; Table 3.7). These successive barriers are ‘nested’ in one another and vary in nature. Some are artificial or ‘engineered’ barriers: these are the *watertight packagings* that enclose the category C waste—the most demanding type of waste in radiological and heat emission terms—and the components of the disposal facility whose task is to limit the migration of radionuclides, like the *backfill materials* and sealing materials of the repository galleries. One barrier is natural: the geological *host formation* that surrounds the engineered barriers. (The *aquifers*, which are on either side of the host formation, and the *biosphere* have no barrier function. They are also prone to drastic modifications in the course of time. They are not considered to be part of the disposal system, but part of its *environment*.) All of the components of the disposal facility, including the waste and that part of the host formation that is *disturbed by the excavation*, constitute the *near field*. The geological barrier and the aquifers form the *geosphere*, also referred to as the *far field* (see Section 3.3 for a fuller description of the disposal facility).

However, it is not the mere number of barriers that is the best guarantee of the safety of a disposal system, but the additional requirements placed on them to ensure that, whatever the disturbances, there will always be a number of mechanisms to prevent the system from posing an unacceptable risk. There are three such additional requirements:

- *diversified mechanisms of functioning*: the action of the different barriers must be based on varied physical and chemical mechanisms so that they are not liable to the same types of failure;

- *partial redundancy*: any failure by one barrier must be sufficiently compensated by some or all of the other barriers;
- *maximum functional independence*: the failure or functioning of one barrier must have as little effect as possible on the functioning of the other barriers.

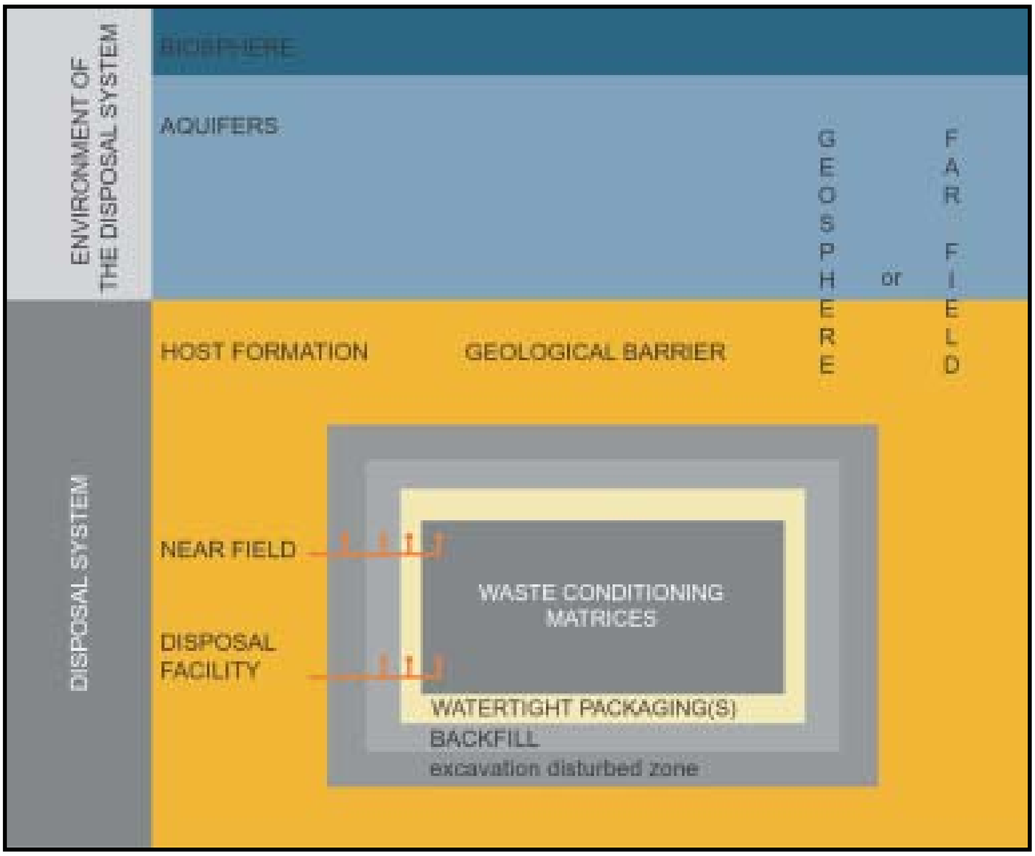


Figure 2.4 Schematic of a deep disposal system and its environment, and related terminology.

The first safety function, that of *physical containment* (C), aims to isolate the radionuclides from their immediate environment, especially from water, which is the most important potential dispersion vector. Such isolation should prevent any significant release of radionuclides. Physical containment also allows to take maximum advantage of radioactive decay before the other safety functions come into action. Radioactive decay is indeed an element of intrinsic safety, as it involves an inevitable reduction in radiotoxicity of the waste, and hence in the overall risk. The reduction is greater the longer the delay before the release of radionuclides into the biosphere.

Physical containment is achieved by interposing engineered envelopes, at least one of which must remain watertight for a minimum period of time (Fig. 2.5). This is in fact necessary mainly for the highly heat-emitting waste, which is also the waste that contains the highest activity of critical radionuclides. This waste is, therefore, enclosed in watertight packagings intended to prevent interactions between water and the radionuclides at least during the so-called ‘thermal’ phase of the disposal system, i.e., the period during which its

Barrier Geological formation or component of the disposal facility that limits the flow of water towards the radioactive waste emplaced in the repository and the migration of the radionuclides present in the waste towards the biosphere.

Environment of the disposal system Entity formed by the aquifers above and below the host formation, and the biosphere.

Biosphere Part of the Earth where humans, animals, and plants live and grow and where they can be exposed to radioactive substances that may be released by the disposal facility.

Near field Entity formed by the components of the disposal facility, including the radioactive waste and the part of the host formation disturbed by excavation.

Far field or geosphere Entity formed by the host formation and the surrounding aquifers.

presence in the disposal facility significantly increases the temperature in and around it (Fig. 2.6). (The watertight packagings are also an element of robustness, as they simplify safety assessments by making it possible to disregard the complex phenomena of radionuclide migration under a temperature gradient—see Section 2.2.2.) The function of physical containment can be subdivided into two sub-functions.

- The sub-function of *watertightness (C1)*: this function is associated with the engineered barriers, and more particularly with the watertight packagings, and aims to *prevent* water from coming into contact with the waste.
- The sub-function of *limiting the water influx (C2)*: this function depends mainly on the natural barrier, but is also due to the capacity of certain engineered barriers to absorb water. It is intended to *defer* the moment when the barriers that perform a sealing function, and then the radionuclides, are contacted by infiltrating water.

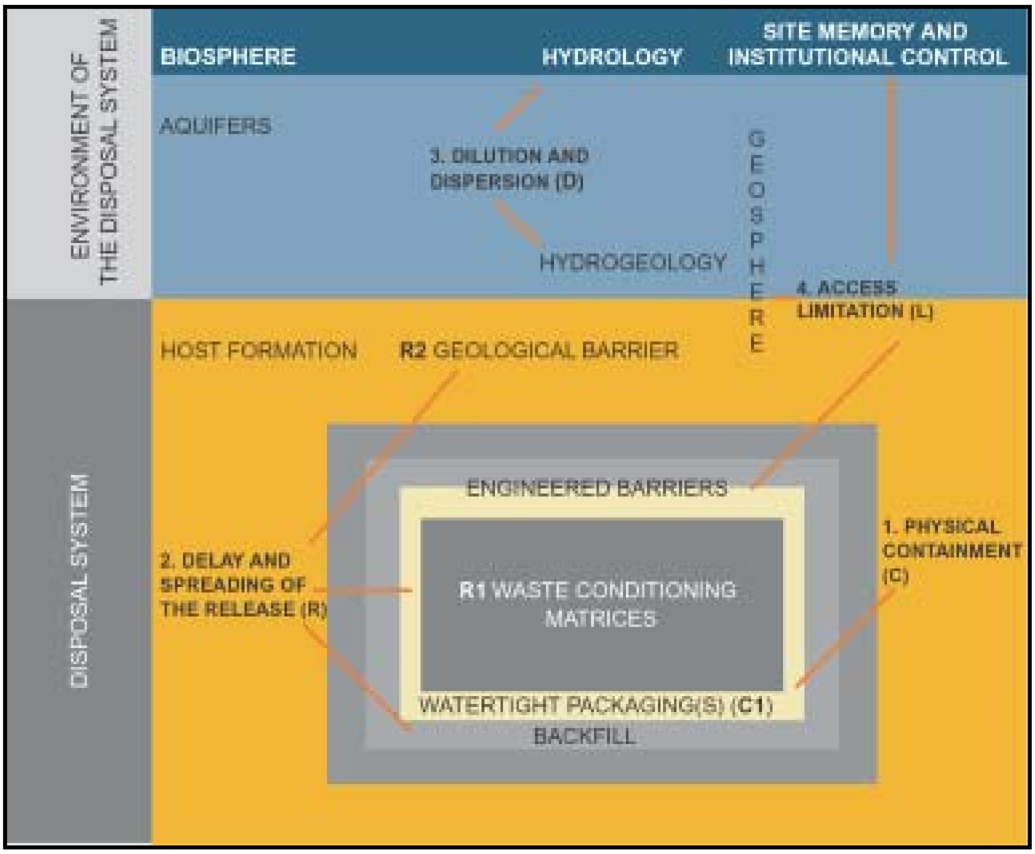


Figure 2.5 The long-term safety functions of the deep disposal system under study that are considered in the long-term safety assessments for the normal-evolution scenario. The various components of the system may perform other safety functions not taken into account in the assessments (see also Section 3.3 and Table 3.7).

Since it is not possible to guarantee perfect physical containment of the radionuclides until the radioactivity in the repository has decayed to a harmless level, a second safety function must be ensured after physical containment has failed. This is the function of *delaying and spreading the releases (R)*, which, so far as possible, must delay the migration of radionuclides towards the biosphere to allow their maximum radioactive decay within the disposal system. It must prevent radionuclides—especially those that are long lived—from being released from the disposal system at any time and reaching the biosphere in unacceptable quantities. This function may also be subdivided into two sub-functions.

- The sub-function of *resistance to leaching (R1)*, i.e., the spreading of the release of radionuclides over time, due to the physico-chemical stability of the waste matrices.
- The sub-function of *diffusion and retention (R2)* of radionuclides once they are released from the matrices. In the disposal system under study, this second sub-function is performed by the backfill material, the disposal gallery seals, and the geological barrier (Fig. 2.5). The backfill is specifically selected for its ability to slow down the migration of radionuclides by sorption processes or by the formation of poorly-soluble precipitates. An argillaceous formation such as the Boom Clay has the capacity to delay the migration of radionuclides and possesses a self-healing power that limits the occurrence of preferential migration pathways.

For the disposal of category B and C waste into clay, the 'delaying and spreading' function is usually the most decisive function for long-term radiological safety. It is performed primarily by the host formation.

Despite all preventive measures, some release of radionuclides to the biosphere is inevitable in the very long term. The potential impact of the releases on humans and the environment will be weaker the more that the releases have been *diluted and dispersed (D)*. This may be achieved either within underground flows of water in the aquifers or within surface flows in the biosphere (Fig. 2.5). This third safety function, provided by the environment of the disposal system, cannot, however, take precedence over the others, since the repository's primary objective is to ensure protection through the principle of concentration and containment. Moreover, the components of the environment of the disposal system that perform the 'dilute and disperse' function do not show a high degree of robustness, their long-term functioning being difficult to assess. They are indeed highly susceptible to alteration due, for instance, to climate change or human activity.

Finally, the disposal system must isolate the waste so as to minimise the probability and consequences of human intrusion, whether deliberate or accidental. This is the function of *limitation of access (L)*, which is performed by the engineered barriers and the natural barrier, the period of control and monitoring that follows the closure of the repository, and the measures put in place to maintain the memory of its presence (Fig. 2.5). (This function implies that the disposal facility should be constructed at a site with no natural resources that could be exploited.) The consequences of any intrusion will be more limited the higher the facility's intrinsic resistance, that is, the less the first two safety functions are affected by the intrusion.

The first three safety functions gradually succeed each other in the overall evolution of the disposal system, but are not mutually exclusive (Fig. 2.6). This evolution has been divided into four phases, which reflect the characteristic stages in the functioning of the system as identified by the safety assessments carried out for the normal-evolution scenario: the operational phase, the thermal phase, the isolation phase, and the geological phase. The function of *physical containment* must be ensured during the *operational phase* of the

Safety function Action or role that the disposal system or its environment must perform to prevent the radionuclides present in the disposed waste posing an unacceptable hazard to humans or the environment.

There are four safety functions.

The function of *physical containment C* aims to isolate the radionuclides from their immediate environment to prevent any significant release of radioactivity.

- The sub-function of *watertightness C1* prevents water coming into contact with the waste.
- The sub-function of *limiting the water influx C2* postpones the moment when the barriers that provide a watertightness function, and then the radionuclides, are contacted by infiltrating water.

The function of *delaying and spreading the releases R* aims to slow down the migration of radionuclides towards the biosphere as much as possible to allow maximum radioactive decay within the disposal system.

- The sub-function of *resistance to leaching R1* spreads the release of radionuclides by the waste matrix.
- The sub-function of *diffusion and retention R2* delays and spreads the release of the radionuclides.

The function of *dilution and dispersion D* brings about a reduction in the concentration of radionuclides that will eventually reach the biosphere, and so reduces their potential impact on humans and the environment.

The function of *limitation of access L* aims to isolate the waste to minimise the probability and consequences of human intrusion.

The first two safety functions are performed by the disposal system as a whole or by one or more of its components. The third function is performed by the environment of the disposal system. The fourth function is performed, together, by the disposal system, its environment, and institutional measures.

repository and during the *thermal phase* that follows. The operational phase lasts from the emplacement of the waste until repository closure, a period of several decades. The thermal phase lasts for a period ranging from several centuries to several thousand years after closure, depending on the waste. Physical containment continues to remain significant during the third phase of the repository, the *isolation phase*, but the main functions are now *resistance to leaching* and *diffusion and retention* by the host formation. This phase is characterised by a virtually zero radiological impact on the environment of the disposal system and lasts for about 10 000 years. The functions of *diffusion and retention* and *dilution and dispersion* are the predominant functions during the *geological phase* that follows and lasts for over a million years. This phase is characterised by a minimal radiological impact on the environment. Finally, the fourth safety function, *limitation of access*, must be active at all times. The four safety functions are not limited in time, however, and the second and the third may be activated prematurely in the event of the failure of the barrier or barriers required to perform the first function, i.e., they exist in a

Safety reserve
The difference between the actual period of time during which the safety function is fulfilled and the period of time which is used in safety assessments, if the latter is shorter.

latent state. The first and the second functions may also continue to be active beyond the period used in safety assessments: the difference represents the *safety reserve*.

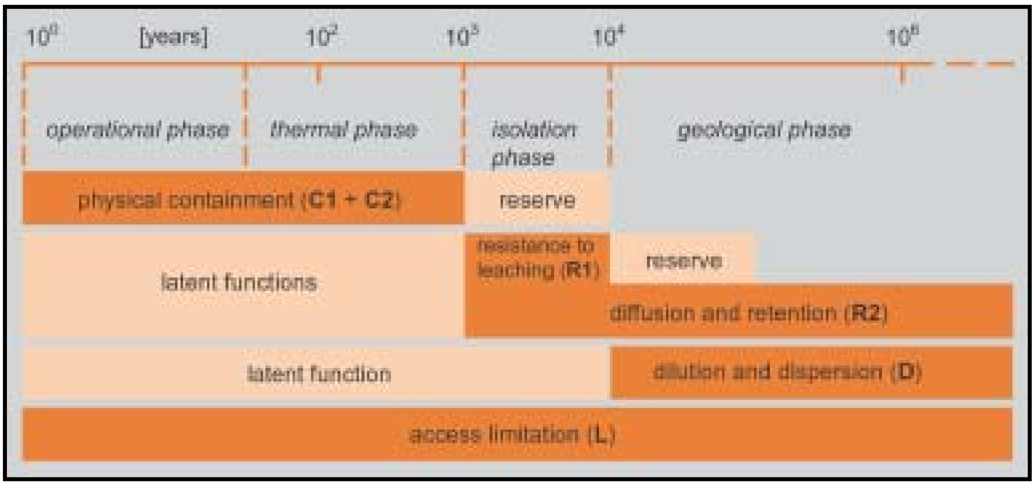


Figure 2.6 The four phases in the normal evolution of a deep disposal system for category C waste, the most demanding waste in terms of radiation and heat emission, i.e., the vitrified waste and spent fuel (see Section 3.1), and the corresponding long-term safety functions.

2.2.2 Robustness

Robustness
A measure of the independence of the true functioning of a disposal system relative to the uncertainties that have not been eliminated.

Since it is not possible to directly demonstrate the long-term radiological safety of a disposal system on the basis of industrial experience, it has to be possible to establish confidence in its safety by assessing it credibly in an indirect way (see Chapter 4). The reliability of safety assessments depends largely on the quality and, more specifically, on the robustness of the disposal system, that is, the extent to which its actual functioning is independent of uncertainties that cannot be resolved. This robustness may result from two complementary types of approach. First, the technical performance of the system can be enhanced, say, by using several engineered barriers instead of one, by over-dimensioning them, and by making them independent from one another. Second, the uncertainties that exist could be eliminated or at least reduced. This might be achieved for instance by opting for a simple repository design and materials whose degradation mechanisms are sufficiently well known, by locating the repository in a hydrogeological environment that is easy to model, or by placing the category C waste that is most demanding in radiological terms in watertight packagings. (This last option can prevent any release of radionuclides during the thermal phase of the repository and so avoid the need to allow for the complex and little understood phenomena of migration under a temperature gradient.) The fact that a disposal system is robust makes it easier to model because it can be simplified.

2.2.3 Operational safety

As well as offering long-term radiological safety, any disposal facility will have to be safe during its operational phase, both for workers and for members of the public. The characteristics of its design and the way in which it is constructed, operated, and closed must therefore be compatible with the legislative and regulatory framework that govern both nuclear and underground facilities. Operational safety will, of course, have to be convincingly assessed before moving from the current phase of methodological research and development to the pre-project phase. Its detailed assessment will not be possible, however, until the design of the repository is sufficiently advanced. The assessment can then be based on the practical experience gathered during the operation of the HADES underground research facility and on the knowledge acquired from the PRACLAY full-scale demonstration experiment in the clay, which is now being prepared (see Section 3.3.3).

An essential aspect of the assessment of operational safety will be to test the hypothesis that applying strict quality and control measures to the radioactive waste packages, including the watertight packagings, will render the risk of contamination of the repository during operation negligible. This would avoid the need to consider the facility as a controlled zone for contamination during the operational phase. Such a decision would indeed have a considerable impact on the operation mode of the repository, an impact that could affect design—especially with the potential multiplication of access paths to the disposal facility—and, hence, long-term radiological safety.

2.2.4 Sub-criticality and compliance with nuclear safeguards

Any deep disposal facility must be designed and operated in a way that drastically reduces the risks directly linked to the presence of fissile materials. The first is the risk of criticality, that is, the risk of a spontaneous and sustained nuclear chain reaction. A criticality episode during waste disposal or the subsequent evolution of the system could indeed modify the properties of the near and far fields and, specifically, could impair the performance of the barriers—due mainly to the associated thermal pulses—and modify the inventory of radionuclides present. The second risk is the risk of fissile materials being ‘diverted’, and so the operation methods of the repository must conform to the requirements of international non-proliferation treaties (safeguards). In particular, they must provide precise systems of accounting and traceability for the fissile materials, which will be subject to international verification. The aspects of sub-criticality have undergone a preliminary assessment, whereas compliance with safeguards has not yet been taken into account in the studies.

2.2.5 Protection of the environment

Any disposal facility must be designed and operated in a way that ensures that its non-radiological impact on the environment remains within applicable standards. For example, the toxic chemicals present in the waste or in the components used to construct the repository must not threaten to pollute its environment, and their levels in drinking water must not exceed the established limits under any circumstances. Likewise, the inevitable temperature increase close to the facility due to the disposal of category C waste must not heat up the groundwater to the point where its chemical and bacteriological composition is adversely affected, as this could make it less fit for human consumption or irrigation use.

Neither must the temperature increase disturb the fauna and flora. Studies in this field, which are still at the preliminary stage, must fit in with a coherent legal framework, one which is at present still incomplete, at any rate so far as the maximum permitted increases in temperature in the aquifers are concerned.

2.2.6 Flexibility

The development and implementation of a disposal facility, including its operation, control, and closure, must be carried out in a flexible way. This flexibility must allow good adaptation to any new types of waste or new methods of conditioning and good adaptation to the conditions prevailing underground. It must also permit easy reversal of previous decisions, whether they are strategic, technical, or management related, and even the temporary postponement of other decisions. This is because the implementation of a repository is a stepwise process lasting several decades and its smooth progress will depend on the right decisions being taken at the end of the different key steps (Fig. 2.2). Specifically, the various options, in terms of host formation and repository site, will therefore have to remain open for a sufficiently long period of time and the different aspects of the facility, such as its design and choice of materials, will have to be allowed to evolve as knowledge increases. This flexible approach can only be justified, however, if the corresponding period is used to optimise the disposal system and to better assess and, if necessary, further reduce the risks associated with it.

2.2.7 Feasibility

The disposal facility under study must of course be feasible, both technically and financially. Its technical feasibility depends directly on the requirements of mining safety and operational radiological safety, and on specific requirements to be met for the Boom Clay (see Section 2.3). The design, construction, operation, and closure of the disposal facility must also be based on the following elements:

- standard and proven engineering practices and techniques;
- a quality assurance programme designed to guarantee that the disposal facility will be built, operated, and closed as planned;
- iterative safety assessments that take account of all scientific and technological developments;
- feedback mechanisms between the results of the iterative assessments and the design, construction, operation, and closure of the disposal facility.

The assessment of technical feasibility is largely based on the practical experience gained during the construction of the HADES underground research facility and will be further reinforced thanks to the PRACLAY experiment that, because it is a full-scale demonstration, includes implementation aspects (see Section 3.3.3). Cost aspects will have to be assessed as part of the repository optimisation exercise. This assessment will weigh up the various possible solutions for optimising the safety of the repository against the cost increases that they would entail.

2.2.8 Retrievability

Retrievability
The ability, for a given period of time, to safely retrieve the waste from the repository with means identical or comparable to those used to emplace it. Retrievability is therefore one of the possible consequences of flexibility.

Although ‘disposal’ implies, by definition, that there is no intention to retrieve the waste, it is nevertheless possible to design and implement a disposal facility that provides a window of time within which future generations could retrieve the waste. Moreover, the importance of retrievability having clearly increased at international level in recent years, it might eventually become a legal requirement in Belgium, as is already the case for category A waste. Although the design of the disposal facility has not specifically allowed for retrievability so far, certain components of the reference design that have been introduced for safety reasons, such as the overpack for the vitrified waste packages, contribute to retrievability too (see Section 3.3.1). Retrievability could also be facilitated by keeping open the access routes to the disposal galleries for some time after waste disposal. Once these accesses have been backfilled and sealed, however, retrieving the waste will become much more difficult, especially because the underground facility, and in particular the lining of the access routes, will probably have been partially dismantled.

Of course, the possible requirement for waste retrievability cannot be allowed to compromise the long-term safety of the disposal system. This is why the duration of the operational phase, i.e., the period from the end of the construction to the closure, during which access to the waste will be relatively easy, must strike a balance between the demand for safety on the one hand and the need for retrievability on the other.

2.3 Requirements specific to the Boom Clay

In the specific case of disposal into the Boom Clay, where the barrier role of the host formation is clearly predominant relative to the role of the engineered barriers for a normal evolution of the disposal system (see Chapter 4), any disposal facility must also fulfil two essential conditions.

- It must extend as little as possible vertically and be as close as possible to the median plane of the host formation so as to maximise the thickness of clay that acts as a barrier.
- It must disturb the properties of the surrounding clay as little as possible, so that the overall performance of the system is not impaired.

There are two main sources for the thermal, chemical, mechanical, and even hydraulic disturbances of the host formation induced by the presence of a repository. The waste, some of which emits large amounts of heat and radiation, can generate gas or modify the characteristics of the near field. In addition, the construction of the repository can induce mechanical and geochemical disturbances. Minimising these different types of disturbance requires a thorough understanding of the compatibility between the various materials used and the different phenomena involved, particularly those that have an impact on the migration properties of the clay.

- *heat* The repository must be designed to ensure that the temperature increase in the near and far fields due to the heat emitted by the category C waste does not jeopardise the containment capacity of the disposal system. The heat will indeed cause all the components of the disposal facility to expand, leading to deformation stresses and even to the rupture of those components that are unable to expand freely. Heating could also modify the properties of different engineered components of the repository, especially the backfill material, and the barrier properties of the Boom Clay (see Section 3.6.1).

- *radiation* The repository must be designed to limit the risk of radiolysis of the water present in the Boom Clay due to the radiation emitted by the waste packages. This risk will be slight, however, due to the presence of the near-field materials, especially the backfill material. Moreover, the amount of hydrogen produced by the radiolysis of the water present in the backfill material and in the Boom Clay will be negligible compared with the quantities of gas that can be generated by corrosion and biodegradation. The impact of radiation on the design of the facility will therefore be reflected mainly by requirements related to operational safety (see Section 3.6.4).
- *gas* The repository design must take account of the problem of gas production due to the corrosion of the metals in the waste, the corrosion of the different types of packaging materials, and the corrosion of any metals that are present in the construction materials of the repository. If this gas production is too rapid to allow the gas to diffuse through the clay, a gaseous phase will form. This will lead to local pressure increases that could damage the clay and affect radionuclide migration (see Section 3.6.3).
- *geochemistry* As well as helping minimise the radiolysis of the interstitial water, the design of the disposal facility must disturb the geochemical characteristics of the repository environment as little as possible. In particular, it must limit the extent of chemical fronts such as the alkaline plume that would be induced by the use of cement-based waste matrices or construction materials, or such as the sodium nitrate front induced by the leaching of certain bituminised waste. The disposal facility must also be constructed and operated in a way that minimises the oxidation of the pyrite and the organic matter present in the Boom Clay, as oxidation could reduce its retention capacity (see Section 3.6.5).
- *excavation* The excavation techniques will have to be selected so that the argillaceous formation is disturbed as little as possible. They will therefore have to minimise over-excavation and to maintain the excavation rate above a critical threshold. Furthermore, the excavated volume will have to be quickly fitted with a lining designed to withstand the rapid convergence of the formation, observed during the construction of the existing underground facility, and to ensure its stability until the end of the operating period, including a period of retrievability if required (see Sections 3.3.2.1 and 3.6.2).

2.4 Quality management and quality assurance

A disposal solution cannot be safe in the short and long term, and socio-economically acceptable, unless its various aspects possess the required qualities. That is, all aspects including the waste and the repository design, construction, operation, and closure must meet predefined requirements. ONDRAF/NIRAS has therefore set about developing a programme of quality management and quality assurance that will eventually become a global quality management and assurance system covering all aspects of the disposal programme. One of the major challenges facing this programme is guaranteeing the quality and traceability of the data, models, decisions, and assumptions, at least until the end of the period of institutional control, which will require their systematic central archiving. Currently, the programme covers certain aspects of research and development—safety assessments and design in particular—as well as management phases prior to disposal, which are primarily the processing and conditioning of the waste and its acceptance (see Chapter 3). The programme sets out the standards that must be complied with, the means and procedures to be used to ensure compliance, and the controls to be exercised.

The iterative process of designing the repository is based on an ongoing process of interaction between the theoretical and the empirical aspects of research and development. Each key stage ends with quality assessments. These are formal systematic and documented critical reviews of the results, especially the results of the safety assessments, which play a central part in the design as they help identify research and development priorities and give direction to the work programme. The quality of the assessments is based chiefly on the following two elements:

- the *quality of information* relating to the disposal site, the repository design, and the engineered barriers (including the waste). This quality depends on the quality of the process used to define the research aims, the quality of the methods used to collect the data, and the quality of the documentation of the collected data.
- the *quality of the methods* and models used to assess safety on the basis of this information. This quality is normally determined by the level of validity of the simulations. This level, in turn, depends on the quality of the conceptual models developed, the quality of the mathematical models (which are the numerical embodiment of the conceptual models), and the quality or accuracy of the parameter values used in these models.

Quality assurance in research and development is based mainly on the following factors:

- the systematic use of *data collection forms* as the interface between research and development and long-term safety assessments: for each parameter that is used, these forms contain its definition, the best estimate of its value, and its statistical distribution;
- the system of *knowledge management* and *traceability* that will be developed progressively: this system must guarantee the availability of the acquired scientific and technical knowledge in the long term by permitting an exhaustive and systematic inventory of all of the results obtained, and it must guarantee the traceability of hypotheses, choices, and decisions;
- the phased *Beltest accreditation* of research and development laboratories of SCK•CEN: this accreditation guarantees that the work carried out in these laboratories conforms to the criteria of European Standard NBN-EN-45001;

- *international cooperation*: this cooperation is used to foster a common understanding of the difficulties involved, to establish consensus on the principles and methods that should be applied, and to conduct benchmark exercises, especially of codes and databases;
- the *use of models and codes that are widely used, tested, and verified* internationally: these models and codes strengthen confidence in the validity of the results obtained;
- *regular critical reviews by independent specialists*: these reviews are used to ensure the quality of the results and of the interpretations.

For the phases that will come after the research and development phase, only the broad principles of the quality management and assurance programme have been established as yet. These broad principles are in accord with the relevant international recommendations, both general (ISO standards) and specific (IAEA recommendations).

3 Generating and organising knowledge: scientific and technical achievements

The ONDRAF/NIRAS current programme of methodological research and development basically comprises two main branches. First, there are the studies and research projects to generate and organise all of the scientific and technical knowledge required to be able to *design and implement* a deep disposal solution capable of safely isolating radioactive waste from the biosphere in the long term (the subject of this chapter). Second, there is the indirect *assessment* of the long-term radiological safety of the developed solution (the subject of Chapter 4). The ONDRAF/NIRAS work programme focuses on the study of a reference host formation and a reference site (the Boom Clay under the Mol–Dessel nuclear zone) and has, so far, given only preliminary consideration to the study of an alternative host formation (the Ypresian Clays beneath the Doel nuclear zone).

Chapter 3 summarises the scientific and technical findings of the second phase of the ONDRAF/NIRAS programme of methodological research and development (1990–2000) in eight sections. These can be linked to eight of the questions that the design of a deep disposal facility ultimately poses.

- *Which waste is intended for deep disposal, and what is its volume?* (Section 3.1)
- *What are the geological and hydrogeological characteristics of the reference host formation and how does water move through and around that formation?* (Section 3.2) (The geomechanical characteristics of the Boom Clay are discussed in Section 3.6.2.)
- *What does the studied deep disposal facility look like, and how does ONDRAF/NIRAS propose to construct, operate, and ultimately close it?* (Section 3.3)
- *How can the disposed waste and the materials that make up the facility be expected to behave under disposal conditions?* (Section 3.4)
- *What are the mechanisms by which the radionuclides present in the disposed waste are likely to migrate through the clay?* (Section 3.5)
- *What disturbances can the construction of the facility and the disposed waste induce in the host formation, and to what extent must they be limited?* (Section 3.6, which also covers the, as yet, exploratory study of the migration of chemotoxic species present in the disposed waste.)
- *How should the transfer of radionuclides to the biosphere be dealt with?* (Section 3.7)
- *What are the principal characteristics of the alternative host formation?* (Section 3.8)

3.1 Conditioned waste

To be suitable for adequate long-term management, the radioactive waste must meet a number of preconditions that can be summarised as follows. It must

- be chemically inert and capable of being handled, and so must have been conditioned in a solid form;
- be sufficiently well known, radiologically and chemically, so that the safety of the repository in which it will be emplaced can be assessed;
- satisfy certain quality criteria to ensure that it does not put the proper functioning of the disposal system at risk;
- have undergone thorough studies of its degradation modes under disposal conditions.

The diversity of the radiological characteristics of the waste has, of course, necessitated the development of an appropriate classification system.

3.1.1 Classification of conditioned radioactive waste

For the purpose of its safe management in the short and long term, radioactive waste, which possesses extremely diverse characteristics, is classified according to certain similarities. The classification systems used internationally—those of the IAEA and the European Union—make no distinction between conditioned and non-conditioned radioactive waste. They comprise two levels, groups and categories respectively, which classify waste according to its activity and half-life (Table 3.1).

Table 3.1 Characteristics of the three categories of radioactive waste according to the international classification.

	Low level	Medium level	High level
Short half-life (30 years or less)	A	A	C
Long half-life (over 30 years)	B	B	C

The countries faced with the issue of radioactive waste management have, however, evolved their own classification systems, which are more detailed and more suited to their management modes. In Belgium, for example, ONDRAF/NIRAS has since 1997 adopted a four-level hierarchical classification system for conditioned radioactive waste. This system is compatible with the main international classification systems and can, if necessary, be adapted to take account of changes that may occur in the management of the waste. This system, based on the characteristics of the waste at the time of conditioning, represents a significant achievement since the SAFIR report and is a major contribution to the technical, administrative, and financial management of the waste (Fig. 3.1).

The **groups** of conditioned radioactive waste, two in total, are defined as a function of the possible disposal solutions for the waste in question.

- The *geological* group, which forms the subject of the SAFIR 2 report, includes the conditioned radioactive waste whose radiological characteristics, that is to say the activity concentrations of the radionuclides that it contains and their half-life, make it imperative that it is permanently isolated from the biosphere. Permanent isolation, which is thus the sole conceivable solution for the long-term management of the waste, is currently judged to be achievable by disposing of it into deep and stable geological layers.

- The *open* group, which is not considered in the SAFIR 2 report, contains the conditioned radioactive waste whose radiological characteristics are such that alternative solutions to geological isolation can be considered, since its activity will decrease to an insignificant level by radioactive decay over a period of time compatible with the period over which control can be exercised, i.e., a maximum of 200 to 300 years.

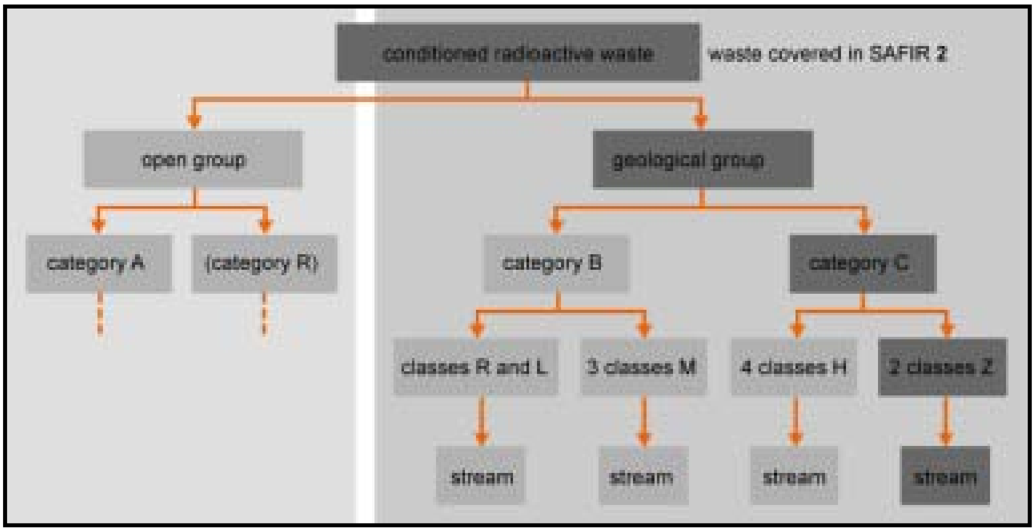


Figure 3.1 Classification of conditioned radioactive waste in Belgium. While the SAFIR 2 report covers all of the waste in the geological group, it deals more specifically with the long-term management of very high-level vitrified waste and non-reprocessed spent fuel, that is, waste from the Z-classes, these being the most demanding classes in radiological and thermal terms.

The three main **categories** of conditioned radioactive waste are defined by a radiological criterion and by a thermal power criterion. Category A belongs to the open group, and categories B and C to the geological group. Category R is more recent and more specific; it has no international equivalent and has been provisionally assigned to the open group.

- The *category A* waste is the one whose radionuclides present specific activities low enough and half-lives short enough to permit surface disposal, i.e., a maximum of 400 to 4000 $Bq \cdot g^{-1}$ of alpha activity according to the generic recommendations of the IAEA and the European Union.

- The *category B* waste is waste that does not meet the criterion for belonging to category A, but does not generate enough heat to belong to category C.

- The *category C* waste contains very high quantities of alpha and beta emitters and generates a thermal power of over 20 $W \cdot m^{-3}$, a figure that marks the limit between categories B and C for disposal into clay. It must, therefore, be allowed to cool down during a period of interim storage, and its residual thermal power at the time of disposal requires either limiting the number of packages per linear metre of disposal gallery, or increasing the distance between galleries.

- Finally, the *category R* waste covers the waste contaminated with radium and stored on the site of the old Olen refinery of the Union Minière. The fate of this waste is still uncertain.

The twenty **classes** of waste are defined as a function of the type of interim storage and the type of disposal for which the waste packages are intended, and sometimes as a function of their origins or technical characteristics. Radioactive waste intended for deep disposal, most of which comes from operations associated with the fuel cycle, is divided into 11 classes (Table 3.2).

- The *class Z* waste (category C, very high level, highly heat-emitting) is the result of the nuclear fuel cycle. The ZAGALC class is the very high-level *vitrified waste* from the reprocessing of spent commercial fuel by the French company COGEMA (activation and fission products and minor actinides, liquid effluents). The ZAGALS class will appear if Belgium abandons the reprocessing option, and will consist of the commercial *spent fuel* assemblies. All of this waste initially generates a large amount of heat, primarily due to the radioactive decay of ^{90}Sr and ^{137}Cs in the case of the ZAGALC class waste, and to the radioactive decay of ^{241}Pu and ^{241}Am in the case of the ZAGALS class waste. For the purpose of deep disposal into clay, this heat emission means that the waste must be allowed to cool down on the surface for some time to avoid compromising the containment capability of the clay. The thermal power per unit of length of the ZAGALC class waste is 378 $W \cdot m^{-1}$ at 50 years after discharge from the reactor. This is the period of interim storage prior to disposal that is currently being considered, although it could be increased to 60 years.
- The *class H* waste (category C, high level, moderately heat-emitting) is the result of the reprocessing of spent fuel. The HAGALC2 class consists of structural materials (*hulls*, *endpieces*, springs, etc.) of the spent fuel assemblies reprocessed by COGEMA and so-called ‘technological’ waste comprising mainly equipment items and laboratory instruments. All of this waste is compacted. The three HAGALP classes are the result of vitrification and, for a small proportion of them, the result of cementation by Belgoprocess in the PAMELA facility of the reprocessing waste produced by Eurochemic between 1966 and 1974.
- The *class M* waste (category B, medium level, low heat-emitting) is more varied in origin than the waste of classes Z and H. The MAGALC class consists of bituminised sludge from the reprocessing of spent fuel by COGEMA. The MAGALE class comprises various types of bituminised waste, mainly liquid Eurochemic reprocessing waste (Eurobitum waste). The generic MAGAL class is made up of waste packages whose contact dose rate is above 5 $mSv \cdot h^{-1}$; it contains mainly waste from the research conducted by SCK•CEN prior to 1989 and dismantling waste, all cemented in PAMELA.

Table 3.2 Inventory of radioactive waste intended for deep disposal. The figures in normal print in the column ‘Expected no. of packages’ correspond to the complete reprocessing option and should be replaced by the figures in *italics* in the case of the direct disposal option (1999 estimates). The activity levels, doses, and powers shown are those at the time of conditioning. (*: the material used to fill the watertight packagings is sand; **: production discontinued)

Category and level	**Class**	**Principal waste streams**	**Matrix**	**Expected no. of packages**	**Ext. vol./ pack. [m^3]**	**Activity [Bq/pack.]**		**Contact dose [Sv·h^{-1}]**	**Power [W/pack.]**
						α	βγ		
C **very high level**	ZAGALC	Reprocessing waste	glass	3915 / *420*	0.180	$1.3 \cdot 10^{14}$	$9.1 \cdot 10^{15}$	> 10^4	602
	ZAGALS	Spent fuel: UO_2 (Doel 1 and 2)	UO_2*	*1669*	0.326	$1.7 \cdot 10^{14}$	$1.5 \cdot 10^{15}$	≈ 10^3	188
		UO_2 (Tihange 1 and 2 / Doel 3)	UO_2*	*4780*	0.444				
		UO_2 (Tihange 3 / Doel 4)	UO_2*	*3266*	0.517				
		MOX: UO_2 / PuO_2 (Tihange 2 / Doel 3)	UO_2/PuO_2*	*144*	0.444	$9.9 \cdot 10^{14}$	$2.3 \cdot 10^{15}$	≈ 10^3	905
C **high level**	HAGALC2	Compacted structural and technological waste	–	6410 / *820*	0.180	$7.9 \cdot 10^{11}$	$1.7 \cdot 10^{14}$	> 2	20
	HAGALP1	Liquid reprocessing waste from the ex-Eurochemic	glass	1501**	0.070	$8.2 \cdot 10^{11}$	$1.3 \cdot 10^{14}$	> 2	5
	HAGALP2	Liquid reprocessing waste from the ex-Eurochemic	glass	700**	0.195	$2.6 \cdot 10^{11}$	$7.1 \cdot 10^{13}$		2
	HAGALP3	Solid reprocessing waste from the ex-Eurochemic	cement	160**	0.195	$6.0 \cdot 10^{11}$	$3.6 \cdot 10^{13}$		3
		Total category C waste		**12686 /*13460***	**2132/*4642 m^3***				
B **medium level**	MAGALC	Reprocessing waste (coprecipitation sludge)	bitumen	480**	0.238	$1.8 \cdot 10^{10}$	$2.6 \cdot 10^{12}$	0.750 to 2	0.1
	MAGALE	Liquid and solid waste from the ex-Eurochemic	bitumen	13406	0.245	$2.0 \cdot 10^{10}$	$2.6 \cdot 10^{12}$	0.005 to 2	0.1
	MAGAL	Secondary waste from PAMELA and its dismantling	cement	186	0.245	$8.6 \cdot 10^{9}$	$2.2 \cdot 10^{12}$	0.005 to 2	0.2
		Waste from the HRA/Solarium	cement	1200	0.500	pm	pm		pm
		Waste from the HRA/Solarium	cement	142	2.500	pm	pm		pm
		Waste from the dismantling of industrial reactors	cement	2075	0.500	pm	$1.1 \cdot 10^{15}$		176
		Waste from the dismantling of reactors of SCK•CEN	cement	67	0.500	$5.1 \cdot 10^{5}$	$2.6 \cdot 10^{13}$		2
B **low level**	LAGAL	Waste from the current production of MOX	cement	1459	0.500	$4.6 \cdot 10^{11}$	$1.0 \cdot 10^{13}$	< 0.005	0.4
		Waste from the dismantling of MOX facilities	cement	1901		$2.7 \cdot 10^{10}$	$2.7 \cdot 10^{11}$		0.02
		Waste from the dismantling of the ex-Eurochemic	cement	642		$3.5 \cdot 10^{11}$	$1.2 \cdot 10^{9}$		0.3
		Miscellaneous waste from the ex-Waste department	cement	170		$1.7 \cdot 10^{11}$	$3.3 \cdot 10^{12}$		0.2
	RAGAL	Waste contaminated with radium	pm	pm	pm	pm	pm	0.005 to 2	pm
		Total category B waste		**21728**	**7556 m^3**				

- The waste of the generic *classes L and R* (category B, low level, low heat-emitting, long lived) have a contact dose rate less than or equal to 5 $mSv \cdot h^{-1}$. The LAGAL class contains mainly waste from the current production of MOX fuel, historical waste, and dismantling waste containing large quantities of alpha emitters, all cemented. The RAGAL class includes all of the radium-contaminated waste that results from the radium production operations of the old Olen refinery (Union Minière) and from the actinium programme of SCK•CEN. (It does not therefore include the category R waste.)

Finally, the waste classes are divided into over 100 waste **streams.** These are defined as groups of packages with homogeneous physical, chemical, and radiological characteristics, produced using the same process to condition the same kind of raw waste.

3.1.2 Inventory of conditioned waste intended for deep disposal

The main achievements with regard to the inventory are the development of waste production forecasts and the acquisition, and systematic and coherent grouping, of a large quantity of data about the waste, especially in terms of qualitative and quantitative radiological content, i.e., the radionuclides contained and the concentration of each (Tables 3.2 and 3.3).

Unlike the inventory given in the SAFIR report, which assumed a complete reprocessing of all types of spent fuel, the inventory given in the SAFIR 2 report, which dates from 1999, looks at two distinct options: an option in which all spent fuel types is reprocessed, and one in which spent fuel is disposed of without reprocessing. These two options are based on the same assumptions regarding the fuel that is, or will be used:

- the seven Belgian commercial nuclear reactors, with a total installed power of 5.7 GWe, will be shut down after an operating period of 40 years each;
- before irradiation, the enriched uranium fuel contains 4.0 % ^{235}U and the mixed-oxide fuel (MOX) contains 4.93 % $^{239}Pu + ^{241}Pu$;
- the fuel is irradiated for 1 450 days and its reference burn-up is 45 $GWd \cdot tHM^{-1}$, or $45 \cdot 10^9$ watt-days per tonne heavy metal (uranium or MOX).

Based on these assumptions, the total consumption of conventional uranium fuel is estimated to be 4 860 tHM, to which some 70 tHM of MOX fuel must be added. The total inventories for the two options are therefore as follows:

- *complete reprocessing option*: reprocessing of all of the 4 860 tU. This option involves the production of 3 920 containers of very high-level vitrified waste (ZAGALC class waste) and 6 410 containers of structural waste from spent fuel assemblies (HAGALC2 class waste), plus some 70 tHM of existing MOX.
- *direct disposal option*: reprocessing stops after the reprocessing of the 630 tU under existing contracts. This option entails the production of 420 containers of very high-level vitrified waste and 820 containers of structural waste from spent fuel assemblies, plus about 4 230 tU non-reprocessed spent fuel and the existing 70 tHM of MOX.

The forecasts of waste production based on the two options and information about the other waste streams indicate a sharp reduction in the waste volume intended for deep disposal. This volume stood at approximately 27 000 m^3 in the SAFIR report (1989), but is now only about 10 000 m^3 for the complete reprocessing option and some 12 500 m^3 for the direct disposal option. As a result of developments in the conditioning processes, the SAFIR 2 report also includes new types of waste, while other waste types have disappeared.

Table 3.3 Inventory, in becquerels per package, of the radionuclides considered in the long-term safety assessments for the most demanding waste in radiological and heat emission terms (see also Section 4.3.2.1). (For the safety assessments, the inventory of ^{36}Cl has been estimated from foreign data. In addition, although ^{59}Ni, ^{94}Nb, and ^{147}Sm have half-lives that should lead to their consideration in safety assessments, the very low intrinsic radiotoxicity of the first radionuclide makes it non-critical, while the radiological impact of the other two according to these same assessments is negligible. They are, therefore, not shown below.)

	^{14}C	^{79}Se	^{93}Zr	^{99}Tc	^{107}Pd	^{126}Sn	^{129}I	^{135}Cs
Vitrified waste	–	$1.7\cdot10^{10}$	$9.1\cdot10^{10}$	$7.1\cdot10^{11}$	$5.2\cdot10^{9}$	$2.9\cdot10^{10}$	$1.5\cdot10^{8}$	$2.3\cdot10^{10}$
UOX fuel	$8.9\cdot10^{9}$	$9.4\cdot10^{9}$	$4.5\cdot10^{10}$	$2.9\cdot10^{11}$	$2.9\cdot10^{9}$	$1.8\cdot10^{10}$	$7.4\cdot10^{8}$	$1.0\cdot10^{10}$
MOX fuel	$4.3\cdot10^{9}$	$8.0\cdot10^{9}$	$3.3\cdot10^{10}$	$2.8\cdot10^{11}$	$5.9\cdot10^{9}$	$2.5\cdot10^{10}$	$9.2\cdot10^{8}$	$9.4\cdot10^{9}$
Hulls and endpieces	$5.0\cdot10^{7}$	$3.9\cdot10^{7}$	$5.6\cdot10^{9}$	$4.0\cdot10^{9}$	–	–	$5.6\cdot10^{7}$	$2.0\cdot10^{8}$
	^{226}Ra	^{229}Th	^{230}Th	^{231}Pa	^{232}Th	^{233}U	^{234}U	^{235}U
Vitrified waste	–	$1.8\cdot10^{3}$	$3.8\cdot10^{4}$	$1.4\cdot10^{5}$	$3.1\cdot10^{0}$	$8.6\cdot10^{1}$	$6.3\cdot10^{5}$	$3.9\cdot10^{5}$
UOX fuel	$4.9\cdot10^{5}$	$3.1\cdot10^{3}$	$2.5\cdot10^{6}$	$8.4\cdot10^{5}$	$1.4\cdot10^{1}$	$1.9\cdot10^{6}$	$1.0\cdot10^{10}$	$2.6\cdot10^{8}$
MOX fuel	$1.0\cdot10^{6}$	$1.8\cdot10^{4}$	$1.1\cdot10^{7}$	$2.2\cdot10^{5}$	$9.3\cdot10^{5}$	$4.4\cdot10^{10}$	$4.4\cdot10^{10}$	$4.1\cdot10^{7}$
Hulls and endpieces	–	–	–	–	–	–	–	–
	^{236}U	^{237}Np	^{238}U	^{242}Pu	^{244}Pu	^{248}Cm		
Vitrified waste	$4.7\cdot10^{6}$	$1.5\cdot10^{10}$	$5.5\cdot10^{6}$	$8.0\cdot10^{7}$	$4.3\cdot10^{0}$	$3.7\cdot10^{4}$		
UOX fuel	$5.6\cdot10^{9}$	$9.1\cdot10^{9}$	$5.4\cdot10^{9}$	$5.1\cdot10^{10}$	$1.2\cdot10^{4}$	$1.5\cdot10^{4}$		
MOX fuel	$3.9\cdot10^{8}$	$7.3\cdot10^{9}$	$5.2\cdot10^{9}$	$2.4\cdot10^{11}$	$7.8\cdot10^{5}$	$1.1\cdot10^{5}$		
Hulls and endpieces	–	$5.0\cdot10^{6}$	–	$5.3\cdot10^{10}$	–	–		

Although assessments of the long-term radiological safety of deep disposal indicate a safety level that is adequate and largely insensitive to the inventories that are used (see Section 4.3.2), these results have yet to be confirmed. Such confirmation is based mainly on a more detailed knowledge of the waste and calls, among others, for the following four types of action:

- on the basis of information that is available—mainly with waste producers—, to identify the inventory of critical radionuclides of the different waste classes, the physical properties of this waste (heat emission in particular), and its chemical characteristics (especially the presence of heavy metals and other chemotoxic elements);
- as part of a transparent system of quality management and assurance, to improve the documentation of knowledge about the waste inventory, so as to make it easier to find back the assumptions and calculation codes used or the measurements carried out (see Section 2.4);

- to refine the waste production scenarios on the basis of a more detailed description of the nuclear fuel cycle and the various changes that it could undergo;
- to study ways of verifying the fundamental characteristics of the waste before it is disposed of.

3.1.3 General rules for waste acceptance and acceptance criteria

To be in a position to ensure the short-term and long-term management of the radioactive waste that is placed in its charge, ONDRAF/NIRAS must be confident enough that the intrinsic characteristics of the waste will not, in principle, threaten the safety of one or more stages of its management. ONDRAF/NIRAS must, therefore, be assured that the waste conforms to a range of criteria that it has established in advance. Under the provisions of the Royal Decree of 30th March 1981 as amended by the provisions of the Royal Decree of 16th October 1991, ONDRAF/NIRAS has laid down the general rules to be used as a reference framework for the development of criteria to be satisfied by the radioactive waste packages before ONDRAF/NIRAS agrees to accept them, and has then established the actual acceptance criteria proper. These general rules and acceptance criteria may be modified at the initiative of ONDRAF/NIRAS or the competent authority in response to changes in, for instance, the repository design, national and international legislation and recommendations, and processing and conditioning techniques. They represent one of the most significant advances in the management and quality assurance of radioactive waste (see also Section 2.4). All radioactive waste packages accepted by ONDRAF/NIRAS must also meet the applicable legal and regulatory requirements. These include the requirements of the operating licences of the nuclear facilities involved, and the international transport regulations.

The *general rules*, which were approved by the competent authority and came into force on 10th February 1999, consider all of the aspects (essentially mechanical, physical, chemical, radiological, and biological) that must be subject to acceptance criteria, and lay down a range of administrative requirements. These include a duty to document all waste packages individually and identify them uniquely, a procedure for package acceptance, obligations for nuclear operators who condition the waste to prove the conformity of their packages with the acceptance criteria, possible alternatives in the case of non-conformity of the packages, technical and administrative arrangements for monitoring their characteristics over time, and revisions of the acceptance criteria.

The *acceptance criteria*, which currently cover the bulk of conditioned radioactive waste production, are established separately for each waste class and are all subject to systematic documentation and justification procedures. Besides certain administrative specifications, they specify the mainly technical requirements for minimum quality that packages must meet before they can be accepted by ONDRAF/NIRAS. Each primary package must satisfy a number of requirements. These relate to its mechanical strength, the maximum percentage of void it can contain, its resistance to radiation, its level of surface contamination and its hazardous substance content, in particular, its radiological content and, more specifically, its content of critical radionuclides. It must not be the source of chemical reactions that could jeopardise the safety of waste management. Moreover, the conditioned waste must form a solid whole with no free fluids. It must be compact, chemically stable, non-dispersible, and unlikely to crack, and it must satisfy a number of criteria that vary according to the type of matrix used to immobilise it. It must not contain putrescible materials. It must not contain complexing agents in quantities large enough to have a significant adverse effect on the behaviour of radionuclides near to the repository. There must be no risk of damage or excessive distortion to the waste packages from the production of gas from the waste. Finally, the packages must satisfy requirements governing their geometrical, mechanical, and corrosion resistance characteristics and, more generally, relating to the maintenance of their integrity.

Compliance with the acceptance criteria is determined primarily by the waste processing and conditioning stage, which is the stage that most broadly controls the physical quality of the waste. The processing and conditioning facilities, and the processes carried out in them, must therefore be qualified by ONDRAF/NIRAS. There are four steps in this *qualification* process. First, the operator who processes and conditions the waste (the producer or a sub-contractor of ONDRAF/NIRAS) submits a technical qualification report to ONDRAF/NIRAS. This describes the operation of the facility, and formalises and justifies the arrangements to guarantee that the conditioned waste packages meet the applicable acceptance criteria. ONDRAF/NIRAS then verifies, possibly with the assistance of an authorised organisation, that the facility fully complies with the conditions of the qualification report by conducting regular technical audits. Then, again assisted by an authorised organisation, it verifies the processes and facilities used by the operator to characterise the radiological composition of the waste conditioned in the facility that is to be qualified. Finally, ONDRAF/NIRAS examines the documentation showing the conformity of the conditioned waste with the acceptance criteria and the conformity of the process used with the data in the qualification report for the facility concerned. Provided all of these checks are satisfactory, ONDRAF/NIRAS qualifies the process and the processing and conditioning facility concerned, as well as the characterisation method and facility. This qualification is then valid for a given period.

The *acceptance procedure* for the packages of conditioned radioactive waste is the administrative process by which ONDRAF/NIRAS uses both administrative and technical checks to satisfy itself that the conformity report that accompanies the waste which the operator asks ONDRAF/NIRAS to accept has been properly prepared and that the waste conforms to that report and, therefore, to the applicable acceptance criteria. Since this operation has technical, financial, and safety implications, each of its phases must be documented in accordance with previously established procedures. In practice, and in simple terms, when ONDRAF/NIRAS receives an application to collect conditioned waste, it first examines the accompanying production file. This file contains the results of calculations of radiological and physico-chemical characterisation carried out by the operator to verify the conformity of his waste with the acceptance criteria in force at the time of production. ONDRAF/NIRAS then carries out physical spot checks on the packages to ensure that they really do conform to the information given in the file, and issues a collection inspection report setting out the results of its checks and any reservations. It then arranges transport for the packages and issues the acceptance report, which certifies the conformity of the packages with the criteria, or sets out the conditions by which they have been accepted, and the transfer report. The packages are then transferred to the interim storage facility that ONDRAF/NIRAS has designated and where it examines them physically and issues the storage inspection report. Under the regulatory provisions that require the party who conditioned the waste to remain liable for 50 years for any hidden defects that might be found, ONDRAF/NIRAS is currently developing a plan for regular checks on the continued conformity of the packages with the acceptance criteria during their interim storage, and, hence, on their compatibility with the reference repository. If a package ceases to be compatible with its ultimate destination, then corrective action must be taken, the most extreme case being reconditioning.

3.2 The host formation and the environment of the disposal system

Long-term radiological safety assessments having repeatedly stressed the dominant role of the natural barrier in the performance of a deep disposal system in the Boom Clay (see Chapter 4), ONDRAF/NIRAS intensified its work on the characterisation and understanding of the Boom Clay beneath, and in the immediate vicinity of, the Mol–Dessel nuclear zone during the period 1990–2000. In accordance with the recommendations of the SAFIR Evaluation Commission (1990), it focused its methodological research and development programme on

- characterising the lithological heterogeneities of the Boom Clay;
- identifying structural discontinuities (faults, etc.) affecting that clay;
- improving the understanding and modelling of the regional and local hydrogeology of the aquifers both above and below the Boom Clay.

It also set about establishing the natural radiological background of the clay and studying the behaviour of the naturally-occurring radionuclides.

(The geomechanical behaviour of the Boom Clay is discussed in Section 3.6.2 dealing with disturbances. Also, given the preliminary nature of the investigation of the Ypresian Clays and the significant difference in the level of progress between the reference option and the alternative option in terms of the development of a deep disposal facility, the body of information relating to the Ypresian Clays is dealt with separately from the information concerning the Boom Clay, in Section 3.8.)

3.2.1 Selection and status of the host formations studied in Belgium

There has been a significant evolution in the approaches proposed at an international level for the selection of geological formations or appropriate sites for deep disposal. This evolution has involved a move away from an approach that applied exclusion criteria associated with the host formation towards a global approach of assessment and optimisation of the performance and safety of the disposal system as a whole. This integrated and system-oriented approach to the selection of host formations and the development of the disposal system and its assessment, however, casts no doubt on the fundamental importance of the geological barrier in guaranteeing long-term radiological safety.

In Belgium, SCK•CEN began to study the deep disposal of category B and C waste in the mid-1970s with the aid of the Geological Survey of Belgium (*Service Géologique de Belgique / Geologische Dienst van België*). Further research into the Boom Clay beneath the Mol–Dessel nuclear zone (Fig. 3.2) was encouraged by the Evaluation Commission for Nuclear Energy, which noted in its final report of March 1976 that, for Belgium, the deep argillaceous layers appeared to offer the best solution for the final disposal of this waste. In the same year, the European Commission began to draw up, on a bibliographical basis, a European inventory of geological formations that might have characteristics favourable for the deep disposal of category B and C waste. For practical reasons associated most notably with the scale of the study, this selection was made solely by applying exclusion criteria linked to the lithology (clay, salt, or granite), the depth, and the thickness of the formations. In Belgium, only argillaceous formations were selected as part of this study. These formations can be divided into two main groups:

- the formations consisting of hard rocks (shales) belonging to the Paleozoic (e.g., in the Cambro-Silurian massifs of Brabant and the Ardennes);
- the formations consisting of poorly-indurated, plastic rocks belonging to the Cenozoic (Ypresian Clays and Boom Clay).

So far as the hard rocks are concerned, little relevant information about their properties at depth was available at the time, and the very encouraging preliminary results on the lithology and containment capacity of the Boom Clay beneath the Mol–Dessel nuclear zone therefore led first SCK•CEN and then ONDRAF/NIRAS to intensify research into this formation and this zone. This choice was further reinforced by practical considerations, such as the advantage of having a well developed multi-disciplinary scientific infrastructure above the considered formation and the guarantees of access offered by the ‘nuclear zone’ status, as shown on the regional planning and development maps.

Fifteen years later, the SAFIR Evaluation Commission (1990) concluded that the decision to study the Boom Clay beneath the Mol–Dessel nuclear zone was justified, but that it might also be worthwhile if other locations were considered, e.g., the Doel nuclear zone (Fig. 3.2) with its underlying Ypresian Clays. Following these conclusions, ONDRAF/NIRAS embarked upon a research programme into these clays at Doel in the early 1990s.

ONDRAF/NIRAS is currently assessing the *potential for safety and feasibility* of two host formations on the basis of studies conducted on two sites for methodological studies. The host formations, both of which consist of poorly-indurated clays, have been selected for technical reasons, while the choice of the two investigation sites is based on historical, institutional, and practical considerations. More specifically, ONDRAF/NIRAS regards

- the Boom Clay as the *reference host formation* for examining a solution for the deep disposal of category B and C waste in Belgium, the aim being to demonstrate that there exists a safe solution for the long-term management of this waste, and one that can be implemented, without prejudging the site where any implementation of that solution could take place;
- the nuclear zone of Mol–Dessel as the *reference site for the methodological studies* related to the Boom Clay;

- the Ypresian Clays as an *alternative host formation* for researching and assessing a deep disposal solution in Belgium;
- the nuclear zone of Doel as an *alternative site for the methodological studies* related to the Ypresian Clays.

In technical terms, designating an alternative makes it possible, first, to have a substitute solution should the reference disposal system prove incapable of performing its safety functions or of being implemented, and, second, to improve the understanding of the two systems under study, in particular by investigating the transferability of knowledge from one formation or site to the other.

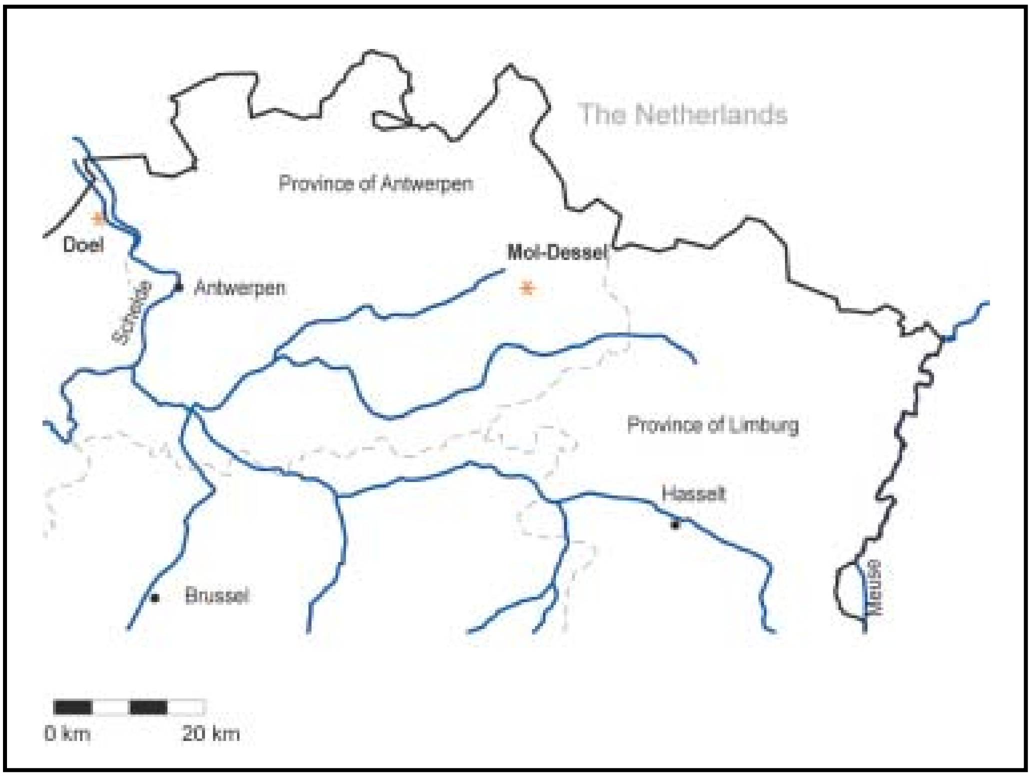


Figure 3.2 Location of the Mol–Dessel and Doel nuclear zones, respectively the reference and alternative sites for methodological studies into the deep disposal of category B and C waste.

3.2.2 The Boom Clay as a host formation

Because long-term radiological safety assessments had repeatedly emphasised the dominant role of the natural barrier, during the period 1990–2000, ONDRAF/NIRAS intensified its work on the characterisation and understanding of the Boom Clay beneath and in the immediate vicinity of the Mol–Dessel nuclear zone.

The lithological and structural heterogeneities of the Boom Clay and of its overlying and underlying formations have been studied primarily by means of geophysical methods, applied either in boreholes (wireline logging), or from the surface (seismic reflection), with additional testing of core material (Fig. 3.3).

The Boom Clay has also been the subject of intense fundamental and applied research outside the framework of the deep disposal programme, whether in the outcrop zone (in clay pits in the regions of the Rupel and the Waasland) or during tunnel excavation (in the Antwerpen underground tramway and the Rupel tunnel).

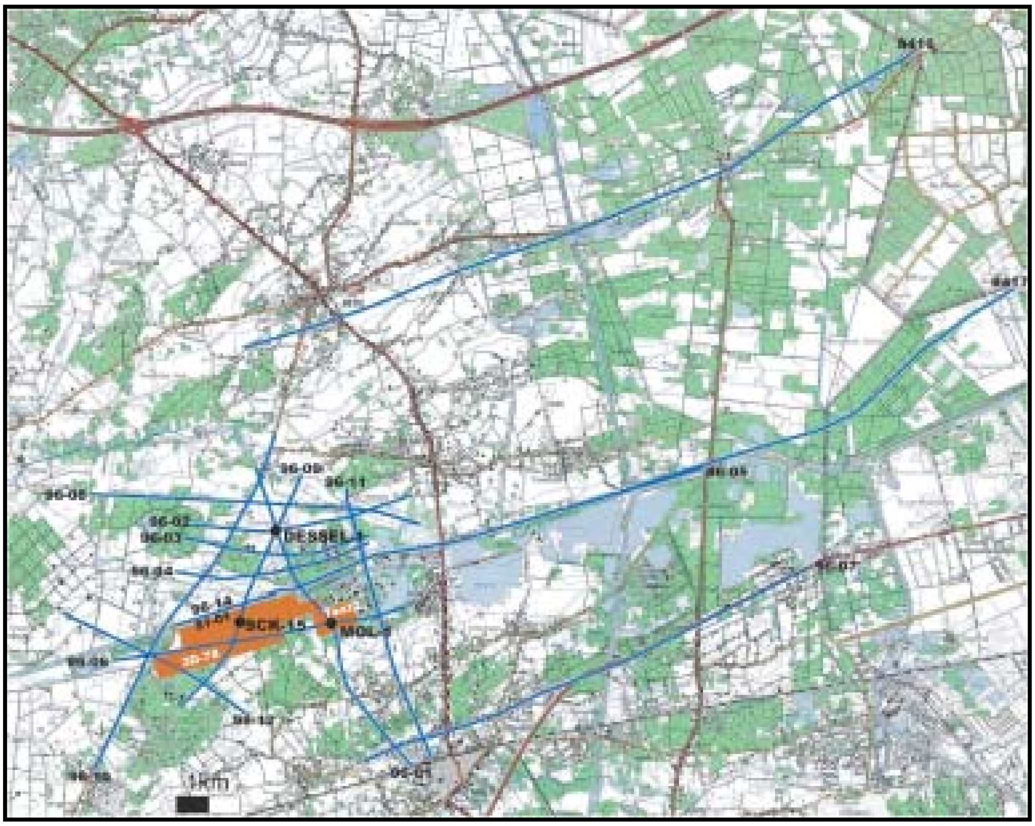


Figure 3.3 Location of the main boreholes and geophysical reconnaissance surveys on and around the Mol–Dessel nuclear zone.

3.2.2.1 Stratigraphical and lithological characterisation

The region in which the Boom Clay is present corresponds roughly to the Campine, i.e., the northeast of Belgium. The Boom Clay, or Boom Formation, belongs to the Rupelian, that geological part of the Tertiary Period which lasted from 36 to 30 million years ago. From bottom to top, it is divided into three members: Belsele-Waas, Terhagen, and Putte.

The Boom Clay is a silty clay or argillaceous silt with a high pyrite and glauconite content in its siltiest bands. One of its most remarkable characteristics is precisely this structure of bands that are several tens of centimetres thick, reflecting mainly cyclical variations in grain size (silt and clay content) due to fluctuations in the wave action on the sedimentation medium and to variations in the carbonate and organic matter contents (Figs. 3.4 and 3.5). Very dark bands that are rich in organic matter are a feature of the Putte Member, while marly bands, which are grey-white, occur throughout the thickness of the formation. It is in these latter bands that the typical concretions, known as septarias, are found (Fig. 3.6).

The clastic sediments (i.e., deposited by the settlement of solid particles in water, ice, or air) are classified mainly by the size of the grains (granulometry) of which they are made, the size being an indication of the energy needed for the transport of the particles and, hence, of the medium in which the sediment was deposited. Very fine particles, for example, can only settle in very still water.

The granulometric scale is divided into different fractions:

clay
$\varnothing_{\text{particles}} < 0.002$ mm

silt 0.002 mm <
$\varnothing_{\text{particles}} < 0.062$ mm

sand 0.062 mm <
$\varnothing_{\text{particles}} < 2$ mm

gravel
$\varnothing_{\text{particles}} > 2$ mm

The sediments that consist of clay, silt, or very fine sand have very low hydraulic conductivities (< 10^{-6} m·s^{-1}) and high porosities frequently exceeding 40 %. Sands and gravels form good aquifers.

The base (Belsele-Waas Member) and top (top section of the Putte Member) of the Boom Clay are distinctly siltier and display a granulometric transition between the 'pure' clay (lowest part of the Putte and Terhagen Members) and the subjacent sandy layers.

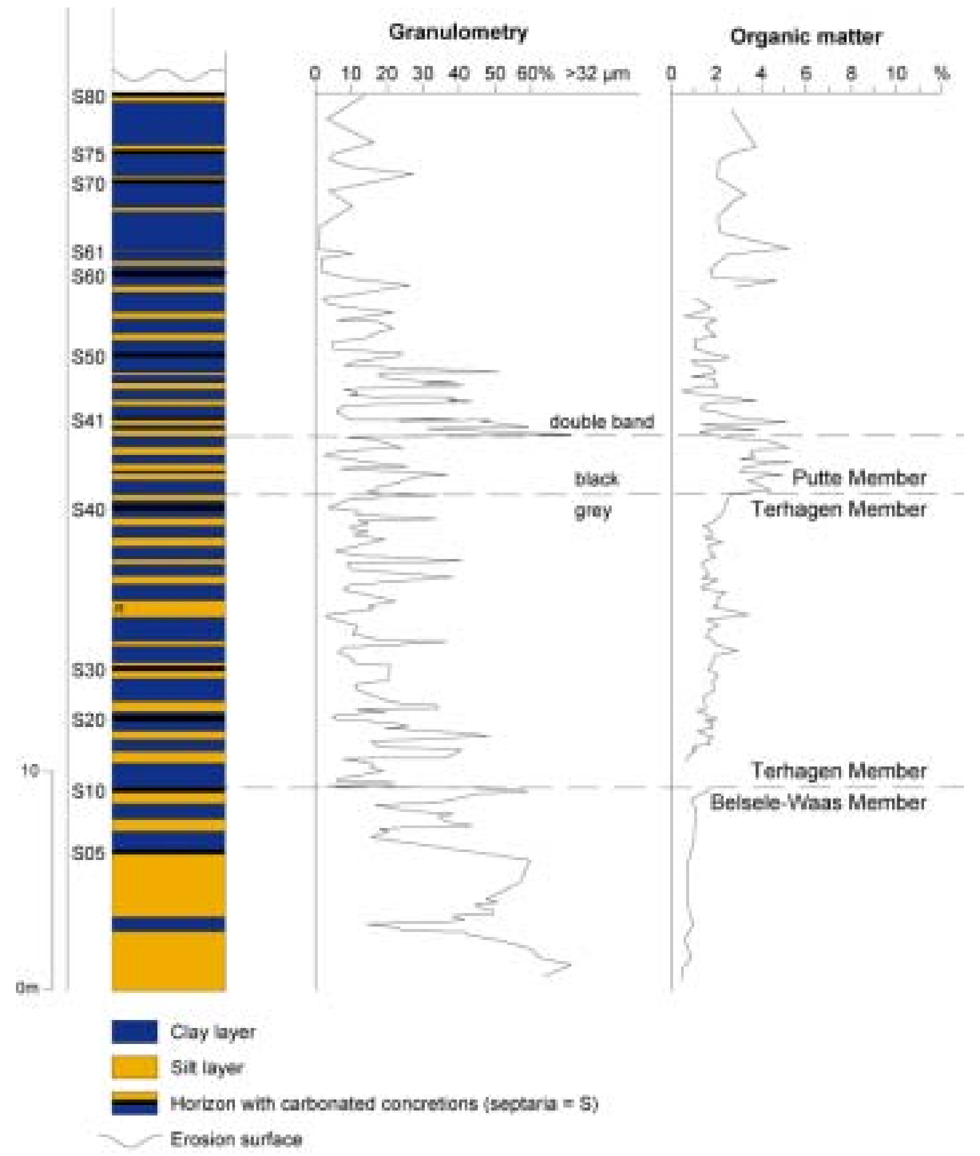


Figure 3.4 Lithostratigraphic profile of the Boom Clay and lithological variations.

The Boom Clay outcrops to the north of the Durme, the Rupel, and the Dyle rivers, and to the north of the Leuven–Tongeren line. This outcrop zone forms a belt 5 to 15 km wide, interrupted in the Hageland by a deeply eroded channel filled with the Diest Sands. However, the outcrop does not display the full stratigraphic sequence of the formation as the top layers were eroded in the course of a continental episode (i.e., an interruption of sedimentation) lasting some 9 million years after their deposition. By geometrical reconstruction, it can be estimated that several tens of metres of clay were eroded over most of the Antwerpen Campine. The thickness of the Boom Clay in the outcrop zone ranges from 30 to 50 metres. It attains a thickness of 75 metres to the north of Antwerpen and is close to 100 metres in the Northern Campine (Fig. 3.7). The thickness of the strictly argillaceous part of the formation decreases, however, towards the east.

Septaria Concretion in the shape of a loaf of bread that can attain a height of 30 cm and a diameter of 1 metre, and is characterised by desiccation cracks or ‘septae’. These cracks are frequently covered with a film of calcite or pyrite crystals. The septarias have formed in bands rich in limestone under the action of diagenetic processes caused mainly by the precipitation of carbonates around rotting organisms (basic micro-environment). Bands of septarias are used to stratigraphically link different clay pits and deep boreholes.

Figure 3.5 General view of a clay pit showing the banded structure characteristic of the Boom Clay.

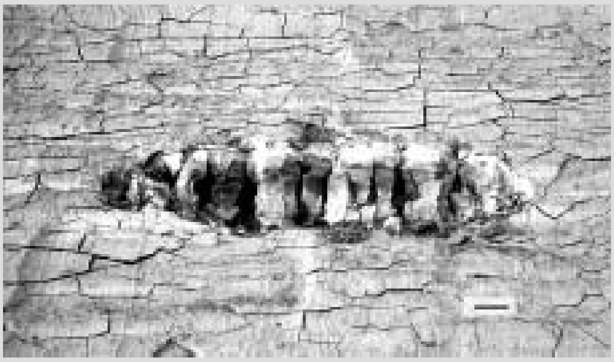


Figure 3.6 View of a septaria.

The Boom Formation displays a 1 to 2 % dip towards the northeast and thickens in this direction. Its base is at a depth of more than 400 metres (Fig. 3.7) in the north of the Province of Antwerpen, near to the border with the Netherlands, but is at a depth of more than 1 000 metres at certain places in the Roermond Graben, as a result of fault activity. It would seem that in the Mol–Dessel region, the Boom Clay has never been at a depth greater than that at which it is now found, i.e., between approximately 190 and 290 metres beneath the surface.

In the 1990s, two drilling programmes through the Tertiary formations took place on the Mol–Dessel nuclear zone. The first borehole (Dessel-1, 1993) reached a depth of 613 metres, while the second (Mol-1, 1996) was drilled to 572 metres. The Mol-1 borehole was also cored between 150 and 332 metres to provide samples of the full thickness of the Boom Formation and adjacent strata (Fig. 3.8).

TAW An acronym designating the reference topographical level (zero level) in Belgium, which corresponds approximately to the sea level.

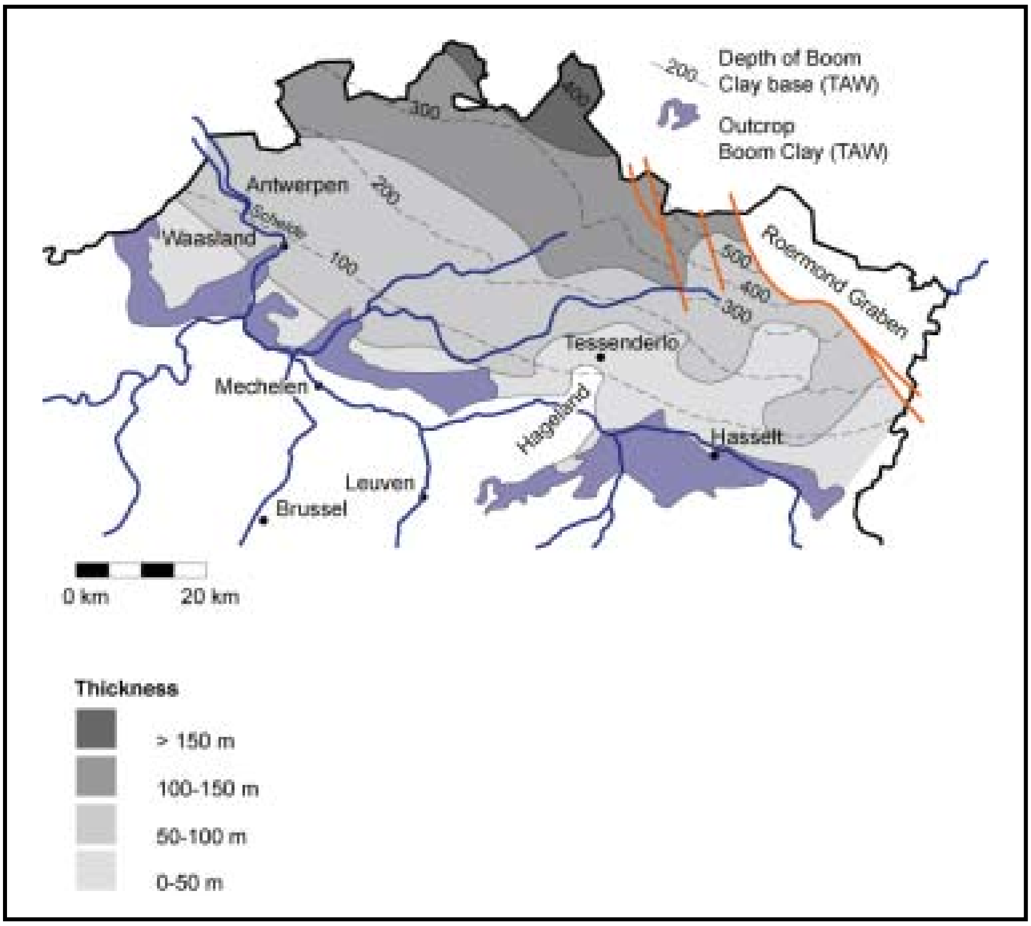


Figure 3.7 Depth of the base, and thickness, of the Boom Formation.

A range of borehole logging tools with high vertical resolution (several centimetres to several decimetres) and/or of very recent design (resistivity imaging, nuclear magnetic resonance) were used to reveal the fine lithological variations within the Boom Clay. A preliminary interpretation of the results shows that these tools, especially those that provide images based on measurements of electrical resistivity, can perfectly visualise the lithological and granulometric variations (clay/silt) and the septarian bands so typical of the Boom Clay (Fig. 3.9). These variations can also be fully correlated with the sequences defined in clay pits more than 50 km away from the nuclear zone, showing the remarkable lateral continuity of this clay. Only the Belsele-Waas Member and the uppermost part of the Putte Member (the top of the transition zone) display geophysical characteristics considerably different from those of the rest of the clay sequence, suggesting the relative homogeneity of the majority of the Boom Clay. In particular, the results obtained with the nuclear magnetic resonance probe indicate a fairly homogeneous distribution of hydraulic conductivities (permeabilities) and porosities, except in this basal section and the top of the transition zone.

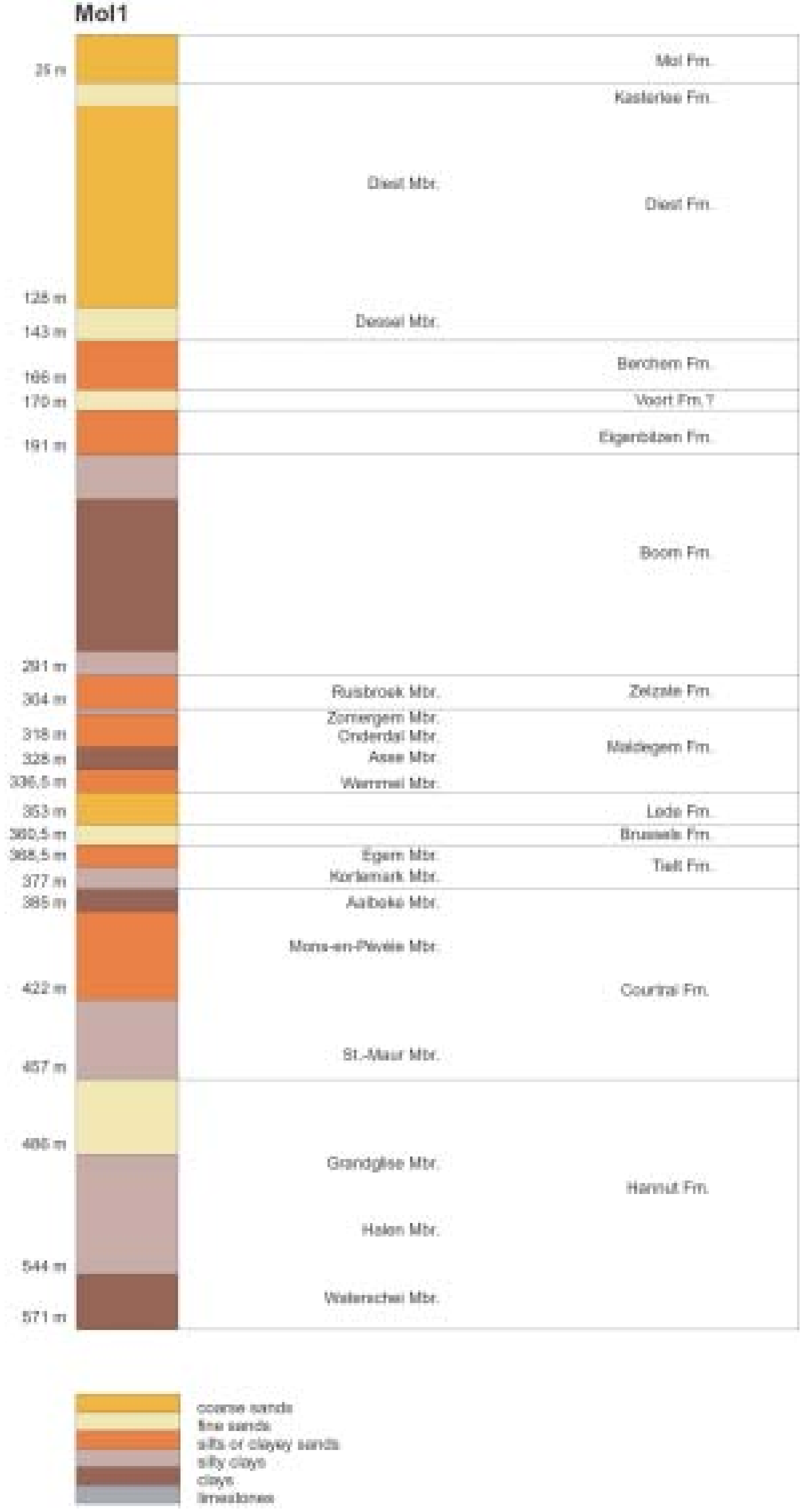


Figure 3.8 Geological section intersected in the Mol-1 borehole (Mbr.: Member; Fm.: Formation).

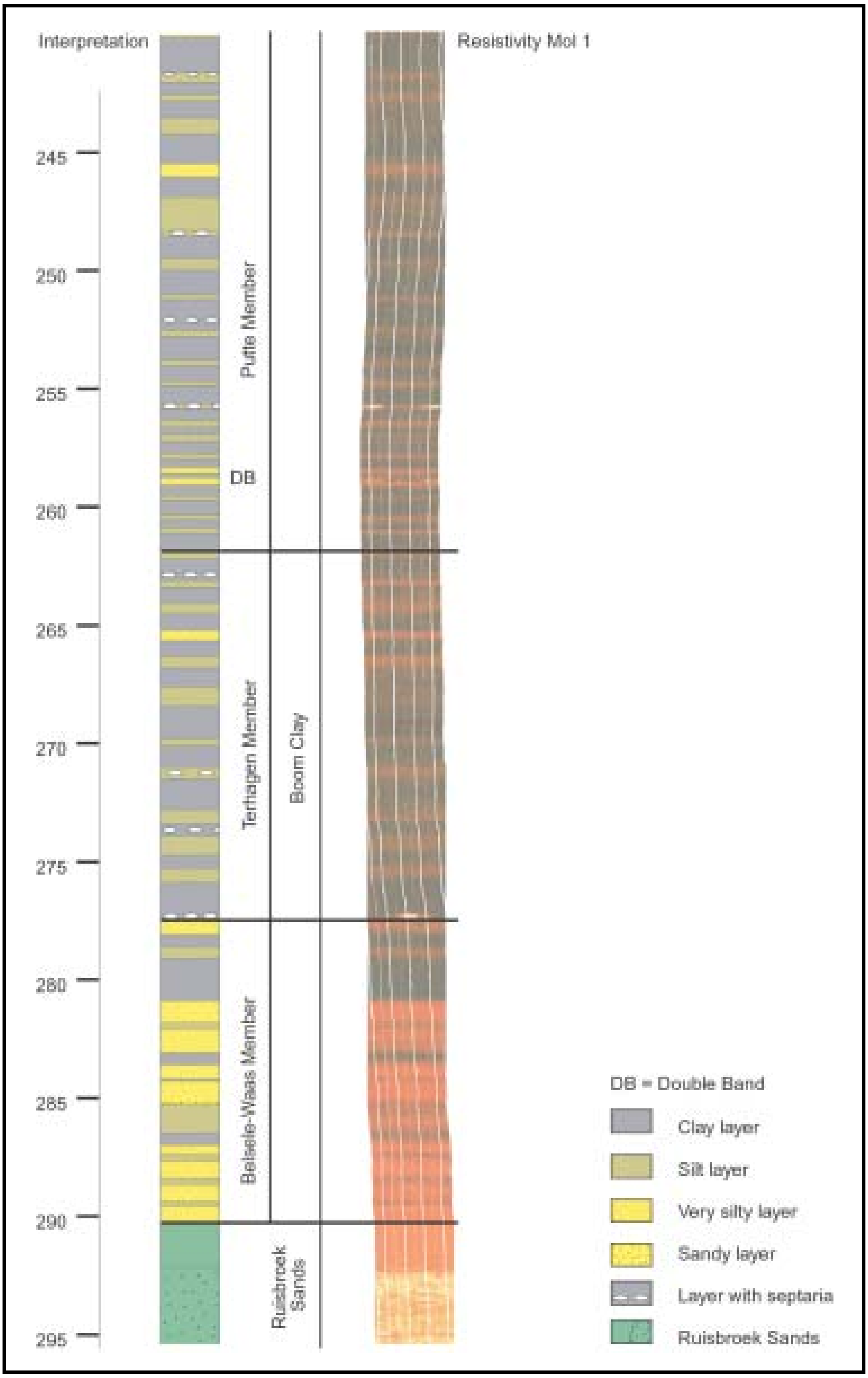


Figure 3.9 Resistivity imaging in the Mol-1 borehole and interpretation based on different wireline loggings and observations on site (see also Figs. 3.4 and 3.5).

Composition

A number of analyses (X-ray diffractometry, Fourier Transform InfraRed analysis) have been carried out with a view to reducing the quantitative and qualitative differences in the *mineralogical composition* highlighted in the SAFIR report. The results of these analyses agree on the proportions of the different mineral fractions present, but differ as to the mineralogy of the clays. The wide variation in the content of clay minerals (phyllosilicates), which ranges from 30 to 70 %, with an average of 55 %, is due to the vertical lithological heterogeneity of the Boom Clay (Table 3.4). In descending order of importance, the non-argillaceous fraction of the sediment consists of quartz, feldspars, carbonates, and pyrite. The detailed quantification of the various clay minerals present, however, remains doubtful.

Table 3.4 Principal mineralogical characteristics of the Boom Clay.

Characteristic	Value
Mineralogical composition [% vol., dry matter]	
■ Clay minerals	30 to 70 (average 55)
– Illite	50
– Smectite	30
– Kaolinite	10
– Chlorite	≈ 5
– Glauconite	≈ 3
■ Quartz	20
■ Feldspars	5 to 10
■ Carbonates	1 to 5
■ Pyrite	1 to 5
Organic matter content [% weight, dry matter]	1 to 3
Water content [% vol.]	30 to 40

A model combining the results of the various wireline loggings together with the calibrations resulting from laboratory analyses has been used to help produce a continuous image of the mineralogy of the formation. In the case of the Boom Clay, however, such modelling overestimates the content of clay minerals. Even so, it is important to pursue this characterisation, especially with a view to modelling the geochemical interactions or radionuclide retardation phenomena onto the mineral phases, or to study the effects of the disturbances induced by the repository (presence of an alkaline plume, thermal impact, etc.—see Section 3.6.5).

The total porosity of the Boom Clay is some 30 to 40 % by volume, as is its total *water content*, as derived from core analyses. Modelling carried out by combining the results of wireline loggings in the Mol-1 borehole produces a relative vertical distribution of the total water content and shows a rise in water content where the formation is richest in clay minerals. This confirms that, in an argillaceous sediment, most of the water is not free, but bound to the clay minerals. Free water is only present in the Belsele-Waas Member and in the upper part of the transition zone.

Finally, the Boom Clay contains approximately 1 to 3 % by weight of *organic matter*, which plays a fundamental role in radionuclide migration (see Section 3.5).

Geochemistry

The ARCHIMEDE–ARGILE project, conducted under the ægis of the European Commission with the aim of improving the understanding of the *geochemistry* of the interstitial water in an argillaceous medium and its evolution, came to the important conclusion that the Boom Clay appears to have been in geochemical equilibrium since the end of its deposition. This tends to confirm its good chemical buffering capacity. The presence of sulphate-reducing and methanogenic bacteria in the Boom Clay has also been demonstrated, which suggests that such microorganisms, trapped inside the clay at the time of its sedimentation 35 million years ago, still exist there in a latent state. New studies will have to confirm this observation that could have far-reaching consequences for the migration of gases through the Boom Clay, the geochemistry of the near field, and the durability of the engineered barriers.

A study will be undertaken into the maintenance over long periods of time of the current geochemical conditions in the Boom Clay, which are very favourable to radionuclide retardation (E_h = – 0.250 V/SHE, reducing; pH = 8.2, mildly alkaline—see also Section 3.5). This is in order to support the definition of the normal and altered geological and hydrogeological evolution scenarios of the host formation and of its environment as part of assessments of long-term radiological safety.

A *radiochemical* characterisation of the solid phase has been undertaken to establish the natural radiological background of the host formation, to support the long-term radiological safety assessments by studying the concentrations and behaviour of the naturally-occurring radionuclides, and to contribute to the assessment of the vertical homogeneity of the formation. The preliminary conclusions of this study are as follows:

- the thorium and uranium isotopes are generally in radioactive equilibrium, which indicates a reduced mobility over periods of the order of a million years;
- the mobility of radium is more variable than that of thorium and uranium, and is clearly controlled by the lithology, radium being more mobile in silty layers;
- isotopic fractioning, indicating a leaching of uranium and radium, has been demonstrated on a sample taken from the ‘double band’, a band characterised by an increase in grain size and, hence, by a porosity and hydraulic conductivity higher than in the neighbouring clay.

Future research into radiochemical characterisation would have to corroborate the low mobility of the radionuclides naturally occurring in the Boom Clay, and will focus on the liquid phase, the fractionation observed in the double band, and the influence of the transition with the overlying aquifer sands.

3.2.2.2 Tectonic and seismic characterisation

The Campine Basin is a sedimentary basin generally devoid of large-scale structural features, having quasi-horizontal strata currently subsiding (drop in the mean level). The northeastern part of the basin is disturbed by a complex system of faults generally running NNW–SSE: this is the Roermond Graben, an active rift valley that affects the Boom Clay in particular. (Subsidence rates of 0.25 to 0.5 mm per year over the last 2 million years are observed in the central section of this rift valley.) The Poppel and Rauw Faults, 5 and 7 km respectively to the east of the Mol–Dessel nuclear zone, are the most westerly signs of this tectonic accident that are visible at the surface.

The biggest earthquake in the past 200 years was the Roermond quake in April 1992, which registered a magnitude of 5.8 on the Richter scale and an intensity of VII on the MSK scale around its epicentre. It is estimated that its origin was at 17 km depth and that the western boundary fault of the Roermond Graben, the Peel Fault, was active over a length of 4 km and suffered a vertical displacement of 10 to 20 cm. The Rauw Fault was still active in the recent geological past, with a mean movement of about one metre per 100000 years.

Current research on the Roermond Graben, most notably the work being carried out under the ægis of the European Commission, relating to the occurrence of major earthquakes in areas of low seismic activity, suggests that earthquakes of greater magnitude and intensity can be expected and with an increased frequency compared with what is currently considered. On the basis of this research, ONDRAF/NIRAS has therefore undertaken to reassess the seismic risk for northeastern Belgium as part of the definition of the possible long-term geological changes in the Mol–Dessel nuclear zone and the Boom Clay, according to a geoprospective approach. On a more local scale, ONDRAF/NIRAS has also started a detailed study of recent movements on the Poppel and Rauw Faults, those closest to Mol–Dessel. For the Boom Clay itself, there is also a study into the origin of the various structural discontinuities (faults, joints, etc.), both natural and those induced by excavation (see Section 3.6.2).

In 1996, ONDRAF/NIRAS conducted a two-dimensional seismic reflection survey (96-ON) on and around the Mol–Dessel nuclear zone with the primary aim of demonstrating the possible presence of flexures (deformations with no rupture) or faults affecting the Boom Clay and surrounding geological formations. Tests were carried out first to optimise the survey and to match the high-resolution methods usually used in oil exploration to the characteristics of the Boom Clay (limited depth, poorly-indurated formation, etc.). The seismic reflection survey consisted of approximately 65 km of acquisition profiles, most of which are oriented west to east, designed to confirm the traces of the closest known faults (the Poppel and Rauw Faults). Where possible, small explosive charges were used as vibration sources; vibrator vehicles were required in built-up areas. Vertical seismic profiles were carried out in the Dessel-1 and Mol-1 boreholes to correlate the seismic data, expressed as a function of time, with the borehole data, expressed as a function of depth. This survey was accompanied by a reinterpretation and, in some cases, by a reprocessing of old seismic profiles acquired among others during the three-dimensional seismic survey carried out in the southern sector of the nuclear zone in 1978.

Magnitude Logarithmic measure of the amplitude of an earthquake. (A variation of one unit on the open Richter scale corresponds to an amplitude 10 times greater.) The Chile earthquake of 1960 is the strongest ever recorded, with a magnitude of 8.5.

Intensity Measure of the effects of an earthquake based on a description of damage to built structures and to the ground surface. The MSK scale ranges from I to XII.

The data gathered from the 96-ON seismic reflection survey are still being interpreted, but the following can already be stated.

- The profiles obtained have a vertical and horizontal resolution of several metres, which should make it possible to detect any fault with a throw of more than 5 metres.
- No fault with a vertical throw of more than 5 metres seems to affect the Boom Clay beneath and in the immediate vicinity of the Mol–Dessel nuclear zone.
- Numerous flexures appear on the regional scale in the Tertiary formations and generally indicate deeper and hence older faults that have not affected the Boom Clay.
- It is possible to define a series of reflectors that coincide with specific bands of the Boom Clay (Fig. 3.10).
- However, the base and top of the Boom Clay do not correspond to clear reflections, owing to the gradual nature of the transitions between the base and top parts of the host formation (made up of silty or sandy clay) and the sandy-argillaceous formations above and below.

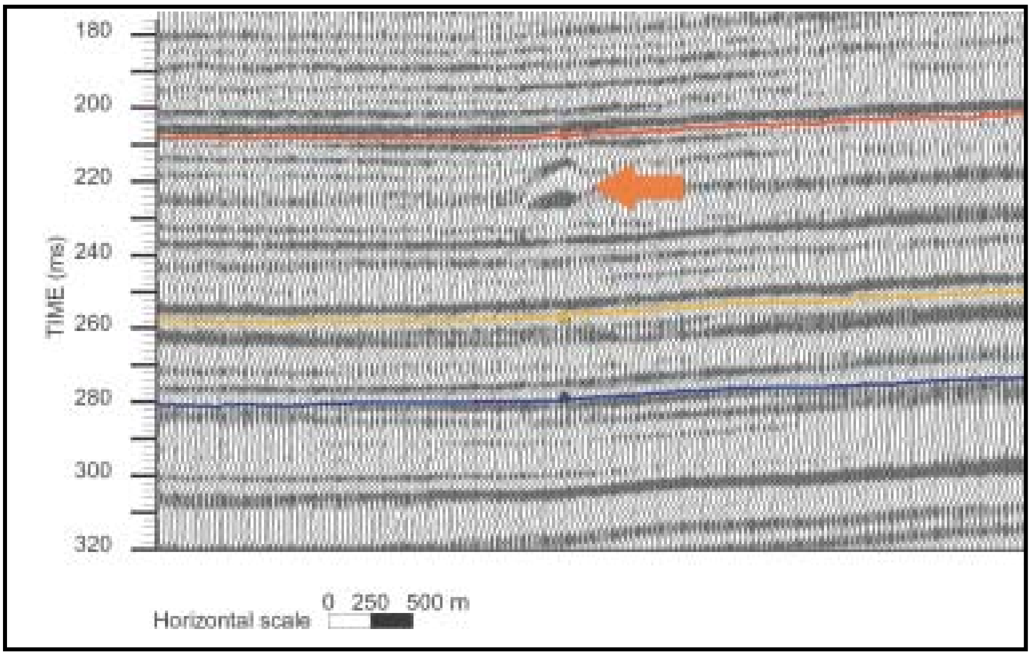


Figure 3.10 Detail of the signal obtained by seismic reflection in the Boom Clay (in red, the base of the transition zone; in yellow, the double band; in blue, the base of the Terhagen Member; in orange, the reflections generated by the HADES underground research facility).

Finally, although there is geothermal potential at great depth within certain Carboniferous, Cretaceous, and Triassic formations on a regional scale, this is not due to volcanic activity within the Campine Basin.

3.2.2.3 Integrated interpretation

In future, the results of all of the geophysical data obtained both within boreholes and from the surface will be combined to provide an integrated and coherent global picture of the geology of the Boom Clay beneath and around the Mol–Dessel nuclear zone. Appropriate seismic processing (inversion, petro-acoustic modelling) and laboratory calibration should make it possible to obtain a spatial distribution of certain petro-physical properties, such as porosity, sand content, and saturation in fluids, along existing seismic profiles. There will also be a systematic analysis of the location of samples relative to the lithostratigraphy of the Boom Clay. This is in order, first, to improve the interpretation of the data on the homogeneity or heterogeneity of the Boom Clay at different scales, and, second, to ensure the traceability of information.

The integrated and coherent understanding (i.e., an understanding in which the results of the investigations of the various earth science disciplines will be tested against one another) that will result from these studies will assist in identifying the effective thickness and the homogeneity of the host formation towards the characteristics and parameters controlling radionuclide migration within it.

3.2.3 Hydrogeology of the Boom Clay and its environment

The hydrogeological characterisation of the Boom Clay and its surrounding aquifers is important in so far as the hydrogeology represents the inescapable interface between the host formation and the biosphere, where the radiological impact of the radionuclide releases from the repository is assessed. The study zone covers all of northeastern Belgium—the Campine—and concerns five large hydrogeological units that encompass the Boom Clay to a depth of some 600 metres.

Aquifer A saturated permeable geological unit containing quantities of water that can be exploited.

Aquitard A geological unit that is sufficiently permeable to allow the passage of large quantities of water but, unlike aquifers, this passage takes place over extensive zones and over very long periods of time. Aquitards cannot be exploited because of their low hydraulic conductivity.

3.2.3.1 Definition of hydrogeological units

Hydrographically, the Campine belongs as much to the Meuse Basin as it does to the Schelde. The region around the Mol–Dessel nuclear zone is drained to the northeast by the Molse Nete, the Kleine Nete and its tributaries, the Desselse Nete and the Witte Nete, the Wamp and the Aa, and to the northwest by the Mark and the Grote Beek. All of these rivers belong to the Schelde Basin.

The thick sedimentary cover of the Tertiary and Quaternary in northeastern Belgium is made up of superposed sandy and clayey layers that rest on the Cretaceous basement that is slightly inclined towards the northeast. It is, therefore, easy to imagine a group of aquifer units bounded by aquitards consisting of argillaceous formations, provided the latter are large enough. These aquifers, which increase in depth towards the north, are also confined there, whereas they outcrop in the south. Their hydraulic characteristics are typically those of a porous medium.

A schematic of the sequence of aquifers and aquitards of the Tertiary and Quaternary in the Campine Basin is shown in Figure 3.11. The central section of the figure shows how these units are conceptualised for regional hydrogeological modelling (see Section 3.2.4.2). The Neogene Aquifer, which schematically groups all of the sands overlying the Boom Clay, is the most important in the region. Its thickness, which frequently exceeds 100 metres, its high hydraulic conductivity, and its low salinity make it an aquifer that is in great demand for the supply of drinking water. It is the second most important aquifer in Belgium in this respect, and the main one in the northeast of the country. It actually consists of a series of three more or less permeable sub-units.

- The first sub-unit contains a group of perched aquifers made up of Quaternary sediments and more or less isolated by argillaceous deposits (Aquifer of the Campine, Meuse terraces, alluvial deposits of the Meuse valley).
- The second sub-unit is made up of fluvial or estuarial sands of the Rhine, which consist of the Sands of Mol, Brasschaat, and Merksplas. A part of the Poederlee Sands and the sands of the Kasterlee Formation could be added at its base. This sub-unit is often referred to as the Pliocene Aquifer, owing to the dominance of deposits of Pliocene age. The Pliocene Aquifer is more or less isolated from the underlying aquifer by the presence of clay in layers or lenses (in the Lillo and Kattendijk Formations to the west and the Kasterlee Formation to the east). This semi-permeable group, or Lillo-Kasterlee Aquitard, contributes to a slight differentiation in the hydraulic regimes of the two surrounding aquifers, but without preventing slow communication between them.
- The third sub-unit is the most important in the region. This is the Miocene Aquifer, occasionally referred to as the Diestian Aquifer, which comprises a small part of the Kasterlee Sands and the Kattendijk, Diest, Dessel, Berchem, and Bolderberg Sands. The Voort Sands and possibly those of Eigenbilzen are also sometimes included; these are in very good hydraulic contact but their hydraulic conductivities are significantly lower.

The Boom Clay plays a cardinal role in the regional hydrogeological system by separating the Neogene Aquifer from the underlying aquifers. However, the various aquifers come into direct contact in the region of Diest and Averbode, owing to erosion of the clay (the Diest erosion channel). In the northeast, the graben-related (but external to the Roermond Graben) faults affecting the Boom Clay could also influence the hydraulic behaviour of the superposed aquifers, but their effect is not known. This zone also coincides with the watershed of the Meuse and Schelde Basins.

Beneath the Boom Clay is the Lower-Rupelian Aquifer, frequently referred to as the Ruisbroek-Berg Aquifer (and referred to as Under-Rupelian Aquifer in the figures that follow). This aquifer is little used for groundwater supply because of its poor yield due to low hydraulic conductivity, its heterogeneity, and its high salinity (though still within the standards for drinking water in Flanders). It quite clearly overlies the Ursel and Asse Clays, at least in the western part of the region. Next comes the Lede-Brussel Aquifer, which, like that of the Lower-Rupelian, is little used in the region owing to its high salinity and low hydraulic conductivity. The Lede-Brussel Aquifer in turn overlies argillaceous formations of the Ieper Group, which form a good hydraulic barrier. Finally, the layers of fine sands of the

Landenian form a thin aquifer, which is virtually unexploited owing to its poor yield and excessive salinity. The aquifers beneath the Landenian are of only limited interest at this stage. Only the Maastrichtian seems to be still exploited locally, despite the high mineral content of its water.

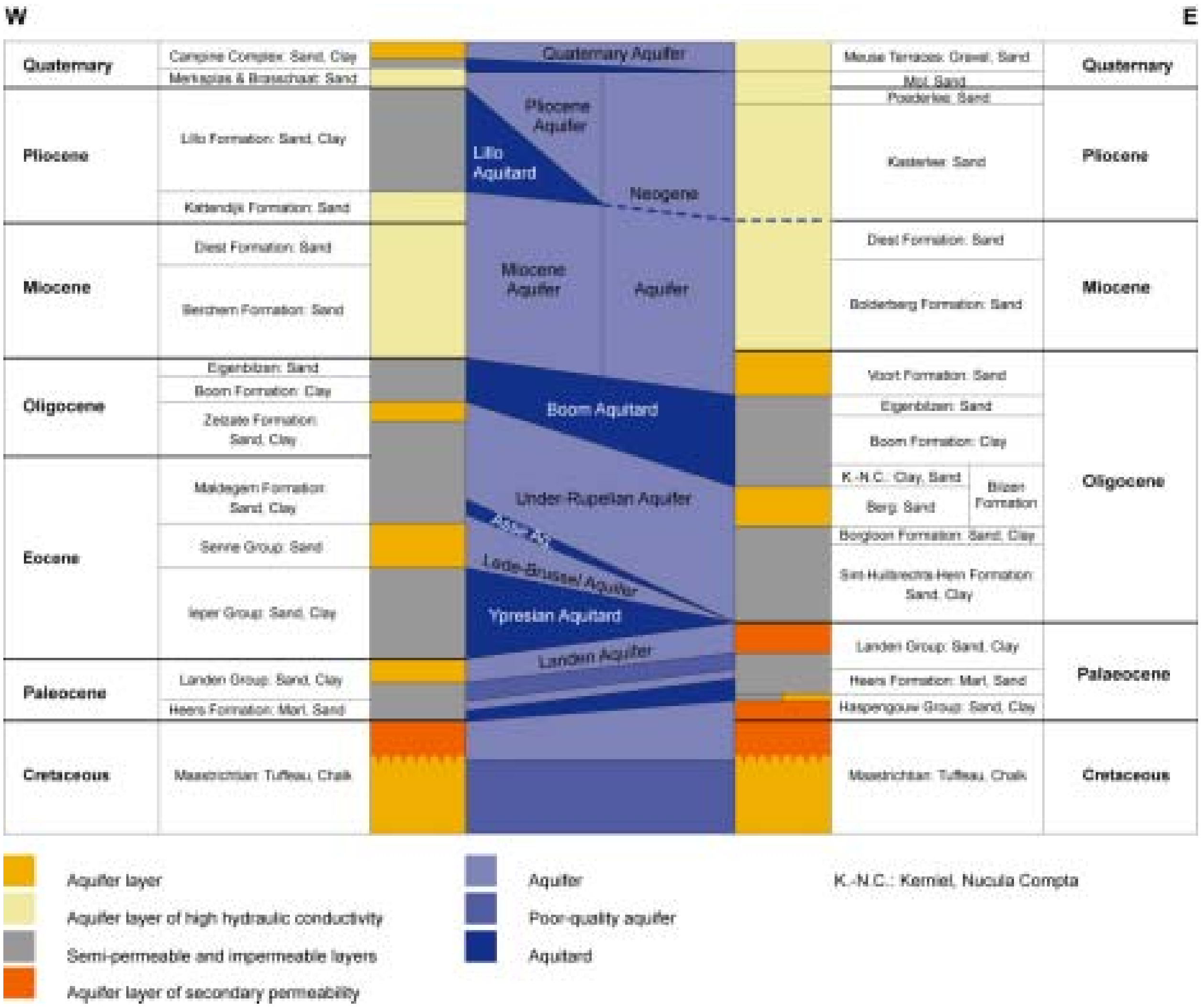


Figure 3.11 Schematic succession (stratigraphy, lithology, and representation for the modelling) of the aquifers and aquitards of the Campine Basin from the Cretaceous to the Quaternary.

3.2.3.2 Piezometric changes

Since the start of the Belgian programme, a total of 130 piezometers have been installed at 40 separate locations—mainly in the Neogene Aquifer—to measure groundwater levels and their changes over time, and so determine the hydraulic gradients and the direction of groundwater flows (Fig. 3.12). These measurements are also used to calibrate hydrogeological models (see Section 3.2.4).

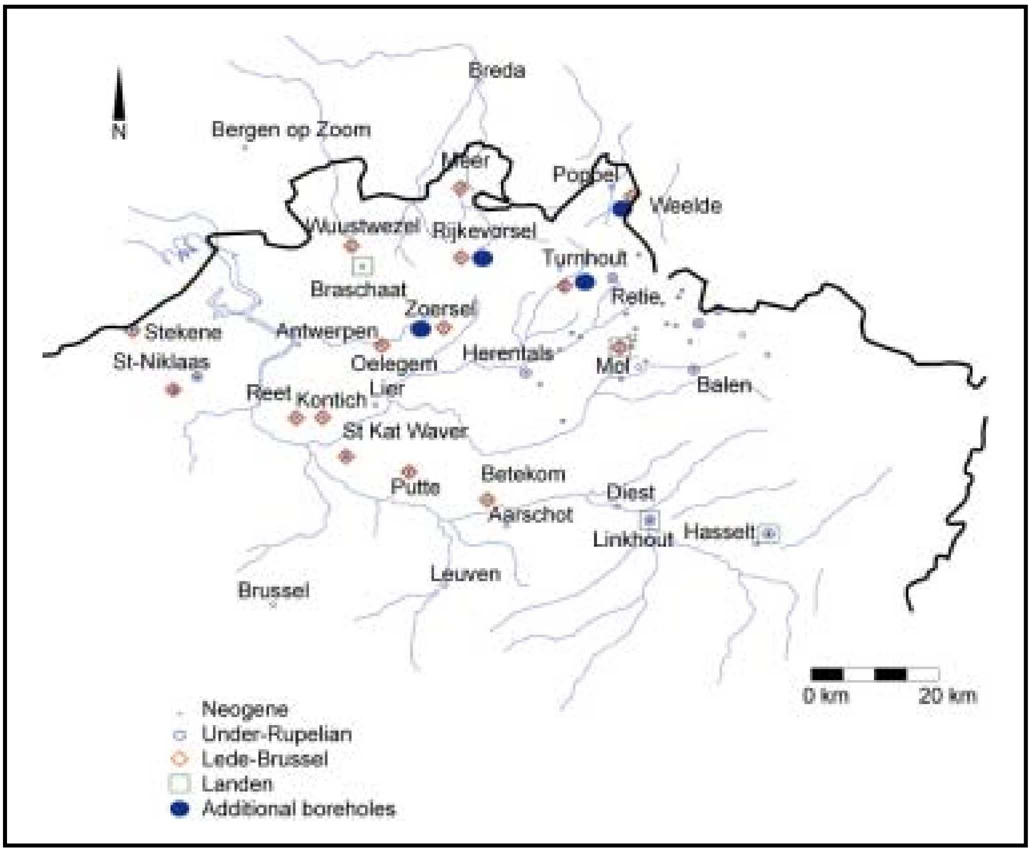


Figure 3.12 Location of the piezometers, including the four boreholes of the last hydrogeological campaign (see Section 3.2.3.4).

The changes in piezometric levels of the Neogene Aquifer (Fig. 3.13) display the typical seasonal variations of groundwater tables. The lowest levels are observed between April and November, with a minimum in July and August; the highest levels are recorded between November and April, almost reaching ground level. The amplitude of these variations is about two to three metres, but may be less at depth, especially where fine or clayey sand beds are present. The Lower-Rupelian and Lede-Brussel Aquifers are confined and so display virtually no seasonal fluctuations. They are, however, more sensitive to any other form of disturbance such as groundwater pumping. Figure 3.13 shows a small but constant fall in levels over time, indicating a groundwater deficit in the Lower-Rupelian Aquifer.

Leakage Slow transfer of water with an essentially vertical component between two aquifers across a semi-permeable layer (aquitard). This transfer is a function, first, of the pressure gradient between the two aquifers, and, second, of the hydraulic parameters of the aquitard and of its thickness.

The phreatic regime of the Neogene Aquifer means that the water flows within it are conditioned by the topography and the hydrographic network, e.g., by the watershed of the Schelde and Meuse Basins. The flow direction is essentially east to west, following the leakage direction of the Schelde Basin. This same general tendency to flow westwards is also found in the deeper aquifers, without their being influenced by the topographical surface. Vertical leakage within the aquitards is generally downwards. Upward leakage through the Boom Clay is observed at Oelegem, near Antwerpen, however, and should be observed along its line of outcrop, as is shown by the modelling results (see Section 3.2.4). The vertical gradient through the Boom Clay, i.e., the difference in water pressure between the Neogene and Lower-Rupelian Aquifers, is generally 2 metres of water per 100 metres of clay. It is more pronounced in the east, in the region of the border faults of the Roermond Graben, suggesting a loss of water along the faults. The potential influence of these faults on the piezometry has been studied by means of variants of the hydrogeological model (see Section 3.2.4.2).

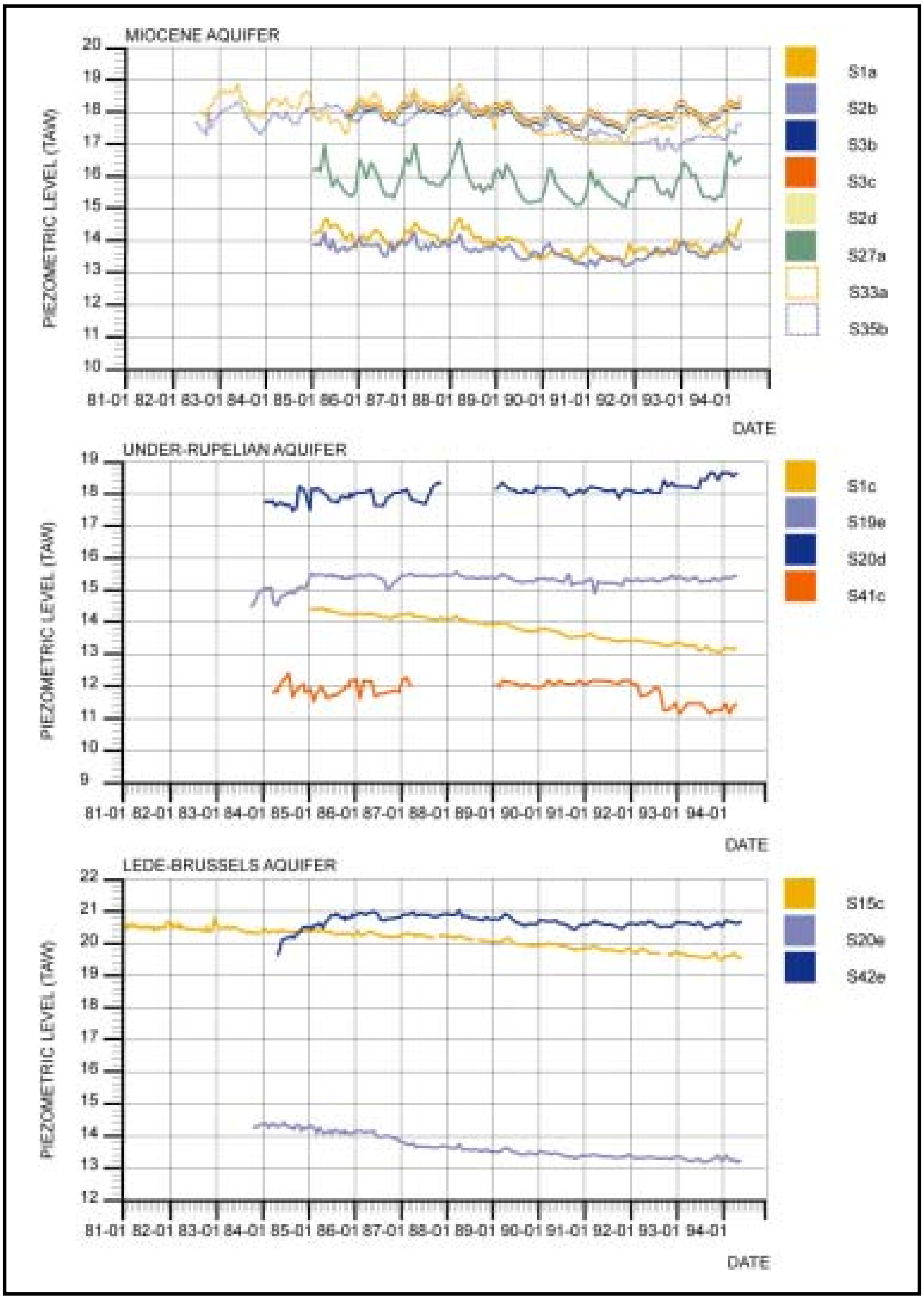


Figure 3.13 Changes in the levels of a number of piezometers representative of the Miocene Aquifer (Diest Sands, Neogene), the Lower-Rupelian Aquifer, and the Lede-Brussel Aquifer.

3.2.3.3 Hydrogeochemistry of the aquifers

Geochemical analyses of the groundwaters within the Neogene Aquifer show that they are of the calcium carbonate type in the upper part of the aquifer, i.e., with a clear predominance of the HCO_3^- and CO_3^{2-} anions and of the Ca^{2+} cation. At depth, they become progressively of the sodium carbonate type (enrichment in Na^+ and K^+ at the expense of Ca^{2+}), while retaining an acid and low alkaline character. Overall, pH and salinity increase with depth in the Neogene Aquifer, whereas the redox potential decreases. The Lower-Rupelian and Lede-Brussel Aquifers are significantly richer in chlorides and dissolved salts. In the Mol–Dessel nuclear zone, a marked resemblance can be seen between the chemical composition of the groundwater in the Lower-Rupelian Aquifer and that of the interstitial water of the Boom Clay (higher mineral content and alkalinity than the Neogene). Hydrogeochemical data for the Lower-Rupelian and Lede-Brussel Aquifers suggest a mixing with fresher and more recent groundwater towards the southeast and a mixing with seawater from the north of the studied region.

The study of the chemical balances controlling the composition of the groundwaters indicates that those of the Lower-Rupelian and Lede-Brussel Aquifers are in general in equilibrium with the mineral phase of the formations, whereas the groundwaters of the Berchem Formation at the base of the Neogene Aquifer are not.

The age of the groundwaters found here, as calculated from ^{14}C measurements, is relatively recent, certainly within 40 000 years. The age of the waters of the Neogene ranges from several thousand years to over 10 000 years in the lowest bands. The groundwaters below the Boom Clay are older, ranging from 15 000 to 37 000 years for the Lower-Rupelian Aquifer, but only from 6 000 to 27 000 years for the Lede-Brussel Aquifer. This difference may be attributable to the greater hydraulic conductivity of the latter aquifer. The relative youth of these waters has been confirmed by a study of isotopic disequilibriums within the uranium family.

The groundwaters of the Lower-Rupelian and Lede-Brussel Aquifers display a tendency to increase in heavy oxygen isotopes towards the north, seeming to indicate that a portion of the groundwater present was recharged under colder palaeoclimatic conditions.

3.2.3.4 Hydrodynamic characterisation

To improve the geometrical and hydrodynamic characterisation of the aquifers beneath the host formation—a characterisation that represents one of the major uncertainties of hydrogeological modelling—a series of hydraulic injection tests and wireline loggings was carried out in four boreholes (Zoersel, Rijkevorsel, Turnhout, and Weelde) purposedly drilled between 1996 and 1998, and supplemented by laboratory tests on cores from two of these boreholes. Hydraulic tests were also carried out in the Dessel-1 and Mol-1 boreholes, intended for geophysical measurements (see Section 3.2.2.2).

Particular efforts were made to confirm the value of the hydraulic conductivity of the Boom Clay measured on core samples (centimetre scale), by means of in situ tests (injection or slug tests) in boreholes (metre scale), or by using the small lateral shaft to the HADES underground research facility (Fig. 3.25) as a large-scale permeameter (decametre scale), and to assess the anisotropy of hydraulic conductivity within this formation. As part of the assessment of the vertical variability of the parameters controlling radionuclide migration, a profile of hydraulic conductivities over the full thickness of the Boom Clay was established from cores taken from the Mol-1 borehole. This profile clearly shows the different behaviour of the Belsele-Waas Member compared with the other members of the Boom Formation (Fig. 3.39), indirectly confirming the continuous qualitative profile of hydraulic conductivity obtained by nuclear magnetic resonance logging in the Mol-1 borehole.

All of these investigations yield coherent values of hydraulic conductivity of the order of 10^{-12} m·s^{-1} for the most argillaceous part of the formation. Table 3.5 lists the values of hydraulic conductivity for the different members of the Boom Formation. The ratio between the horizontal and vertical conductivities, as determined in the laboratory from permeameter cell measurements, is about 2 for the Putte and Terhagen Members. It is very variable in the Belsele-Waas Member. The total porosity of the Boom Clay is close to 30 to 40 %.

Table 3.5 Best estimates and confidence intervals for the horizontal and vertical hydraulic conductivities of the Boom Clay.

	Horizontal hydraulic conductivity K_h [m·s^{-1}]		**Vertical hydraulic conductivity K_v [m·s^{-1}]**	
Transition zone	10^{-11}	10^{-12} to 10^{-10}	$6 \cdot 10^{-12}$	10^{-12} to 10^{-10}
Putte and Terhagen Members	$6 \cdot 10^{-12}$	$3 \cdot 10^{-12}$ to 10^{-11}	$3 \cdot 10^{-12}$	$7 \cdot 10^{-13}$ to $7 \cdot 10^{-12}$
Belsele-Waas Member	10^{-10}	10^{-12} to 10^{-9}	$6 \cdot 10^{-11}$	10^{-12} to 10^{-9}

The best estimates of the hydraulic conductivities of the other units taken into account by the model are respectively 2 to $3 \cdot 10^{-4}$ m·s^{-1} for the Neogene Aquifer, $7 \cdot 10^{-13}$ to $3 \cdot 10^{-7}$ m·s^{-1} (K_v) and $2 \cdot 10^{-12}$ to $2 \cdot 10^{-7}$ m·s^{-1} (K_h) for the Lower-Rupelian Aquifer, 10^{-13} to 10^{-11} m·s^{-1} for the Asse Aquitard, and $5 \cdot 10^{-11}$ to $5 \cdot 10^{-6}$ m·s^{-1} for the Lede-Brussel Aquifer.

3.2.3.5 Outlook

The future of the research and development programme on the characterisation of the hydrogeological units will be based primarily on the needs for modelling and sensitivity analyses. As well as the maintenance and measurements of the regional piezometer network, particular attention will have to be paid to assessing the large-scale hydraulic conductivity of the Boom Clay, especially the influence of faults (the western border of the Roermond Graben) and the, albeit very limited, possibility of advective flow in the Boom Clay itself, mainly within the silty double band. Consideration will also have to be given to the following essential matters:

- improving the knowledge of the geometry and hydraulic properties of the units beneath the Boom Clay;

- assessing the role of the semi-permeable layers or lenses in the Neogene Aquifer;
- identifying the origin, age, and evolution of the groundwaters in order to improve the understanding of the hydrogeological system and confirm the results of hydrodynamic modelling as far as possible.

3.2.4 Hydrogeological modelling

Hydrogeological modelling aims to acquire a good understanding of the underground hydraulic regime in and around the Boom Clay in the region of the Mol–Dessel nuclear zone. It attempts to reproduce the observations made by the hydrogeological characterisation programme, in particular the piezometric levels and the hydraulic conductivities, using mathematical models to obtain indications of the groundwater flows in the various geological formations and of the hydraulic balances between them. Hydrogeological modelling is conducted in close, permanent, and iterative association with geological and hydrogeological characterisation.

The roles of hydrogeological modelling were defined during the period covered by the SAFIR 2 report. The results of studies into the hydrodynamic and migration characteristics of the Boom Clay clearly demonstrated that the advective component (movement along water pressure gradients) of the migration of the species in solution through this formation is negligible relative to the diffusive component (movement along chemical gradients) (see Section 3.5). However, the advective component is fundamental in the aquifers surrounding the Boom Clay, which, it will be remembered, are not part of the disposal system but perform the long-term safety function of dilution and dispersion. The demonstration of the local nature of radionuclide discharge from the repository meant that it was possible to focus, as regards migration, on the hydrogeology of the immediate vicinity of the Mol–Dessel nuclear zone (local model). The regional model, therefore, has been used mainly to assist in understanding the overall hydrogeological system and to provide some indication of the likely perturbations in this system and of their effects, especially following natural or anthropogenic changes in climate conditions (warming or cooling) or an increase in the rates of groundwater pumping.

In terms of the techniques used, a new calculation code has been introduced (MODFLOW) and the initial regional model has been subdivided into three models. These consider increasingly smaller spatial and geological scales, so as to refine the influence of the hydraulic and hydrogeological conditions in the Mol–Dessel nuclear zone.

The regional model covers nearly the whole of northeastern Belgium over an area of 7 000 km^2, and simulates all of the hydrogeological units (aquifers and aquitards) globally located between the sandy top of the Ieper Group and the Quaternary Aquifer (Fig. 3.14). Because of its geographical coverage, the model can explicitly allow for certain natural boundary conditions, such as the extent of the aquifers and how they are recharged (rainwater infiltration) in the outcrop zones. It also serves as a basis for determining the boundary conditions of the two other models. The use of natural boundaries to the regional model makes it the most suitable of the three for simulating changes in climatic and geological conditions.

The sub-regional model covers a total area of some 1 500 km^2 and the local model an area of 300 km^2, centred on the Mol–Dessel nuclear zone (Fig. 3.14). These two models are primarily intended to study groundwater flows in the Neogene Aquifer in greater detail, as it is this unit that forms the interface between the geological barrier and the biosphere. Because they provide a more accurate estimate of the preferential pathways of radionuclide migration towards the biosphere, they have been used to show the local nature of the groundwater discharges. It is therefore the local model that is used directly to assess radionuclide migration within safety assessments (see Section 4.3).

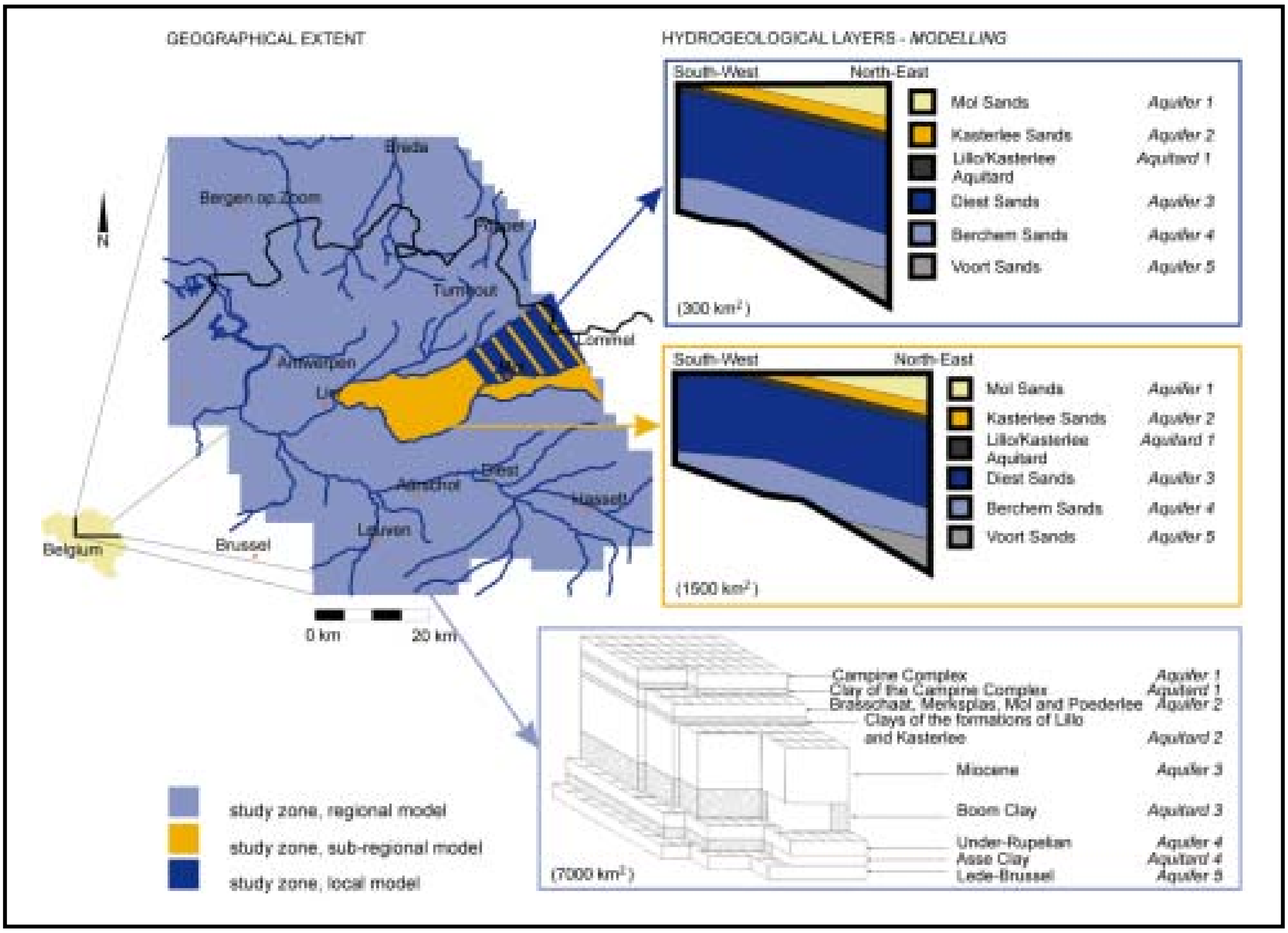


Figure 3.14 Geographical and geological delimitation of the three hydrogeological models.

3.2.4.1 Mathematical models, resolution methods, and calculation codes

All of the mathematical models used in the hydrogeological modelling consider steady-state conditions, that is to say that the simulated groundwater flows do not change explicitly with time. Major changes in the flow directions and flow rates that could result from, say, climatic or geological change are evaluated by means of simulations (variants) in which the conditions and the values of the model parameters are modified. This makes it possible to build a picture of the impact of such changes, and this is consistent with the general approach to assessing long-term radiological safety, which does not aim to predict precisely how the disposal system and its environment will evolve.

The code used for the regional model is the NEWSAM code. The MODFLOW code has also been used in more recent exercises, in particular for developing the sub-regional and local models. These two codes, developed in the academic world and verified by numerous users, apply a numerical method based on finite differences to simulate flows in a large-scale, multi-layer hydrogeological system. They assume essentially two-dimensional flows parallel to the aquifers, and contact between them across the aquitards by vertical leakage under static conditions. Sub-regional and local modelling has been used to produce a quasi three-dimensional simulation of the Neogene Aquifer by dividing it into a series of sub-layers (aquifers and aquitards) that are coupled vertically.

3.2.4.2 Regional model

The starting point for studies of the regional hydrogeological system in the past ten years has been the model created with the NEWSAM code developed in 1984. It is the 1994 version of this model, constructed with the aid of the same code, that is currently used (Fig. 3.14). In this latest version, the Neogene Aquifer is divided into three distinct sub-units (the Quaternary, Pliocene, and Miocene Aquifers), separated by two thin argillaceous layers with a relatively low flow resistance, allowing hydraulic contact between the various aquifer units.

Several simulations of the hydrogeological system have been conducted with the revised regional model to obtain a good representation of the piezometric levels in the Neogene Aquifer (Fig. 3.15); it is this version that has been used as a reference for the subsequent simulations.

Since the continuity of the clay layer formed by the Lillo-Kasterlee Aquitard in the western part of the studied region is not known, a number of variants of the reference model have been tested to analyse the efficiency of the separation of the Pliocene and Miocene Aquifers. They have shown that, on the regional scale, a reduction in the isolating capacity of the aquitard has no major effect on the piezometry of the aquifers in question.

The modelling results show that, for the Lower-Rupelian and Lede-Brussel Aquifers, the recharge, which is mainly from the south, is diverted into east–west groundwater flows, and that an additional source of recharge is possible. The technique of analysing variants of the regional reference model has also been used to improve the representative nature of the modelling results of the aquifers beneath the Boom Aquitard, whose piezometry, when calculated using the reference version of the model, did not agree with observations (Fig. 3.16).

For the aquifers underlying the Boom Clay, several types of variants that allow for additional groundwater recharge (so as to raise the piezometric level) have been studied. The most important of these are the following:

- an increase in the global hydraulic conductivity of the Boom Clay;

- the existence of a local hydraulic contact between the Miocene and Lower-Rupelian Aquifers via faults located to the east. These faults have been modelled as zones with a higher hydraulic conductivity (although the piezometry measured in these zones indicates a greater hydraulic gradient across the Boom Clay).

The results obtained with these variants still underestimate the piezometry of the Lower-Rupelian and Lede-Brussel Aquifers. The closest agreement between the results of modelling and observations has been obtained when the Boom Clay is given a hydraulic conductivity of 10^{-10} $m{\cdot}s^{-1}$, which is significantly greater than that measured in the area of the Mol–Dessel nuclear zone.

Sensitivity studies have also been used to demonstrate the significant impact of minor changes in the hydraulic conductivity of the Lower-Rupelian Aquifer on the calculated piezometry. At this stage in the study, therefore, it was clear that the uncertainties surrounding the geometry and hydraulic properties of the deep aquifers were such that it was impossible to continue with the modelling exercise, and in particular the process of calibration, without an additional effort being made to characterise these aquifers. This realisation led to the drilling of the four boreholes at Zoersel, Rijkevorsel, Turnhout, and Weelde (see Section 3.2.3.4). The results of this hydrogeological reconnaissance survey will be used for the new iteration of regional modelling planned for 2002.

Given the timescales that need to be considered in the safety assessments of a project such as the deep disposal of radioactive waste, it is important to consider possible changes to the disposal system and its environment over long periods of time, especially changes in the groundwater flows. The effect of the various possible changes on the hydraulic gradient through the Boom Clay and on the mean flow rate in the Neogene Aquifer has been investigated using the 1984 and 1994 models. The changes that have been analysed (Table 3.6) take account of variations in the hydrogeological system in response to natural climatic variations, and in particular consider changes in infiltration and sea level, as well as the resulting incision of rivers. The results of these studies have not yet been fully integrated into the analyses of scenarios required for long-term radiological safety assessments (see Chapter 4).

Table 3.6 Overview of the possible hydrogeological changes considered.

Change	Impact on the hydrogeological system
Climate	Increased precipitation and resulting infiltration Reduction in rainfall (drought)
Eustasy	Rise in sea level
Submarine erosion	Erosion channel reaching the Boom Clay
Denudation	General lowering of the topography
Fluvial erosion	Incision of rivers
Diapirism	Decompaction of the Boom Clay

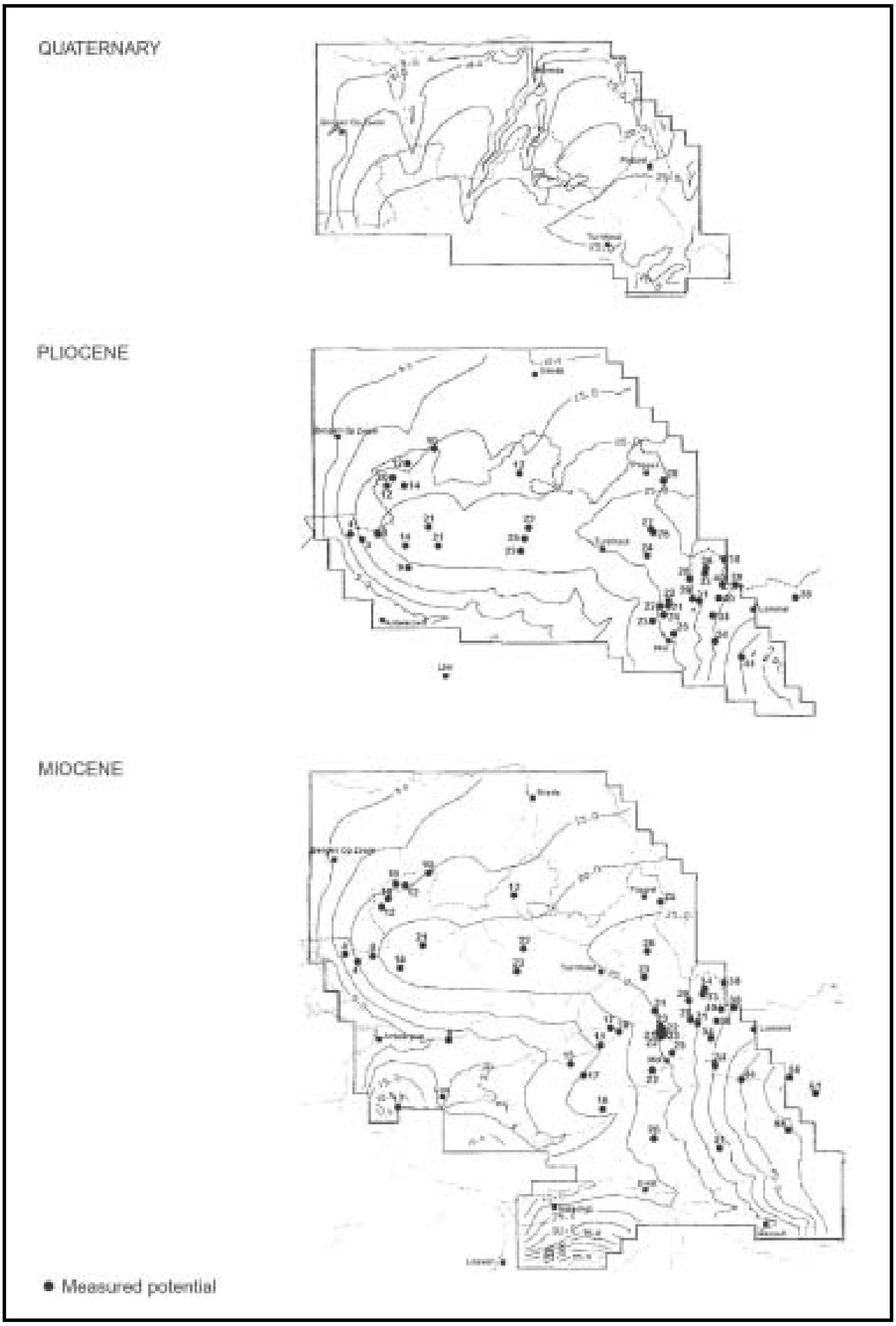


Figure 3.15 Piezometry of the Neogene Aquifers calculated with the reference version of the regional model (potentials measured at precise points can be compared with the calculated lines of isopotential).

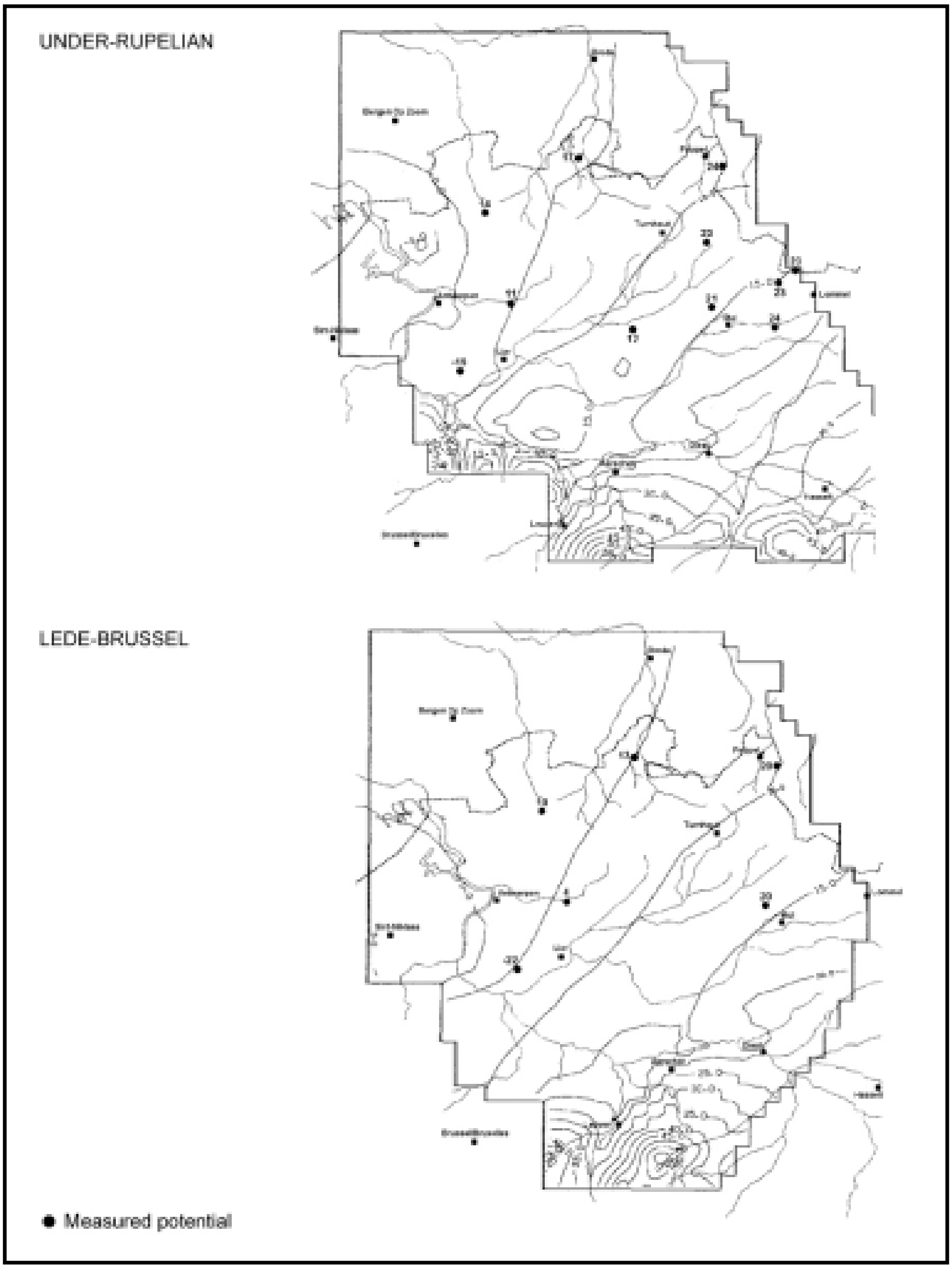
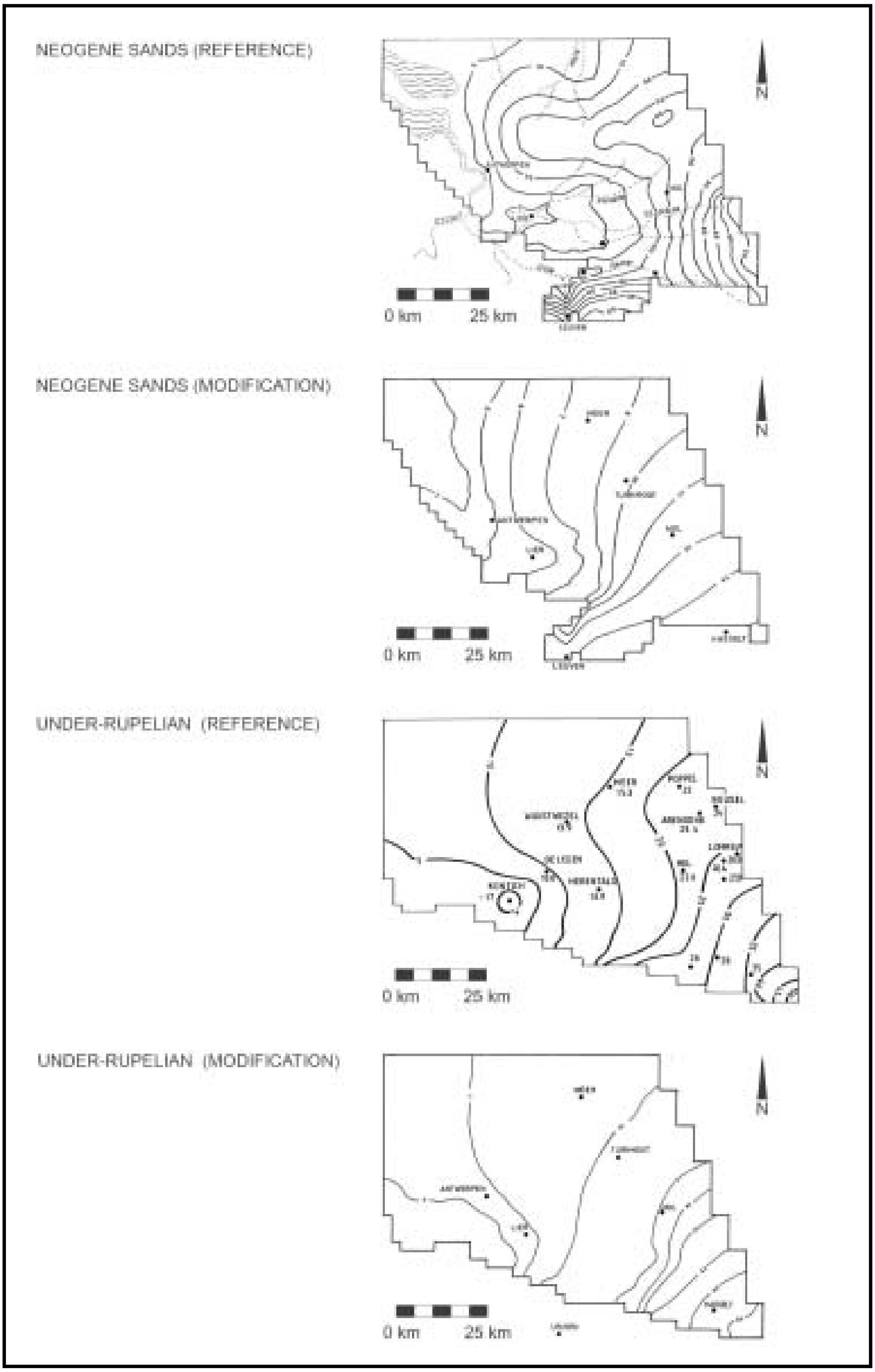


Figure 3.16 Piezometry of the Lower-Rupelian and Lede-Brussel Aquifers calculated with the reference version of the regional model (potentials measured at precise points can be compared with the calculated lines of isopotential).



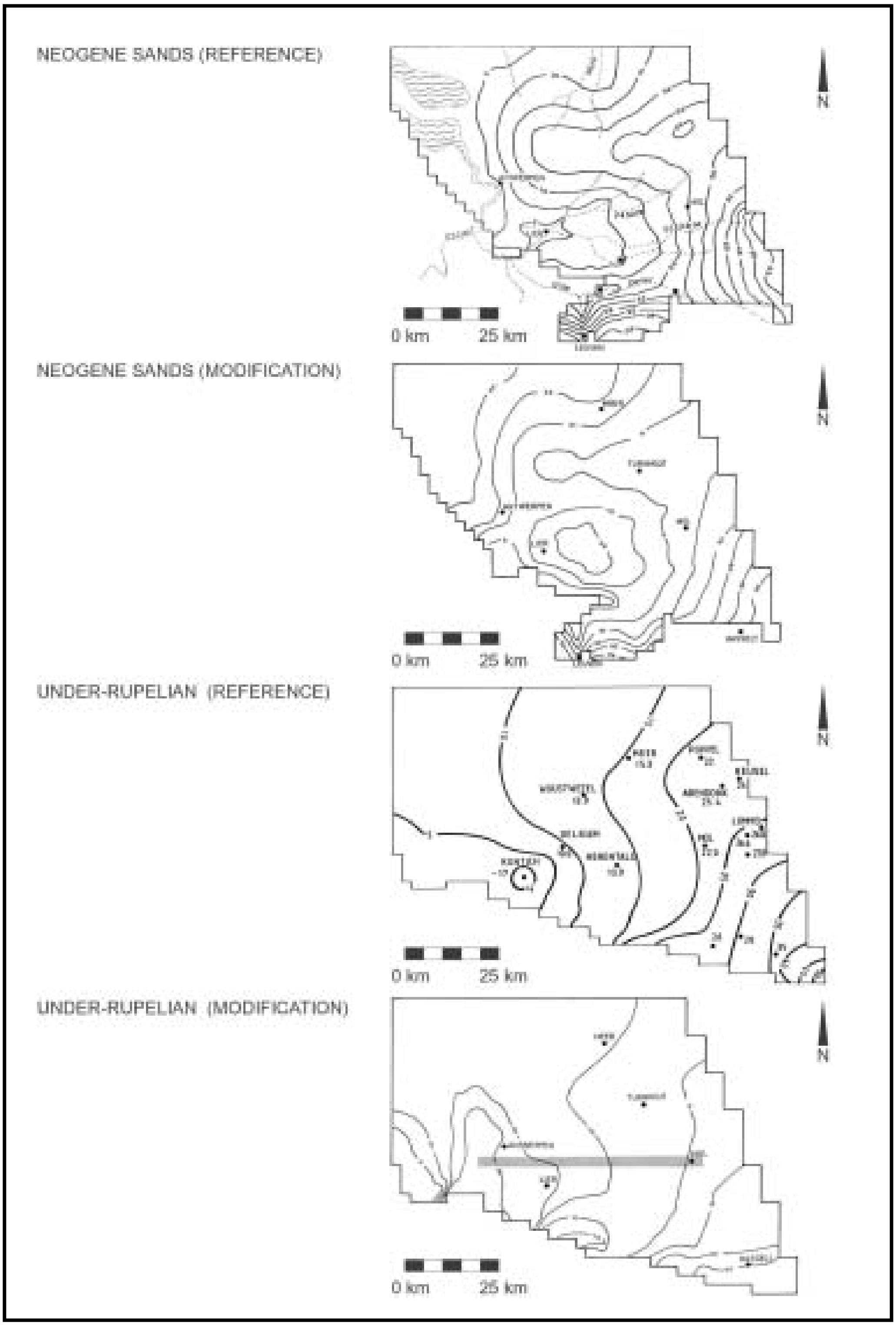
NEOGENE SANDS (REFERENCE)

NEOGENE SANDS (MODIFICATION)

UNDER-RUPELIAN (REFERENCE)

UNDER-RUPELIAN (MODIFICATION)

Figure 3.17 Impact of a decrease in infiltration by a factor of 3 (drought) on the piezometry of the Neogene and Lower-Rupelian Aquifers.


NEOGENE SANDS (REFERENCE)

NEOGENE SANDS (MODIFICATION)

UNDER-RUPELIAN (REFERENCE)

UNDER-RUPELIAN (MODIFICATION)

Figure 3.18 Impact of a fluvial erosion (schematised by the grey channel) caused by a drop in sea level on the piezometry of the Neogene and Lower-Rupelian Aquifers.

The simulations have been made maintaining steady-state conditions and based on the present hydrographic network, in the belief that introducing changes to this network in the model would have been too arbitrary. They indicate that it is the drought and fluvial erosion scenarios that induce the biggest changes in groundwater flow.

- In a drought scenario, piezometric levels fall sharply and in a differential pattern over the studied region, leading to smaller gradients within the Neogene Aquifer (Fig. 3.17). Levels fall less sharply in the Lower-Rupelian Aquifer. Generally speaking, the aquifers are only drained over a very small section of their outcrop zone, upstream of the rivers and near to their confluence with the Schelde, i.e., to the west. The leakage through the Boom Clay is reduced and even reversed; thus, ascending movements are observed in the Mol–Dessel region.
- In the river erosion scenario, which is caused by a drop in sea level, the groundwater flow is significantly affected by the local drop in piezometry caused by incision of the rivers (Fig. 3.18).
- Phenomena that make the Boom Clay locally more permeable, such as the presence of an underwater erosion channel or decompaction of the clay by diapirism, have only a local impact on groundwater flow.

The likely natural evolution of the climate over the next 125 000 years, when translated into consequent variations in infiltration, could reverse the vertical hydraulic gradient across the Boom Clay and replace it with a value that is identical or double, depending on the harshness of the climate, and could reduce the groundwater flow rate in the aquifers.

It has not yet been possible to undertake a more detailed investigation into these climatic phenomena and to assess their impact on the hydrogeological system, as such an exercise would involve

- either a new conceptualisation of the hydrogeological system beyond the geographical boundaries of the existing regional model;
- or too arbitrary an adaptation to the geometry of the hydrogeological units and the hydrographic network. This would apply in the event of a glaciation, with either the presence of permanently frozen soil (permafrost), which would modify the infiltration, or an extension of the ice cap as far as the north of Belgium. While this latter scenario may appear less likely, it could create significant sub-glacial erosion, which, when combined with the other climatic effects, would greatly modify the landscape and the hydrogeological environment. Allowing for continental subsidence or uplift would also entail a redefinition of the hydrographic network.

3.2.4.3 Sub-regional model

In order to study the Neogene Aquifer in greater detail, a model that is smaller in area (1 500 km^2) and with a reduced number of hydrogeological units was extracted from the regional model. This sub-regional model divides the Neogene Aquifer into five aquifers that are in good hydraulic contact with one another (Fig. 3.14). Its lower boundary is formed by the top of the Boom Aquitard.

Unlike the simulations of the regional model, those of the sub-regional model have used the new MODFLOW code. Because the sub-regional model considers more aquifers in the Neogene than the regional model and because their modelling is quasi three-dimensional, the boundary conditions of the regional model could not be used directly. Natural watercourses, such as the Grote Nete and the Kleine Nete, as well as the watershed between the Schelde and Meuse Basins, were therefore used as boundary conditions as far as possible.

The sub-regional model was used, on the one hand, to calculate the piezometry of the Neogene Aquifer (Fig. 3.19) and to compare it with measured values and, on the other hand, to study—by means of a sensitivity analysis—the following three types of uncertainty concerning this aquifer:

- the role of the Lillo-Kasterlee Aquitard (see also the regional model);
- the presence or absence of Quaternary deposits (studied indirectly by modifying the properties of the Mol Sands);
- the influence of the rivers on the piezometry.

The two main conclusions of these studies are that the piezometry is influenced primarily by changes in hydraulic connectivity between the rivers and the groundwater system, and that it is the presence of the argillaceous layer of Lillo-Kasterlee between the Diest and the Kasterlee Sands that affects the flows more than its actual thickness.

The sub-regional model has also been used to produce an initial plot of the trajectories of the water particles leaving the Boom Clay above a potential disposal facility located beneath the Mol–Dessel nuclear zone (a process known as ‘particle tracking’). The results show that all of the trajectories are directed towards the Witte Nete and the Kleine Nete; they therefore remain relatively close to the reference site. (These results are consistent with those of particle tracking carried out using the local model (Fig. 3.20).) The presence of the argillaceous layer of Lillo-Kasterlee retards the flows and modifies the vertical trajectories whilst still retaining the same discharge areas.

3.2.4.4 Local model

The conclusions about the local character of the discharge areas obtained with the sub-regional model have led to developing a local model allowing a more detailed discretisation and that can be used for the migration calculations needed for the assessments of the long-term radiological safety (see Section 4.3.2). This model uses the same calculation code as the sub-regional model and considers the same number of hydrogeological units and the same boundary conditions. Water particle tracking from the reference site beneath the Mol–Dessel nuclear zone confirms the local character of the possible groundwater discharge areas (Fig. 3.20). This is one of the important hydrogeological findings of the 1990–2000 research and development programme.

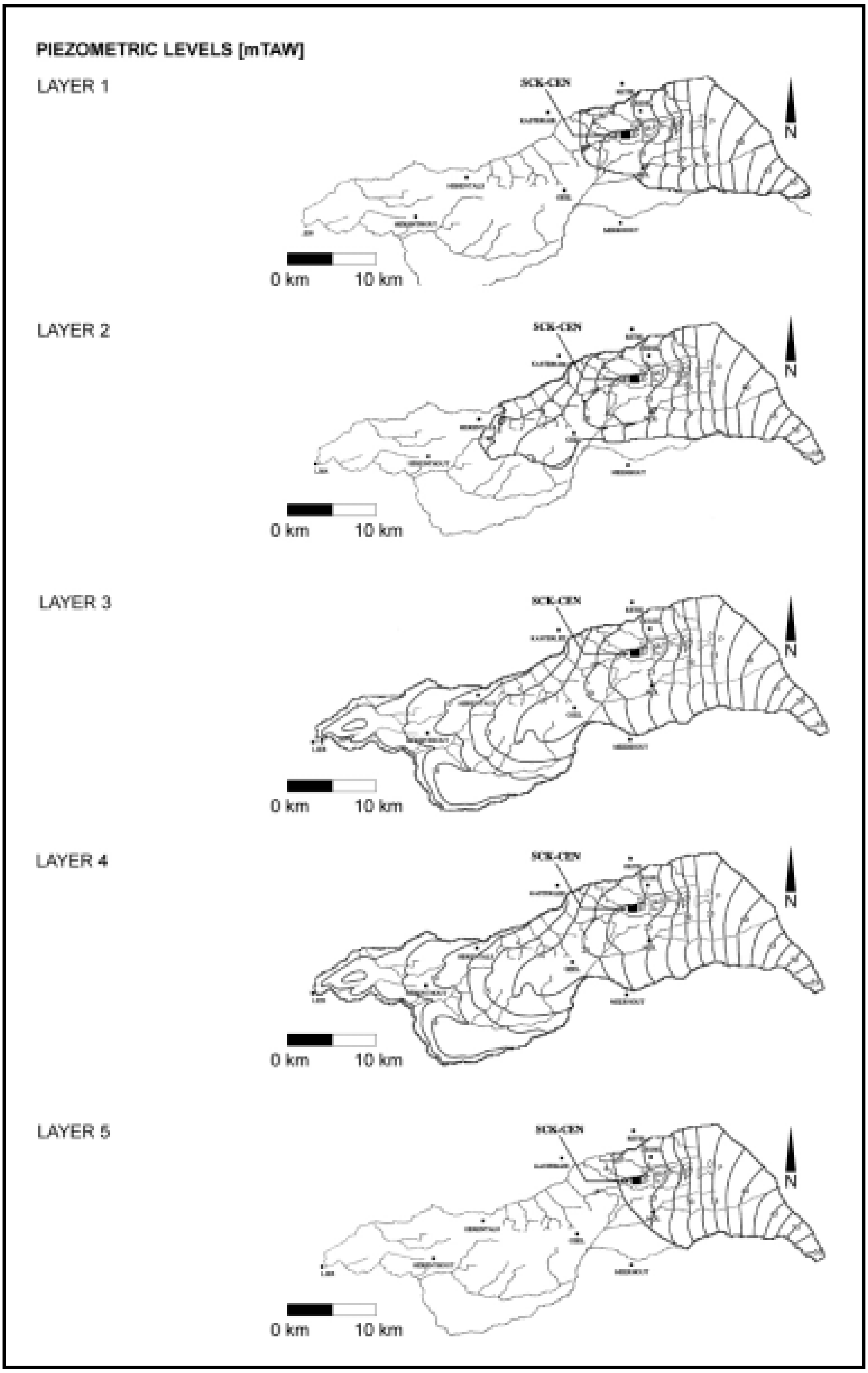


Figure 3.19 Piezometry obtained with the sub-regional model.

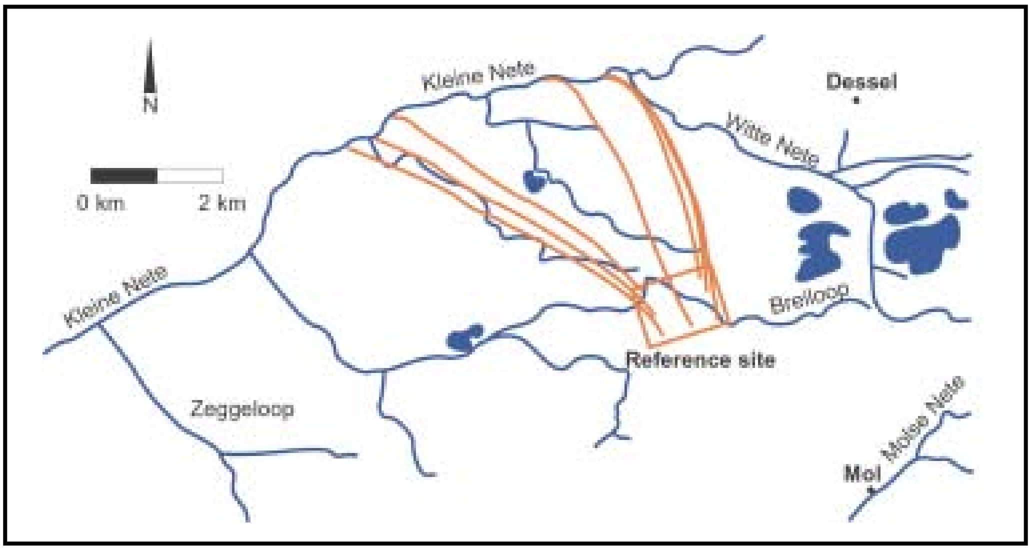


Figure 3.20 Determination of trajectories of water particles leaving from the top of the reference site, using the local model.

3.2.4.5 Outlook and recommendations

In an effort to resolve the inconsistency found between the values of hydraulic conductivity of the Boom Clay measured locally (10^{-12} m·s^{-1}) and those produced by one of the variants of the regional hydrogeological modelling (10^{-10} m·s^{-1}—see Section 3.2.4.2), and to make decisions on future work within the geological and hydrogeological characterisation programme of the host formation and its environment, priority has been given to pursuing the hydrogeological modelling and, in particular, to the following:

- to develop a new version of the hydrogeological regional model, so as to take explicit account of the aquitards and to consider the vertical and horizontal heterogeneities in the hydraulic conductivity within the Boom Clay and the Lower-Rupelian Aquifer, which will necessitate an assessment of the possibilities of extrapolating measurements of hydraulic conductivity both in space and from one scale to another;
- to improve the calibration of the regional model with a better assessment of the groundwater recharge and discharge (precipitation, groundwater pumping, short-circuit via fault), which should also make it possible to analyse the sensitivity of the hydrogeological system to disturbances induced by groundwater pumping;
- to reinforce the integration of the three hydrogeological models, most notably by harmonising the calculation codes and boundary conditions;
- to confirm the influence of the rivers on the groundwater flow throughout the whole of the Neogene Aquifer and the local character of discharge from the Boom Clay to the biosphere.

Hydrogeochemical studies could also help verify the results of the hydrogeological models. Ultimately, a link between groundwater flow and hydrogeochemistry is conceivable.

Finally, it is important to continue to investigate the potential changes in groundwater flow and hydrogeochemistry of the Boom Clay and its adjacent formations that could result from changes in the environment. This includes climate changes that could lead to glacial or periglacial conditions (permafrost) or, contrastingly, to warming and, hence, to a rise in sea level. Such changes are an essential aspect in evaluating the long-term evolution scenarios of the disposal system and its environment, an evaluation that is necessary for the safety assessments (see Chapter 4).

3.3 The deep disposal facility

The reference design of the deep disposal facility developed in Belgium, that is to say the geometry of the facility and the materials used to construct it, has been adapted among others as a result of the recommendations of the SAFIR Evaluation Commission (1990). Its principal design remit is to comply with all of the safety requirements, especially with the long-term safety functions (see Section 2.2), and with the requirements specific to the host formation at the proposed depth, in this case the Boom Clay beneath the Mol–Dessel nuclear zone (see Section 2.3). It should be reminded that this site is not a disposal site, but a reference site for methodological research and development (see Section 3.2.1). Initially, the reference design—which is still evolving—applied only to the vitrified waste. This is because up until the time of the SAFIR report, it was assumed that all of the spent fuel would be reprocessed, and the vitrified waste was thus considered to be the most demanding waste class in radiological and thermal terms. It is therefore for this waste that the reference design is now most advanced. In the meantime, certain of its aspects have undergone preliminary modifications to take account of the characteristics of spent fuel. Finally, the repository design will be extended to other classes, or sets of classes, of waste belonging to the geological group in a future phase. Ultimately, the repository, assumed to be unique, will incorporate the disposal solutions developed for each class, or coherent group of classes, of waste.

The concept of the deep disposal facility is based, as far as possible, on the use of known materials and standard techniques, which have been adequately proven. This does not prejudge the development of new technologies or improvements in technologies that are currently available. The concept is also based on the experience that has been gathered during the construction of the HADES underground research facility in the Boom Clay at Mol, and will derive significant benefits from the lessons learned from the PRACLAY full-scale demonstration experiment that is now being prepared. The design of the repository and its operation are of course two aspects that are also very closely linked.

3.3.1 Reference design

The reference design of the deep disposal facility developed in Belgium envisages a network of rectilinear galleries situated in the median plane of the Boom Clay layer, at about 240 metres below ground level. Access to the underground is by two shafts with an effective diameter of approximately 6 metres and linked at their base by a connecting gallery, 400 metres long and 2 metres in diameter, which also serves as an escape gallery.

The shafts give access to two main galleries 3.5 metres in diameter, which lie at right angles to the connecting gallery. The disposal galleries that will receive the radioactive waste branch out from this H-shaped vertebral column. Those for the vitrified waste and spent fuel are on one side of the connecting gallery, and those for the other waste in the geological group are on the other side. The plane of the disposal facility follows the dip of the clay layer, which is 1 to 2 %. This can be done by aligning the main galleries (or the disposal galleries) on this dip and arranging the disposal galleries (or the main galleries) horizontally on the median plane of the clay layer, or by a combination of these two options. The choice of gallery and shaft diameters is based on practical, technical, economic, and safety considerations: they must be large enough to convey construction and backfill materials as well as waste packages at the desired rate, but must not be oversized, as this would unnecessarily enlarge the clay zone disturbed by excavation and increase the costs of construction and backfilling.

The current reference design displays a number of fundamental differences compared with the design proposed in the SAFIR report:

- the *separation* of the vitrified waste and the spent fuel from the other waste in the geological group to prevent physico-chemical interactions which could compromise long-term safety (increased robustness), to facilitate thermal calculations and, more generally, to allow more convincing safety assessments;
- the use of *watertight packagings* of sufficient corrosion resistance for the primary packages of vitrified waste (the overpacks, Fig. 3.21) and the spent fuel so as to ensure the function of physical containment of the radionuclides, at least during the thermal phase of the disposal system. This avoids the need to consider the complex interactions between components and radionuclide migration under a temperature gradient (increased robustness). The thermal phase—the period during which the presence of the waste increases the temperature in the near field by more than ten degrees above that of the undisturbed clay (approximately 16°C)—is around 300 years for the vitrified waste and around 2 000 years for the spent fuel of the UO_2 type.
- the use of watertight and corrosion resistant *disposal tubes* to facilitate the emplacement of the vitrified waste and spent fuel into the disposal galleries.

The reference design for the *vitrified waste* (Fig. 3.22) assumes that there will be a total of 3 915 packages to be disposed of: 420 packages produced under existing reprocessing contracts, plus 3 495 packages that would be produced under any new contracts. (If Belgium ultimately rejects the reprocessing option, then the existing vitrified waste will be incorporated into the disposal solution developed for the spent fuel.) To accommodate the vitrified waste, the two main galleries service eight disposal galleries that are at right angles to them, each 800 metres long and 2 metres in diameter. The disposal galleries are divided into three segments: two segments of 200 metres outside the main galleries and one of 400 metres between them. The first disposal gallery is 100 metres from the connecting gallery, with subsequent disposal galleries spaced at 40-metre intervals. This is to limit the mean temperature increase in the Neogene Aquifer, which ONDRAF/NIRAS has set at 6°C in the absence of any regulatory norm. The facility intended to receive the vitrified waste would thus occupy an area of 0.224 km^2.

Figure 3.21 The overpack used for demonstrations in the HADES–PRACLAY hall.

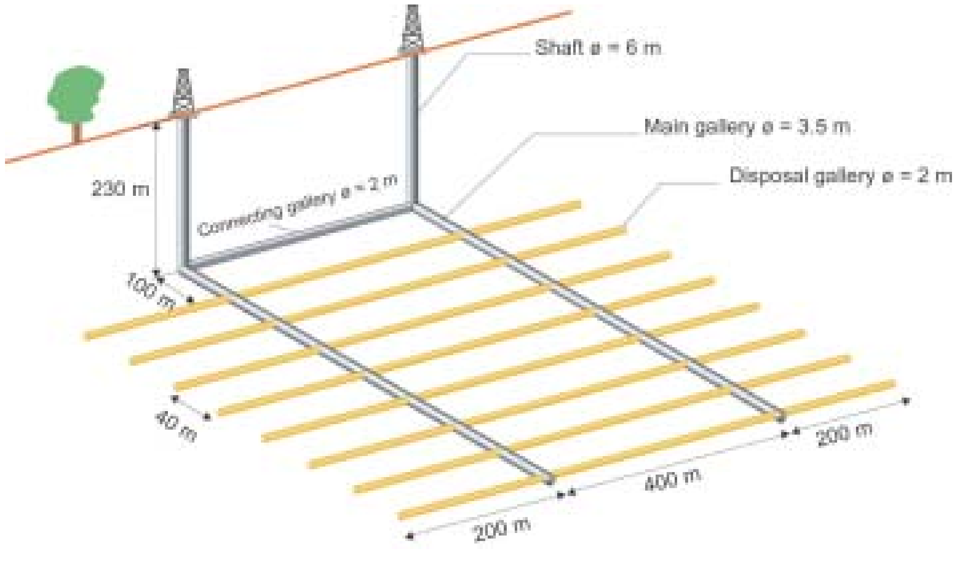


Figure 3.22 The reference design of the deep repository for the vitrified waste.

Under the principle of multiple barriers, the design of the disposal galleries provides for a succession of concentric envelopes—the engineered barriers—around the waste packages (Fig. 3.23). The primary package of vitrified waste, surrounded by its overpack, is pushed into a stainless steel tube, the 'disposal tube', aligned on the centreline of the gallery. On each end of the overpack are four wheels mounted at 90°, with permanent brakes to prevent the package moving accidentally; a gripper head is also mounted axially at one end of the overpack. Each disposal tube consists of sections hermetically welded to one another so that water cannot come into contact with the waste, as this could generate steam and induce unwanted geochemical phenomena. The space between the tube and the gallery lining has previously been filled with a backfill material that is naturally or, if necessary, artificially hydrated before the waste is placed, to make it swell and fill the interstitial voids. This material consists of prefabricated segments made from a mixture of bentonitic clay ('FoCa' clay, a natural product containing 80 % swelling clay), sand, and graphite. The latter is to improve the thermal conductivity of the mixture, and so dissipate the heat emitted by the waste more efficiently. Each tube is closed at the main gallery end by a temporary shield protecting the operators from the ionising radiation emitted by the packages already in place, and that can be replaced by a permanent system when the tube is full. Once full, each disposal gallery is sealed with a plug made from FoCa swelling clay and with a second plug designed to resist the swelling pressure. The gallery walls and the walls of the access shafts are lined with prefabricated concrete segments.

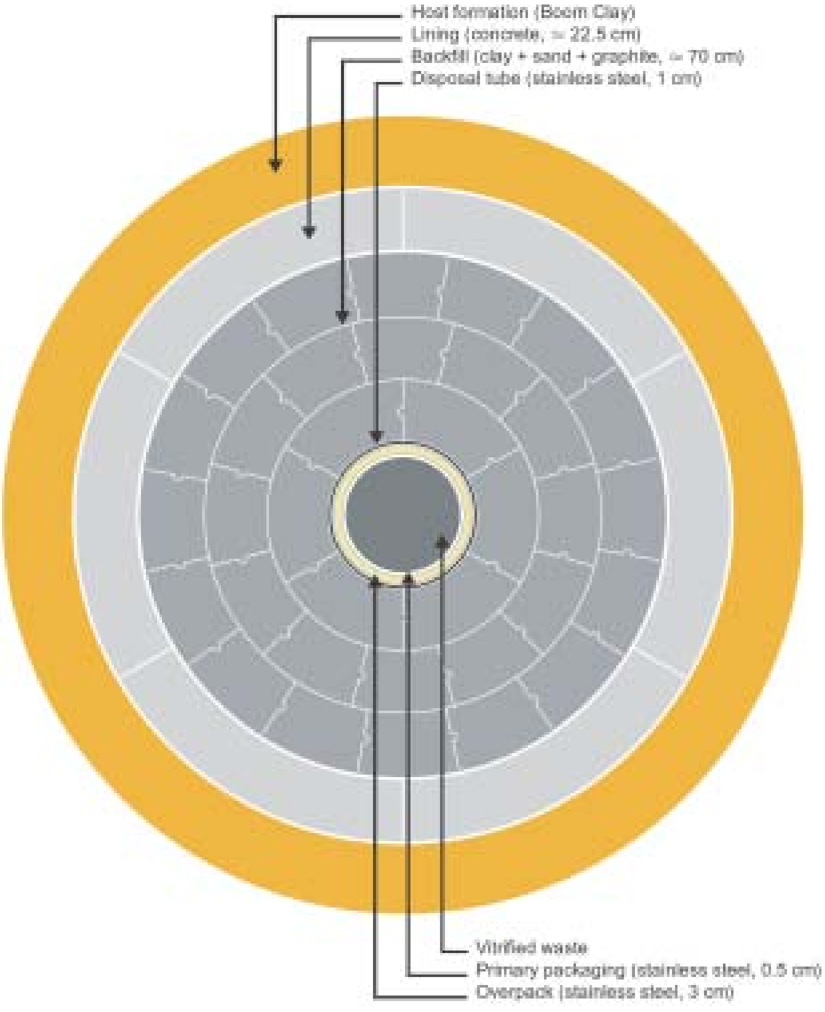


Figure 3.23 Transverse section through a disposal gallery for vitrified waste, showing the multiple-barrier principle.

The reference design for the disposal of *spent fuel* (Fig. 3.24) is an adaptation of the design developed for the vitrified waste to make it suitable for longer packages (5 metres instead of 1.6 metre), that cool down more slowly. The main differences are as follows:

- the angle between the main galleries and the disposal galleries has been reduced (from 90° to 45°) to allow longer packages to be transferred into the disposal galleries;
- the gallery spacing has been increased (from 40 to 110 metres) to prevent the mean temperature in the Neogene Aquifer rising by more than 6°C;
- to prevent the mean temperature in the Neogene Aquifer rising by more than 6°C, the number of packages has been adjusted to the acceptable thermal output per metre of gallery (four disposal tubes per gallery for the UO_2 fuel arranged in a square about the centreline of the gallery; a single disposal tube for the MOX fuel, aligned on the centreline of the gallery).

The gallery network would comprise 800 metres of galleries for the 420 overpacks of vitrified waste and 10.8 km of galleries for the 9859 spent fuel assemblies that are anticipated. It would thus cover an area of approximately 1.3 km^2.

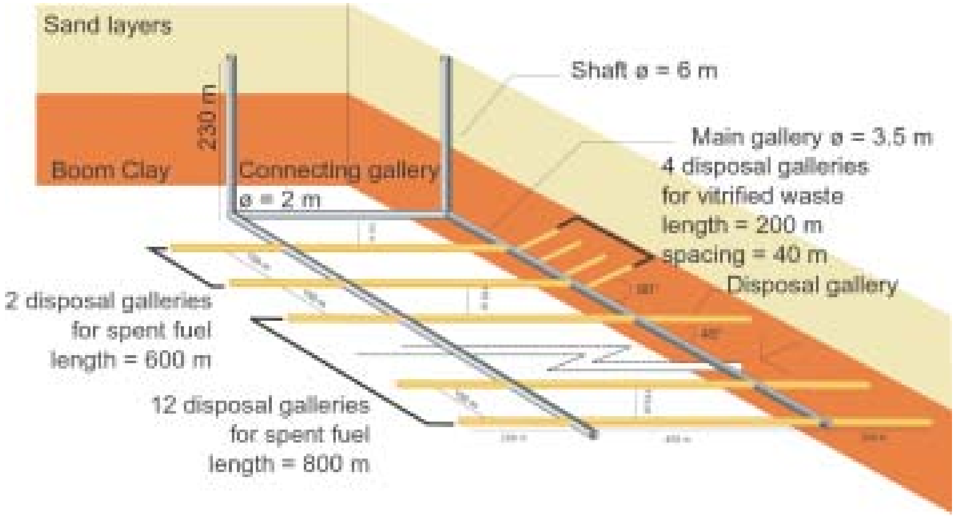


Figure 3.24 The reference design of the deep repository for the spent fuel.

Each of the various components of the disposal facility performs one or more functions (Table 3.7 and Fig. 2.5). Some perform the safety functions of 'physical containment' and 'delaying and spreading the releases', and are taken into account in long-term radiological safety assessments, i.e., assessments of radiological safety after the closure of the repository (see Chapter 4). These are the waste matrices (glass and UO_2), that retard the leaching (function *R1*), the overpack for its watertightness (function *C1*), and the material used to seal off the galleries and shafts, that retains the radionuclides (function *R2*). Other components such as the primary package and the disposal tube play a safety role that is short term and potentially longer term, but their actual contribution to safety is disregarded in safety assessments, representing instead a 'safety reserve'. Finally, some components are needed to ensure the mechanical stability of the repository and, hence, of the host formation (the gallery and shaft lining, and the backfill material), to facilitate waste emplacement (the disposal tube), or to ensure operational safety (the closure and shielding system for the disposal tube). None of these components should adversely affect the performance of the others, especially the performance of components that have long-term safety functions. Each must, for example, be chemically and mechanically compatible with the others, i.e., it must not aid corrosion or induce significant mechanical disturbances. Finally, no component should, by its presence, assist radionuclide migration towards the biosphere.

Finally, the *other category C waste*, which emits less heat, and the *category B waste* would be stacked by classes in galleries 3 to 6 metres in diameter, with the voids between the packages being backfilled with concrete or a similar material. The number of packages allowed for each section of gallery will depend, among other things, on the need to limit the mean temperature increase in the Neogene Aquifer to 6°C and on the total percentage of voids in the waste. This should not exceed 20 % so as to minimise the risk of the packages and backfill material being crushed by the pressure of the host formation, and, hence, of the host formation becoming unevenly decompacted, leading to disturbances.

3.3.2 The various operational stages of a deep repository

The operational phase of a deep repository can be divided into four main stages: construction, operation (i.e., the placing of the waste, followed possibly by a waiting period prior to closure), closure, and institutional control. During the operational phase, the disposal system must be closely *monitored*.

Monitoring the disposal system involves continuously or discretely observing and measuring—on the surface and underground—parameters that can be used to assess the behaviour of certain components of the system and to assess the impact of the repository and its operation on the environment. Monitoring must not affect the functioning of the repository barriers, and should not increase the risk of human intrusion. It starts before the construction of the repository and continues until the end of the institutional control phase. It has four primary objectives:

- before the construction of the repository, *to determine the parameters and natural processes characterising the disposal site and its environment*. This characterisation must ultimately indicate the changes to the initial situation induced by the presence and operation of the repository, and it must provide the information necessary to develop the repository design and to assess safety.
- from the start of the construction phase until the end of the institutional control phase, to assess the impact of the disposal facility on the operating personnel, the public, and the environment, so as to ensure compliance with applicable standards and make adjustments as necessary, and, also, *to compare the behaviour of the various components of the disposal system with the behaviours assumed* in the assessments carried out.

Table 3.7 Main characteristics of the repository design proposed for the vitrified waste, functions performed by the main components safety for the normal-evolution scenario (C1 = watertightness; R1 = resistance to leaching; R2 = diffusion and retention. Access

Components	Characteristics	Safety functions during phases				Other functions
		operational	thermal	isolat.	geolog.	
Matrix	Borosilicate glass	Immobilisation	–	R1	R1	Retrievability
Primary packaging (welded cylindrical container)	Stainless steel AISI 309 height: 1.34 m external ∅: 43 cm thickness: 5 mm mean filled weight: 492 kg	Mechanical strength	C1	R2	–	Handling Retrievability
Overpack (welded cylindrical container fitted with 2 × 4 wheels at 90°)	Stainless steel AISI 316L hMo height: 1.58 m internal ∅: 46 cm thickness: 30 mm mean filled weight: 1000 kg	Radiological protection	C1	R2	–	Handling Reduction of thermal power per unit length Retrievability
Disposal tube	Stainless steel AISI 316L hMo internal ∅: 55 cm thickness: 10 mm length of sections: 3 to 4 m length of segments: 200 or 400 m	–	C1	R2	–	Emplacement Retrievability
Backfill material of the disposal galleries	Prefabricated blocks made from a mixture of bentonitic FoCa swelling clay (60 %), sand (35 %), and graphite (5 %)	Mechanical stability	C2	R2	R2	Heat dissipation
Lining of the disposal galleries	Prefabricated concrete segments min. thickness: 22.5 cm	Mechanical stability	–	–	–	Retrievability
Galleries	Int. ∅ total length spacing [m]					
disposal	2 8 × 800 40	–	–	–	–	Disposal
main	3.5 380 400	–	–	–	–	Handling
connecting	2 400 –	–	–	–	–	Connection
Access shafts	Internal ∅: 6 m	–	–	–	–	Handling
Access shaft lining	Concrete and asphalt	Mechanical stability Watertightness	–	–	–	Retrievability
Backfill material of the rest of the facility	Mixture of FoCa swelling clay and sand	Mechanical stability	C2	R2	R2	–
Gallery and shaft sealing material	Mixture of FoCa swelling clay and sand Concrete	Radiological protection Mechanical strength	C2	R2	R2	–

of the disposal system and of its environment and, in bold print, functions considered in assessments of the long-term radiological limitation L is not shown.)

Principal studies still needed to confirm the reference design
confirm that the durability of the glass matrix largely exceeds 10 000 years
–
confirm the choice of material and determine its minimum thickness decide on the method of manufacture, the place and method of filling, as well as the method of closure by welding decide on whether a filling material such as glass frit will have to be introduced between the primary packaging and the overpack to improve heat dissipation and enhance mechanical strength while minimising degradation of the glass matrix decide on whether the use of overpacks makes it possible to declare the repository a ‘zone not controlled for radiological contamination’
confirm the choice of the material and the dimensional characteristics of the sections, and establish tolerances examine how to place the sections and then weld them with perfect alignment, and how to close the end of the tube verify whether, up to the end of the period of retrievability (if any), the tube will stay watertight and free from distortion, and whether it will retain an internal surface smooth and clean enough for an overpack to be pushed or pulled over a distance of 200 metres decide on the space to be left between two overpacks to allow them to expand freely under the effect of heat study the behaviour of the tube under the effect of the thermal load and an uneven swelling pressure decide whether a filling material (glass frit) must be introduced between the overpack and the tube
confirm the choice of backfill material and optimise its composition so as to obtain adequate thermal conductivity and an even swelling pressure that will neither disturb the clay nor crush the tube determine the form (blocks, pellets, etc.) in which the backfill material will be handled in the galleries and how it will be placed study the risk of the filled tube sinking into the backfill material under its own weight study the kinetics of natural hydration and any use of artificial hydration to obtain the desired swelling pressure
confirm the choice of material, optimise its composition, and decide on the dimensions of the segments determine the maximum distance between the segments and the working face, and the over-excavation
establish an emergency escape plan determine the characteristics to be given to the connecting chambers between disposal galleries and main galleries confirm the minimum distance between the connecting gallery and the first disposal gallery confirm the diameter
–
–
confirm the choice of backfill material, optimise its composition, and decide how to place it
study the design and composition of the plugs for galleries and shafts

Safeguards
Requirements established by international treaties on the non-proliferation of fissile materials designed to prevent their diversion for any purpose. These requirements include specifically the accountability and traceability of fissile materials placed in a repository (see also Section 2.2.4).

- after several years or decades of operation, *to provide a decision platform* based on experience by making it possible to optimise those aspects of the design that still offer a certain amount of flexibility and presenting all of the parties concerned with concrete and convincing arguments whenever important decisions have to be taken, especially the decision to close the repository.
- for a repository containing large amounts of fissile materials, *to ensure*, in accordance with IAEA requirements on safeguards, *that these materials cannot be diverted.*

3.3.2.1 Construction

The construction of the HADES underground research facility beneath the SCK•CEN site at Mol dates from the 1970s and was part of the first research and development programme of SCK•CEN (1975–1979) relating to the disposal of category B and C waste. This programme mainly aimed to assess the extent to which it is possible to construct, at a depth of some 220 metres in the Boom Clay layer at Mol, a network of galleries of the type proposed for the disposal of waste packages so as to protect humans and the environment from radiation doses above those that are reasonably acceptable. These galleries were also required for conducting in situ experiments to accompany those carried out at the surface on samples taken during exploratory drilling.

In line with its mission of long-term management of radioactive waste, ONDRAF/NIRAS took over the SCK•CEN project in 1985 and confirmed the Boom Clay beneath the Mol site as the reference formation for its disposal programme, thus in particular for assessing new construction techniques. Started at that time, the extension of the underground facility is still in progress. It has shown that it is possible to safely excavate shafts in aquifer sands that have been frozen and to excavate the facilities needed for disposal into the Boom Clay without the need for freezing. Together with the results of long-term safety assessments, it has also highlighted the importance of limiting the disturbance of the clay by excavation, as clay is the main barrier to radionuclide migration. Work is now at the stage of technical and economic optimisation: it must culminate in the selection of an excavation process and a lining that are easy to use, safe, and economical. This process must also limit disturbances to the formation. At least part of this optimisation will take place during excavation of the galleries required for the PRACLAY demonstration project (see Section 3.3.3).

Changes in excavation and lining techniques

The construction of the HADES underground research facility (which is still ongoing) has seen five phases since 1980 (Figs. 3.25 and 3.26). These phases have mainly involved a simplification of the excavation techniques and changes in the type of lining; this has followed increases in the knowledge of the geomechanical behaviour of the clay. The whole facility is equipped with measuring instruments placed in the clay before the lining is emplaced, as well as instruments mounted on the lining itself to measure its deformation. The different types of lining also have apertures of various sizes to allow access to the clay for experimental purposes. Finally, the research facility is not in the middle of the Boom

Clay layer, but in its upper section, at a depth of 223 metres, this being a result of the geometrical characteristics envisaged for the repository design when construction began.

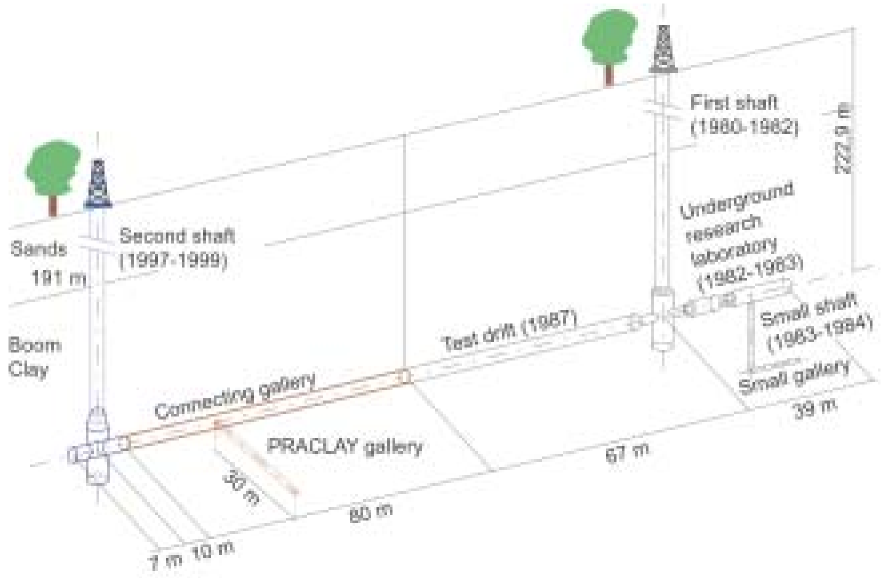


Figure 3.25 The HADES underground research facility. The excavation of the connecting gallery and of the PRACLAY gallery (in brown) is foreseen in, respectively, 2002 and 2006.

Figure 3.26 General views of the HADES underground research facility.

SCK•CEN took maximum precautions when constructing the *first access shaft* to the clay formation. This shaft was dug between 1980 and 1982 using pneumatic drills and shovels in soil previously frozen to a temperature between – 10 and – 15°C by 2 × 16 freezing tubes evenly arranged in two concentric circles. This standard procedure for excavating through aquifer sands was used, first, to hydraulically separate the shaft from the aquifer before installing the watertight lining (a sheet of polyethylene sandwiched between two 40-cm-thick layers of shotcrete) and, second, to ensure the geomechanical stability of the excavation in the sands and in the Boom Clay until the lining had been placed. The diameter to be excavated was fixed at 4.3 metres so as to produce an effective diameter of 2.65 metres minimum. The first shaft, with a depth of 214.7 metres, opens out into a connecting chamber 13 metres high and with an inside diameter of 4 metres.

The *HADES experimental gallery* was built in 1982–1983, again following freezing of the clay formation. It has an effective diameter of 3.5 metres over most of its length, and is 39 metres long from the outside face of the connecting chamber up to and including the 2-metre-thick reinforced concrete plug closing its end. SCK•CEN opted for the 'tunnel' approach rather than the 'mine' approach when designing the lining. In the mine approach, the lining is only designed to stabilise the formation in the short and medium term, while allowing rectification of the gallery diameter if required (not easy to carry out in operation). In the tunnel approach, it is designed to withstand the long-term stresses. This approach is also safer for the personnel and minimises disturbances to the formation. The lining design parameters were the lithostatic pressure (4.5 MPa), a coefficient of pressure of soils at rest K_o (ratio of horizontal to vertical pressure) of 0.6, and the conventional safety factors. The high stresses and moments calculated from these cautious design assumptions led to the choice of a very rigid lining: segments made from galvanised nodular cast iron (Fig. 3.27).

Since the freezing technique and the use of nodular cast iron segments seemed economically unrealistic for an actual disposal facility, SCK•CEN decided to assess the possibilities of excavating galleries in the clay without freezing and of using a cheaper lining. In 1983, it thus embarked on the construction of the *small shaft*, 2.5 metres from the end of the HADES gallery. This shaft was excavated by hand through the clay, which became less and less frozen as work advanced. The small shaft is 23 metres deep, has an effective diameter of 1.4 metre, and was lined with concrete segments 30 centimetres thick separated by timber spacers to reduce rigidity. The *small gallery* on which it opens has the same diameter but is only 7 metres long; it was excavated in 1984 and lined in the same way (Fig. 3.27). The clay face at its far end was left exposed so as to better monitor the movements of the formation over time.

As the construction of the small shaft and small gallery showed that it was possible to excavate the Boom Clay without freezing it, ONDRAF/NIRAS and SCK•CEN decided to explore the possibility of constructing a gallery, with a similar diameter to that of the galleries envisaged in the actual repository, without freezing the clay but still lining it with concrete segments. This gallery would also be used to conduct experiments in Boom Clay that had not been disturbed by freezing. This time, the design parameters for the linings were the lithostatic pressure (4.5 MPa), a K_o of 0.7 instead of 0.6, and lower factors of safety than previously used. The *Test Drift*, which is 3.5 metres in diameter and 67 metres long, was excavated in 1987 with pneumatic drills. It is lined with two types of support material:

concrete segments 60 centimetres thick and, over a short section operated by the French Agency for Radioactive Waste Management (*Agence Nationale pour la Gestion des Déchets Radioactifs* or ANDRA), metal sliding ribs (Fig. 3.27), which are less rigid and so tolerate a certain degree of convergence of the formation.

Figure 3.27 The three types of lining so far used in the underground facility. At the top: nodular cast iron segments (HADES experimental gallery); in the middle: concrete segments (small gallery and Test Drift); at the bottom: sliding steel ribs (Test Drift, ANDRA section).

Finally, the *second shaft* was excavated between 1997 and 1999. This was to comply with mining regulations that required the existing underground facilities to have an additional access before work began on the excavation of the gallery intended to be used for new experiments, specifically the PRACLAY experiment. It was excavated 90 metres from the end of the Test Drift (to which it will be connected by the so-called ‘connecting’ gallery) using a jack-hammer mounted on a hydraulic arm and hand-operated pneumatic drills; only the aquifer sands and the first few metres of clay were frozen. Like the first shaft, it has a constant effective diameter (3 metres) and a multi-layer lining in the aquifer sands, and opens out into a larger connecting chamber. Its lining was redesigned, however, so as to be more watertight than that of the first shaft, to improve the distribution of stresses in its inner part, and to isolate these stresses from the stresses in its outer part. The outer shotcrete lining, the thickness of which gradually increases from 0.2 to 0.4 metre, has therefore been separated by asphalt from the inner lining, which is made of hollow prefabricated concrete cylinders 0.3 metre thick and is hooped with a watertight steel sheet. The asphalt presents a viscous behaviour in the long term, and exerts a pressure on the inner lining that is equivalent to its hydrostatic pressure, setting up isotropic stresses within it. It also isolates the behaviour of the inner lining from that of the outer lining, which is exposed to the lithostatic and hydrostatic pressures from the formations through which the shaft passes.

The base of the second shaft, the connecting chamber, and the starting chamber of the connecting gallery (Fig. 3.28) were excavated based on what was then the most up-to-date knowledge of the behaviour of the non-frozen Boom Clay, namely that it has an elasto-visco-plastic behaviour and that its convergence can be rapid (see Section 3.6.2). It was, therefore, essential to install a support capable of limiting this convergence as soon as possible after excavation, both for safety reasons and to prevent the formation from becoming excessively decompacted. A temporary lining made from sliding steel ribs was therefore rapidly placed (Fig. 3.28). The permanent lining made out of concrete poured in situ over steel reinforcements was not placed until excavation was complete. Even so, slip planes and fractures that were several metres long and several millimetres wide in places appeared in the upper section of the starting chamber of the connecting gallery. These were due mainly to the fact that this zone was already decompacted by the excavation of the shaft and to delays in the execution of the work (Fig. 3.29). The characterisation programme that has been initiated in the meantime should answer questions about the origin of these phenomena (fractures that are neoformed, i.e., strictly excavation-induced, or natural fractures reactivated by the excavation), their extent, their impact on the hydraulic conductivity of the formation, their long-term behaviour (self-healing), and their impact on operational and long-term safety.

In 2002, the base of the second shaft will be linked to the existing facility by a connecting gallery. The hydromechanical behaviour of the argillaceous formation and the rate of advance of the working face will be monitored during the excavation of this gallery by sensors installed from the face of the Test Drift (CLIPEX project); these sensors were installed well in advance, to allow the instrumentation and the rock to stabilise. The connecting gallery, which will be lined with an expandable system of concrete blocks based on the wedge block technique to limit the convergence of the rock as much as possible (see below), must in particular allow the excavation of the PRACLAY gallery in 2006 (see Section 3.3.3).

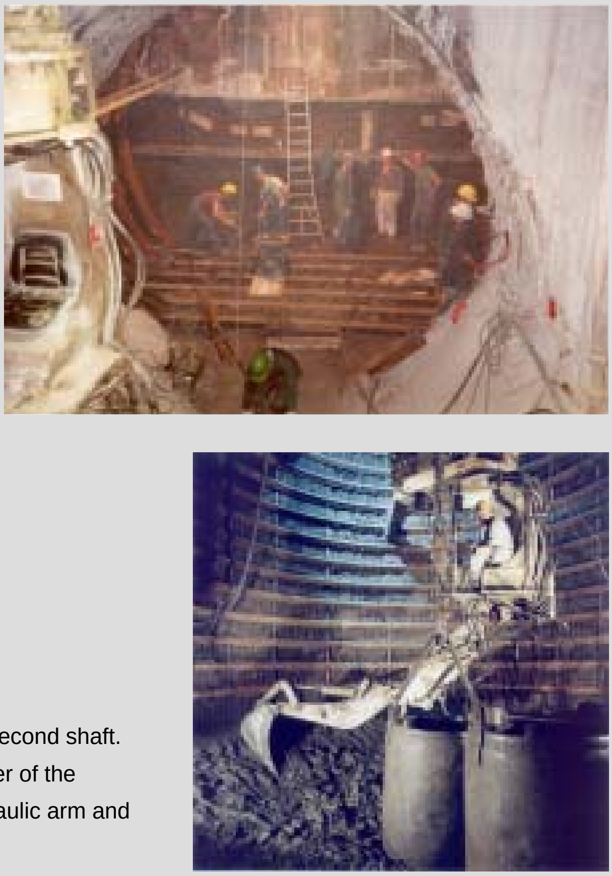


Figure 3.28 Excavation of the second shaft. Excavation of the starting chamber of the connecting gallery (top) and hydraulic arm and metal sliding ribs (bottom).

Minimising disturbances around the excavations

While it is now known that large-diameter galleries can be constructed in the non-frozen Boom Clay, it is still essential that the techniques used disturb the properties of the formation as little as possible within the bounds of technical and economic feasibility (see Section 3.6.2). Optimising the choice of excavation and support techniques suitable for the construction of the repository aims to limit the geomechanical and hydraulic disturbances around the excavations by minimising convergence during excavation. These disturbances depend on the excavated diameter; however, for a constant excavated diameter, their impact will also be smaller

- the faster the excavation rate;
- the shorter the time between clay excavation and lining placement;
- the smaller the over-excavation;
- the closer the contact between the lining and the excavated profile;
- the more rigid the lining.

(A third type of phenomenon affecting the excavation-disturbed zone in clays is the change in the geochemical properties of the medium following the oxidation of the clay, especially of the pyrite, which can release sulphates and acidify the medium.)

Figure 3.29 Excavation of the second shaft. Slip planes (top) and fractures (bottom) observed during excavation of the starting chamber of the connecting gallery.

Current knowledge suggests that the tunnelling techniques, which are commonly used by civil engineers to dig long tunnels (including tunnels in soils that behave like the Boom Clay) but at shallower depth, plus the use of expanded concrete segmental lining using the wedge block technique, will meet the demand for minimising disturbances. (The microtunneller method associated with the pipe jacking technique, commonly used at shallow depths, has been considered as a potential alternative to conventional excavation techniques for digging galleries 200 metres long but only 60 cm in diameter. However, this is currently regarded as hardly feasible at the depth proposed for the repository, at least when using a conventional microtunneller, owing to the rapid convergence of the clay and the resulting high friction forces that increase the risk of jamming.)

Mechanised tunnel boring machines offer a number of advantages.

- They produce a circular excavation section, which is the most stable configuration mechanically.
- They can attain an advance rate of at least 10 metres a day. This rate far exceeds that above which the rate of axial convergence ahead of the working face is low, i.e., above which the formation is less disturbed. (This critical excavation rate has been estimated at 2 metres a day for galleries of 2 metres effective diameter.)
- They can be fitted with a cylindrical shield to support the clay, pending the installation of the permanent lining behind the machine, which must be done as rapidly as possible.

- They are safe, demountable, have a modular capability, and their cost effectiveness increases with the length of the gallery.

The difficulty with tunnelling techniques is finding the right compromise for the over-excavation. This must be small relative to the nominal diameter of the lining so as to minimise disturbances to the formation, yet large enough to prevent the tunnel boring machine jamming due to the convergence of the clay and the high lithostatic pressure at this depth. The value of the total convergence—the total movement of the rock on the periphery of a gallery compared with the rock prior to excavation, including the convergence ahead of the working face—is currently estimated to be between 4 and 9 cm over an excavation radius of 2.5 metres.

An expanded concrete segmental lining based on the wedge block technique also offers a number of advantages.

- It is intrinsically stable because—like keystones in an arch—the wedge-shaped key or keys (which give their name to the technique), which are force-fitted between the concrete blocks forming each ring of the lining, place the ring in post-stress directly in contact with the clay. (The lining rings are assembled immediately behind the tunnel boring machine, with the concrete blocks being held by an erector until the wedges are fitted.)
- Concrete as a material behaves very well in compression, the main load mode occuring in a circular lining subjected to virtually isotropic external stresses ($K_o \approx 0.9$—see Section 3.6.2).
- Concrete is an inexpensive material.

Such a lining is not watertight, but this is not a disadvantage in the operational phase, since the low hydraulic conductivity of the Boom Clay will make the flow of water towards the galleries insignificant, and this water will be completely evaporated and dissipated by ventilation.

The wedge block technique cannot, however, be used where a gallery intersects other underground structures. The main galleries that will serve the disposal galleries will, therefore, be fitted with an additional lining or with a different lining designed to take the additional stresses that occur during the construction of gallery intersections, minimise the resulting disturbances in the clay, and thereby maximise the usable length of the disposal galleries. Furthermore, the construction of connecting chambers between the shafts and the galleries, which is difficult to mechanise, will inevitably induce more significant decompaction in the near formation; the repository design allows for this by specifying a minimum distance between the shafts and the first disposal gallery.

The excavation in 2002 of the gallery intended to connect the second shaft to the Test Drift, which will be 84 metres long and have an effective diameter of 4 metres, should make it possible to demonstrate that the tunnelling technique can be used at the depth of the repository and that, when combined with the wedge block technique, it can meet the safety requirements in the short term while also minimising disturbances. The excavation will also provide an opportunity to assess the over-excavation that is needed. The advance rate of the excavation will have to be at least 2 metres a day and will probably be limited by the capacity of the second shaft in terms of removing the spoils and transporting the blocks. The hypotheses used for calculating the sections are, on the one hand, P_v = 3 MPa and P_h = 2.7 MPa, and, on the other hand, a temperature increase of 8°C, corresponding with the expected thermal load on the connecting gallery induced by the PRACLAY demonstration experiment.

3.3.2.2 Operation

Although there has so far been relatively little research into the operation of the deep repository, experience gathered from the daily operation of the HADES underground research facility and from the many experiments that are conducted in it, some of which have used or are using radioactive sources, represents a valuable fund of knowledge in operational matters.

Specifically, the operation of the deep repository will involve both *conventional underground operations* (such as ventilation, the operation of the lifting systems in the access shafts, transport and handling, lighting, and the maintenance and inspection of equipment), and the radioactive waste *disposal operations* proper. Research into the disposal operations advances as the repository design is developed and new knowledge is acquired, but it has so far been limited to the vitrified waste and spent fuel and has not progressed beyond the stage of a feasibility study for these waste classes. The disposal operations for these two waste classes should be quite similar; the main differences arise from the difference in the length of the packages, which can be as much as 5 metres for the spent fuel. These operations will be entirely mechanised and performed by remotely-controlled robots, and will be accompanied by precautions designed to guarantee the radiological protection of the operators.

In the current reference design, the *vitrified waste* is received in a surface facility at the disposal site where the overpacks are removed from their transport packaging and placed in a transfer wagon which will take them to their final destination. The transfer wagon has a shielded barrel with four chambers, each of which can contain one overpack; the barrel is at right angles to the track on which the transfer wagon runs. The wagon is then taken to one of the access shafts and lowered down to the level of the underground galleries where it runs to the entrance of the designated disposal gallery. There its moving chassis is raised until it is level with the disposal tube and then advances to allow the shielding valve on the barrel to dock with the shielding valve of the disposal gallery to ensure continuity of the radiological shielding. The two valves are locked together by rams and are then opened, and the barrel rotates to bring the first chamber into line with the tube. A device known as the ‘pushing robot’, which is installed in a housing on the wagon, now pushes the first overpack into its final position in the disposal tube. Once it has placed the overpack in position, the robot returns empty to its housing. This sequence is repeated three more times (for the three remaining overpacks), after which the two shielding valves are closed, the rams retracted, and the chassis lowered. The transfer wagon returns to the shaft and is raised back up to the surface to be loaded with four more overpacks.

The transfer wagon and the pushing robot are already in an advanced stage of development: almost full-scale prototypes of each machine are being demonstrated in the HADES–PRACLAY exhibition hall at Mol (Fig. 3.30). Depending on the location of the repository within the clay layer, either the transfer wagon or the pushing robot will have to be capable of negotiating a dip of 2 %. The pushing robot will also be required to push packages weighing about 1 000 kg over a distance of 200 metres and should have a positional tolerance of around one centimetre in order to be capable of leaving a small space between two successive overpacks to allow for thermal expansion. The clamp that is fitted to the robot will allow it to grip the head of the overpack for retrieval, if necessary. The conclusive tests that have been carried out with weighted overpacks over at least ten metres have yet to be corroborated by tests over 200 metres, and the effects of temperature and radiation on the electronic and mechanical systems must also be studied in greater detail.

Figure 3.30 The handling device for the overpacks of vitrified waste being demonstrated in the HADES–PRACLAY hall.

The disposal of *spent fuel* packages would be a variant of the disposal of vitrified waste overpacks. Because these packages are too long to be lowered into the disposal facility horizontally, they would be placed in a shielded transfer container, which would be lowered vertically down the access shaft, rotated into the horizontal position at the bottom of the shaft, and placed on a wagon that would take it to the designated disposal gallery. Like the transfer wagon for the vitrified waste, this wagon could line up the shielded container with the disposal tube and would be equipped with a pushing robot. Because of their size, however, the use of transfer containers with four chambers like the barrel on the transfer wagon would involve enlarging the main galleries in the disposal gallery area to a diameter of 6 metres, a complicated and expensive exercise. Using ‘single-seater’ transfer containers would be an alternative solution.

3.3.2.3 Closure

According to the reference schedule, the closure of the repository, which will involve the decommissioning of the surface facilities and the permanent isolation of access routes to the waste, will take place several years after completion of the disposal activities at the latest. A decision to close the repository will not be taken until, first, the monitoring of the facilities during the operation has confirmed that the system functions properly and, second, the authorities responsible and all of the other parties involved are confident that the system is robust and offers an acceptable level of passive safety. In theory, however, the main galleries and shafts could be kept open longer to provide a significant level of flexibility in the decision-making process. Such a decision would have to be fully justified, based in particular on a detailed analysis of its potential adverse impact on safety. This open phase could certainly not last for more than a hundred years or so without having a considerable impact on operational and long-term safety. Major maintenance and refurbishment works would be required in such a situation, and different types of disturbance could affect the containment capacity of the disposal system and its robustness. Changes in economic conditions could also interfere with the decision-making process, with the open disposal facility being neglected and even left unsupervised in the long term.

As well as marking the transition from a system of active monitoring of the waste to one of passive containment, the closure of the repository is vital to ensure its long-term safety. Closure must indeed

- ensure the geomechanical stability of the host formation, so as to prevent the gradual collapse of the disposal galleries with the attendant risk of crushing the waste packages and enlarging the disturbed area of the formation (backfilling);
- prevent any preferential migration of radionuclides via the galleries and shafts (sealing);
- reduce the probability and consequences of any human intrusion on the site, whether on the surface or underground (sealing and backfilling).

The proper execution of the closure will thus make a major contribution to the future performance of the repository, and so the conditions of its implementation, especially as regards the choice of materials and installation techniques, will require careful study (see Section 3.4.2.2).

In practice, the closure of the repository will mainly involve first *backfilling*, with a swelling clay-based material mixed with sand, and then *sealing* the main galleries, the connecting gallery, and the access shafts to prevent the formation of preferential migration pathways for the radionuclides. (The disposal galleries will have been gradually backfilled before or during the phase of waste emplacement, then sealed off once filled.) Although the lining of the galleries and shafts has a higher hydraulic conductivity than the Boom Clay and can therefore be a preferential migration pathway for the radionuclides, it will be kept, except where the main galleries are sealed, where it will be removed together with the clay that has been disturbed by excavation. The resulting cavity will then be packed with a swelling clay of the same type as the backfill material used for the disposal galleries. This will thus exert pressure on the argillaceous formation and will be sandwiched between two concrete anchoring plugs. Each main gallery will be sealed with at least two such watertight plugs placed in series. These plugs must have a hydraulic conductivity that is at least as low as that of the host formation, they must resist the lithostatic pressure and disturb the initial geomechanical and geochemical characteristics of the host formation as little as possible.

There will be two final stages to the closure phase of the repository: marking the site and archiving, for an indefinite period of time, all of the data characterising the disposal system and the disposed waste. Clearly *marking the site* using several types of surface and underground markers mainly aims to minimise the likelihood of human intrusion. The *archiving of data* will facilitate waste retrieval (if required) over a certain period of time. It will also help prevent any human intrusion in the medium and long term by administrative means, and may be useful in the medium term as a basis for appropriate decisions following any human intrusion. This data could be stored on a variety of different media and a number of copies deposited with one or more bodies, including a foreign or international organisation. Ideally, they would be backed up periodically before each data medium expires. Finally, the location of the repository would also have to be shown on all national and regional topographical documents covering the repository site.

3.3.2.4 Institutional control

Although the period of institutional control following the closure of the deep repository certainly cannot guarantee its safety, a monitoring programme, which would last from several decades to several centuries depending on the choices made by future generations, could help sustain the confidence of the public and of the other parties involved in the effective safety of the disposal system. As well as inspection and monitoring activities, which should not, of course, compromise the long-term passive safety of the repository, this control would include measures designed to prevent the uncontrolled use of the site and to ensure that knowledge of and about it is preserved. This active monitoring would then gradually give way to a period of basic official checks, after which the site would be finally released for unrestricted use. Knowledge about the disposal facility would then gradually dissipate, but the location of the site would have to be remembered.

3.3.3 The PRACLAY demonstration project

The main objective of the PRACLAY demonstration project (Preliminary Demonstration Test for Clay Disposal), begun in 1995, is to demonstrate by direct experiment between now and around 2015 that it is technically and economically possible to dispose of vitrified waste into the Boom Clay, while meeting the requirements that emerge from safety studies. This key project, which is open for international collaboration, involves constructing in situ a full-scale section of disposal gallery identical in all aspects with the galleries proposed in the reference design. This will be done using the industrial excavation techniques and materials currently proposed in that design, so far as possible. The gallery will then be filled, the waste being simulated by electric heater elements but no radioactive sources (Fig. 3.25). The project also aims to promote a better understanding of the disposal system and of the interactions between its various components. This is to confirm the results that will have been obtained by the end of the phase of methodological research and development ('enhancing confidence' in the models, their underlying assumptions, and their predictions) and to then optimise the reference design and its components. Finally, the project will include the design and construction of an intersection between a main gallery and a disposal gallery. This project is managed by the EIG EURIDICE (European

Underground Research Infrastructure for Disposal of Nuclear Waste in a Clay Environment), which at the end of 2000 took over from the EIG PRACLAY set up in 1995 by SCK•CEN and ONDRAF/NIRAS. EURIDICE has expanded its activities to include the complete operation and valorisation of the HADES underground research facility.

A full-scale instrumented mock-up of the underground gallery has been built on the surface in preparation for the in situ experiment (Fig. 3.31). The OPHELIE mock-up (On Surface Preliminary Heating Simulation Experimenting Later Instruments and Equipment) has a threefold purpose:

- to show that it is possible to place the backfill material and study its behaviour under conditions of temperature, pressure, and hydration that are representative of actual conditions;
- to confirm that placing the instrumentation system on the disposal tube, in the backfill material, and on the lining will not significantly disturb the clay;
- to confirm the performance and dependability of the measuring instruments and equipment under severe experimental conditions that are representative of the conditions in situ, before they are used underground.

The results and final conclusions of the tests carried out will be available when the mock-up is dismantled in 2002. It is already clear, however, that a number of instrumentation systems are not able to withstand the severe repository conditions for the required periods of time. This was also found during the experiments conducted in situ in the HADES underground research facility. Furthermore, the presence of chlorides in the mock-up will need to be analysed both in terms of their source and in terms of their potential impact on the durability of metal materials and on the behaviour of radionuclides. Finally, the construction of the OPHELIE mock-up and preparations for the PRACLAY experiment have already been used to highlight or formulate a set of unanswered issues about the practical implementation of the reference design (Table 3.7).

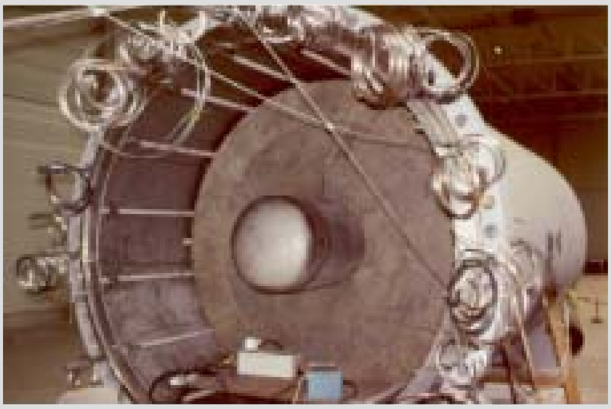


Figure 3.31 The OPHELIE mock-up.

The PRACLAY experiment proper, which will run from 2008 to around 2013, aims to study the thermo-hydro-mechanical behaviour of the Boom Clay in the near field, of the lining, of the backfill material, and of the disposal tube, when exposed to a temperature increase. It will also investigate the geochemistry of the interstitial water and the interactions between the various components of the system during the hydration and heating phases. Data about their behaviour will have to be collected under conditions that are as near as possible to those prevailing in an actual repository. Most of the measurements in the argillaceous formation will have to begin as soon as excavation work starts and continue throughout the experiment. The instrumentation around the future PRACLAY gallery will be installed at the start of the project in around 2005, and will be duplicated to ensure the gathering of data until the end of the experiment.

Although it is a demonstration experiment, PRACLAY has certain intrinsic limitations:

- in the absence of any hard evidence of really inappropriate choices, its duration (ten years) is too short for it alone to produce any convincing findings about the choice and behaviour of materials and measurement systems in the long term;
- it cannot be used to prove long-term safety, which can only be indirectly demonstrated;
- it is being conducted without a radiation field.

Under the present schedule, the 30-metre-long PRACLAY gallery will be excavated in 2006 starting from the connecting gallery, with the various components of the near-field design (disposal tube, hydration system for the backfill material, backfill material, sealing, etc.) and instrumentation of PRACLAY itself being installed in 2007. The experimental facility will then be heated up over a period of five years, allowed to cool down for one year and then dismantled, and the data collected throughout the experiment will be analysed.

3.3.4 Outlook

Although the reference repository design is at a relatively advanced stage of conceptual development for the vitrified waste and spent fuel, the many very specific issues raised by the preparation of the OPHELIE mock-up and the PRACLAY experiment, and during the drafting of the SAFIR 2 report, are good reasons for it to be reassessed in depth. This will be done as it is being extended to cover the other waste classes in the geological group. This development, which remains iterative, must be systematic and system-oriented, and based on the safety functions as an essential analysis tool. The future programme will seek mainly

- to define consistent technical criteria for the general design of the repository, its components, and its environment, especially in terms of acceptable temperatures and retrievability;

- to review all of the design bases of the disposal facility in the light of the requirements of long-term radiological safety and of operational safety;

- to develop an overall repository design that incorporates the solutions developed for each class, or homogeneous group of classes, of waste and, hence, to refine the design of the repository intended for the spent fuel, and to develop a disposal design for a waste class of category B that is regarded as especially demanding;

- to optimise the repository design as a whole, i.e., optimise the geometry of its different components and the choice of all of the materials used (Table 3.7), while taking all of the interactions between them into consideration;

- to continue the work on the practical aspects of the excavation of underground facilities;
- to describe in detail the operational aspects, both as regards conventional underground operations such as ventilation and fire protection, and as regards disposal operations;
- to define in detail the aspects of closure;
- to ensure the representative nature of the PRACLAY demonstration experiment by confirming the key characteristics of the disposal design intended for the vitrified waste;
- to continue the PRACLAY demonstration experiment;
- to specify the role of repository monitoring and its links with retrievability and safety, and to define—especially on the basis of possible future legislation, for example regarding safeguards—what aspects should be monitored, i.e., aspects that are representative both of the state of the disposal system and of its evolution, and that are likely to involve a corrective action that is measurable in practice;
- to assess the economic aspects of the construction and operation of the disposal facility.

3.4 Behaviour of waste and materials under disposal conditions

There are two aspects to the study of the behaviour of the waste forms and of the proposed materials for the construction of the underground disposal facility. First, the way in which each evolves under disposal conditions can be studied, i.e., analysing their individual performance, especially their durability. Second, their compatibility can be studied, i.e., analysing their effect on the performance of the other components of the disposal system. For example, the adverse effect of the waste matrices on the properties of the near field must not be excessive (see Section 3.6.5), and the backfill material should not adversely affect the corrosion of the overpacks.

3.4.1 Behaviour of the conditioned waste

As well as obtaining basic data that is vital for long-term radiological safety assessments (see Chapter 4), studying the behaviour of the waste forms in the Boom Clay aims to validate some of the simplifying hypotheses used in those assessments. These studies, carried out by SCK•CEN, have so far mainly concentrated on the vitrified and bituminised waste (see Table 3.2 for the inventory of waste belonging to the geological group).

Compatibility
Property of a conditioned waste package in a disposal facility, or of a material used for the construction of the facility, of having no adverse effect on the anticipated behaviour of the other components of the disposal system, especially on that of the Boom Clay.

3.4.1.1 Vitrified waste

In addition to the various tests conducted in the surface laboratory, one particular element in the studies of the glass behaviour conducted as part of the Belgian disposal programme are the in situ tests performed in the underground facility on samples of inactive and weakly-doped glasses (^{134}Cs, ^{90}Sr, ^{239}Pu). These glasses have been shown to possess a behaviour representative of that of real active glasses. At the end of the 1980s, for example, SCK•CEN embarked upon a series of long-term experiments in the HADES underground research facility. In these in situ experiments, the studied materials (types of glass, waste-embedding materials, concrete, and the metal packaging and overpack materials) were placed in three types of situation that were believed to be typical of disposal conditions, at 16, 90, and 170°C, and for periods of time ranging from 2 to over 7 years. The corresponding three types of experimental device placed in the clay from the HADES gallery were sample-carrier tubes made from stainless steel and long enough (over 5 metres) to reach the zone not disturbed by excavation. The example of the CERBERUS in situ experiment is even more specific: here a field of gamma radiation representative of the vitrified waste was also used (see Section 3.6.4). All of these studies have an international context through participation in a number of European programmes, and have benefited from the many studies in argillaceous media conducted in France in particular.

Studies carried out during the past ten years have identified the basic processes likely to occur during glass dissolution. These processes are interdiffusion, dissolution of the silica, condensation of the silicates in the gel layer formed on the glass surface, precipitation/ diffusion/sorption of the silicates in the surrounding medium, and formation of secondary phases. This dissolution takes place in three main steps:

- interdiffusion, resulting in the formation of a hydrated zone that is impoverished in alkaline elements (ionic exchange with the alkalines in the glass);
- hydrolysis of the glas network;
- condensation and/or precipitation of the hydrolysed species resulting in the formation of an amorphous altered layer.

This dissolution process is schematised in Figure 3.32.

With most of the glass types that have been studied, the experimental results show that the dissolution rate falls by several orders of magnitude over time, reaching very low levels under so-called saturation conditions, which are a function of the system considered (dynamic equilibrium). The interpretation of this drastic drop in the dissolution rate (dissolution law based on the notion of chemical affinity or formation of a protective gel layer) and the interpretation of the persistence of a very low dissolution rate under saturation conditions is still open to debate.

The various tests that have been carried out, or that are still in progress, in the surface laboratory or in situ, cover a very broad range of conditions and have been used to identify the effect of the following parameters on glass dissolution:

- *effect of temperature* The glass dissolution rate increases significantly with temperature (by two to three orders of magnitude between 16°C and 90°C). Hence, the glass will have to be isolated from the interstitial water during the thermal phase of the repository, a period of about 300 years. This function of physical containment will be performed by the overpack.

- *effect of the engineered barriers* The glass dissolution rate is not significantly influenced by the presence of the engineered barriers. The many tests carried out have shown very clearly that the impact of the backfill material (FoCa clay) on glass dissolution is comparable with that of the Boom Clay. Therefore, Boom Clay has been designated as the reference medium for assessing the durability of the vitrified waste under disposal conditions, particularly since it is the host rock that will determine the physico-chemical conditions in the near field in the long term.

- *effect of radiation* Glass dissolution is not significantly affected by the self-irradiation of the matrix or by the irradiation of the surrounding medium.
- *effect of devitrification and fracturing* The kinetics of devitrification are extremely slow, so that the extent of this process will be very limited over the durability anticipated for this type of matrix. Dissolution tests carried out on partially devitrified glasses show that devitrification does not alter their behaviour. Moreover, modelling results of glass fracturing reported in literature indicate that this phenomenon does not appear to determine the overall durability of the glass either. French research clearly indicates that the durability of the glass could be significantly enhanced under disposal conditions by adding siliceous additives to the backfill material and/or in the annular space between the canister of vitrified waste and its overpack (pre-saturation of the medium before dissolution of the vitrified waste).

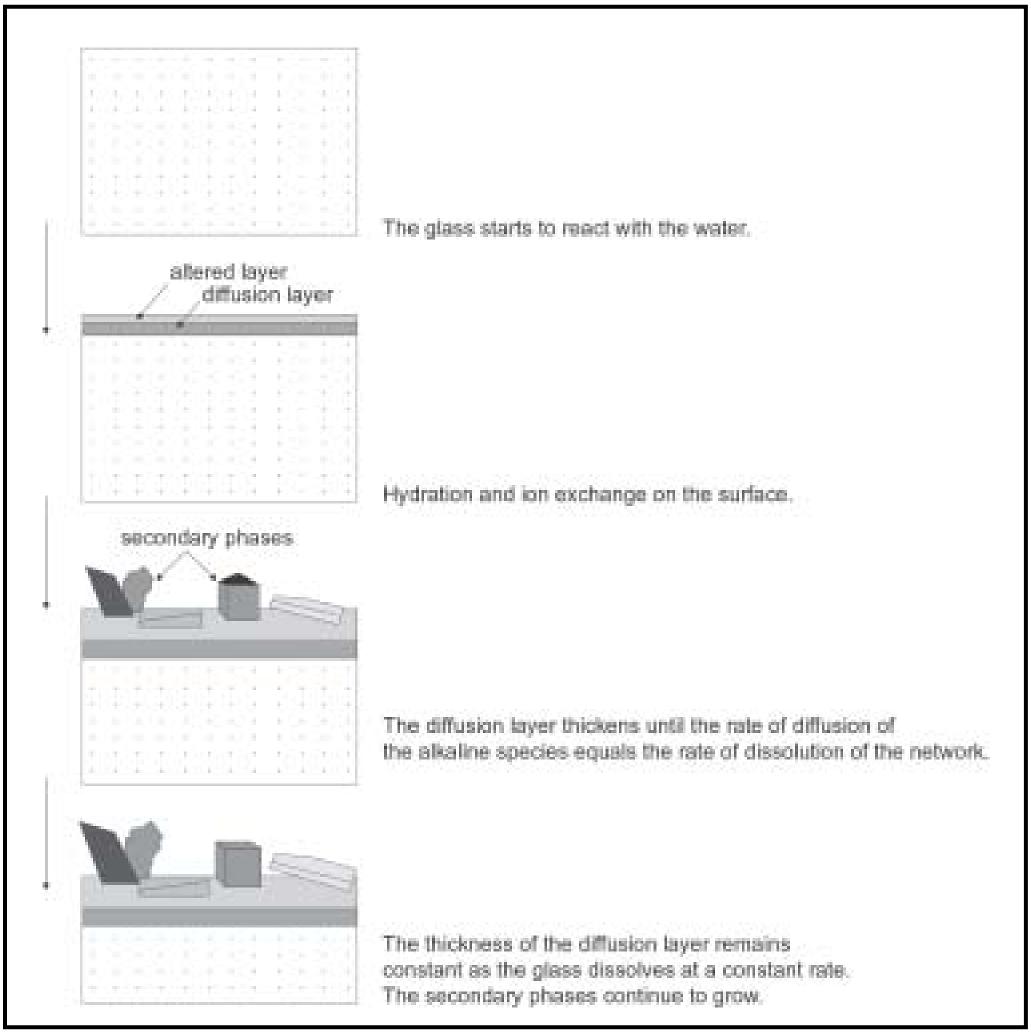


Figure 3.32 Principal steps in the dissolution of vitrified waste.

The retention of radionuclides in the altered layer on the glass surface depends on the nature of the element considered, the pH, and the presence or not of solid phases such as the Boom Clay or the FoCa clay (competition between the glass and the clay minerals). Since this retention process does not appear to make any significant contribution to the retention of the radionuclides under actual repository conditions, safety assessments assume that radionuclide leaching is determined by the glass dissolution rate (retention factor of 1). The low solubility and/or the sorption of the radionuclides by the solid phases entails that the mobile fractions for most of the radionuclides studied are, however, small relative to the leached quantities. In an initial stage at least, they appear to be determined by the composition of the glass, the progress of the reaction, and the initial concentration of the radionuclides in the glass. Over long periods, the concentrations in solution stabilise in most cases.

Modelling exercises on glass dissolution consider two distinct areas:

- *geochemical modelling* aims to identify the secondary phases that are likely to form and to control the concentration of key elements like silica and critical, or potentially critical, radionuclides released in the medium when the glass dissolves;
- *modelling of glass dissolution (kinetic model)* aims to develop an analytical model linking the law of glass dissolution with the diffusion and sorption of silicates in the surrounding medium. This modelling has made some significant progress and has been helped by a very promising and original technique recently developed by SCK•CEN for studying dissolution mechanisms (including the formation of the altered layer) at microscopic level, and hence for verifying some of the hypotheses used to elaborate an analytical model.

The results of the geochemical modelling of the glass–water–clay system suggest that the Boom Clay could act as a silica pump: the medium could be theoretically maintained in conditions of non-saturation towards the glass. Within the limits of the thermodynamically selected data, the model predicts no formation of secondary phases. The dynamics of the processes of glass dissolution could, however, impose steady-state conditions different from those corresponding to thermodynamic equilibrium.

So far as kinetic modelling is concerned, the dissolution law as initially proposed by Grambow is still being used provisionally because of its conservative nature and the absence of any alternative suggestions that can be processed in existing analytical models. This approach will, however, have to be reviewed and/or adapted as work progresses.

The huge increase in computing power in the past decade has made it possible to develop new modelling methods. These include the Monte-Carlo simulation method and the molecular dynamic method. The Monte-Carlo method is based on assigning probabilities to the processes concerned and can be used to investigate dissolution mechanisms at microscopic level, while maintaining a good compromise between simplicity and computing time. It is one of the research methods recently recommended for modelling exercises, although it makes no claim to replace the analytical models, which still remain the principal tools for assessing the durability of glass under disposal conditions. The molecular

Conservatism In the framework of the long-term safety assessments, approach aimed at making and justifying choices regarding hypotheses, phenomena or processes, events, parameter values, models, etc., in order to create assessment conditions that are less favourable than those expected and, hence, to overestimate the radiological and environmental impact of the disposal system. These choices are thus careful choices.

dynamic method is based on the interaction potential calculated from Newton's law (F = m·a). It is more accurate but has the disadvantage of allowing only very small computing steps ($t < 10^{-10}$ s).

Given the present uncertainties about the glass durability in the Boom Clay, long-term safety assessments conservatively assume that the glass–water–clay system does not evolve towards saturation conditions. Despite this assumption, the durability of glass under repository conditions is several tens of thousands of years, the minimum durability calculated from the theoretically possible maximum dissolution rate (initial rate V_0 corresponding to a nil concentration of silicic acid in solution) being approximately 10 000 years. Because safety assessments show that the glass durability has no significant impact on the radionuclide flux at the interface between the Boom Clay and the aquifers, a reduction in the uncertainties, here, could only have minimal impact on estimates of long-term safety. It is not justified, therefore, to commit the considerable resources that would be needed to achieve any further reduction in uncertainties.

Future research programmes into glass will have to demonstrate the ultra-conservative nature of the lower limit of durability used for modelling the near field, not to determine its absolute value. They will aim to provide convincing qualitative or semi-quantitative arguments to show that the glass durability will, very probably, be several hundreds of thousands of years, i.e., at least one order of magnitude longer than under the most conservative assumption used in long-term safety assessments. This will also make it possible to estimate the safety reserve associated with this durability. Future programmes will also have to show that the addition of glass frit in the near field would improve durability. They will mainly comprise the following studies:

- interpreting the phenomena observed under so-called saturation conditions;
- identifying the mechanisms controlling glass dissolution in the long term;
- extending studies of the leaching behaviour of radionuclides to include other elements regarded as critical or potentially critical (^{79}Se, ^{126}Sn, ^{107}Pd, and ^{93}Zr);
- developing a geochemical model and an analytical model;
- assessing the above models by means of three complementary approaches: simulation of dissolution mechanisms at microscopic level with the Monte-Carlo method, long-term in situ demonstration tests (already begun), and study of natural analogues under conditions representative of the undisturbed Boom Clay. (Basaltic volcanic glasses, which have been shown to behave similarly to nuclear waste glasses, have been found in the Boom Clay. Interestingly, they show no evidence of dissolution.)

3.4.1.2 Spent fuel

An initial study of the solubility of UO_2 in the Boom Clay as a function of key parameters such as the concentrations of dissolved carbonate and organic carbon indicates that the organic matter has no significant effect on the solubility of uranium, which is very low in a reducing medium such as the Boom Clay (approximately 10^{-8} mol·l^{-1}). The influence of the carbonates is only observed in less severe redox conditions (complexation of the hexavalent uranium present in solution). According to the data reported in literature, the

UO_2 matrix should also have significant durability over the timescales considered in the safety assessments.

Despite the importance of the spent fuel, the literature provides few data about its behaviour in an argillaceous environment. The first (recent) safety assessment of the disposal of spent fuel into the Boom Clay therefore defined the source term by extrapolating to clay the data available for disposal in granite. Studying the behaviour of spent fuel is further complicated by the need to consider different components, each characterised by a specific release rate and isotope inventory, and requires simplifications for safety assessments. Studies give priority to the UO_2 matrix, which of course contains most of the activity.

A critical review of the literature has recently made it possible to define an initial research and development programme devoted to the behaviour of UO_2 fuel in the Boom Clay. This programme will validate the source term used in safety assessments, make any necessary adjustments to it, tasks that will involve investigating the dissolution mechanisms at work (Fig. 3.33), and study aspects associated with justifying the simplifications necessary for safety assessments. Initially, the research will focus, not on spent fuel, but on uranium oxide and uranium oxide doped with alpha emitters to simulate the chemical composition of an uranium oxide spent fuel with a high burn-up (SIMFUEL). Conditions representative of those that will prevail in a deep repository will be applied. This programme, which has an international context through participation in the framework programmes of the European Commission, includes the following tasks:

- critically reviewing the available data on the characterisation of uranium oxide spent fuel and MOX spent fuel;
- determining the dissolution rate of the SIMFUEL under conditions that will exist at six different periods in the evolution of the disposal system, ranging from 500 to over 100 000 years, and determining the relationship between the alpha activity of the SIMFUEL and its dissolution rate in the Boom Clay;
- determining the influence of the clay minerals on the dissolution rate of the SIMFUEL (possible increase in the dissolution rate by adsorption of U(VI) or U(IV) species released into the medium);
- studying the compatibility of the various materials proposed for the engineered barriers with the SIMFUEL;
- geochemical and kinetic modelling. Kinetic modelling will first involve a critical review and selection of existing models, then an initial calculation of the durability of the spent fuel types, taking into account the parameters of the Boom Clay.

Integrated tests in the surface laboratory with real spent fuel and in situ tests with SIMFUEL should be carried out in the medium term, subject to the necessary authorisations being obtained. The potential contributions of natural analogues will also be examined.

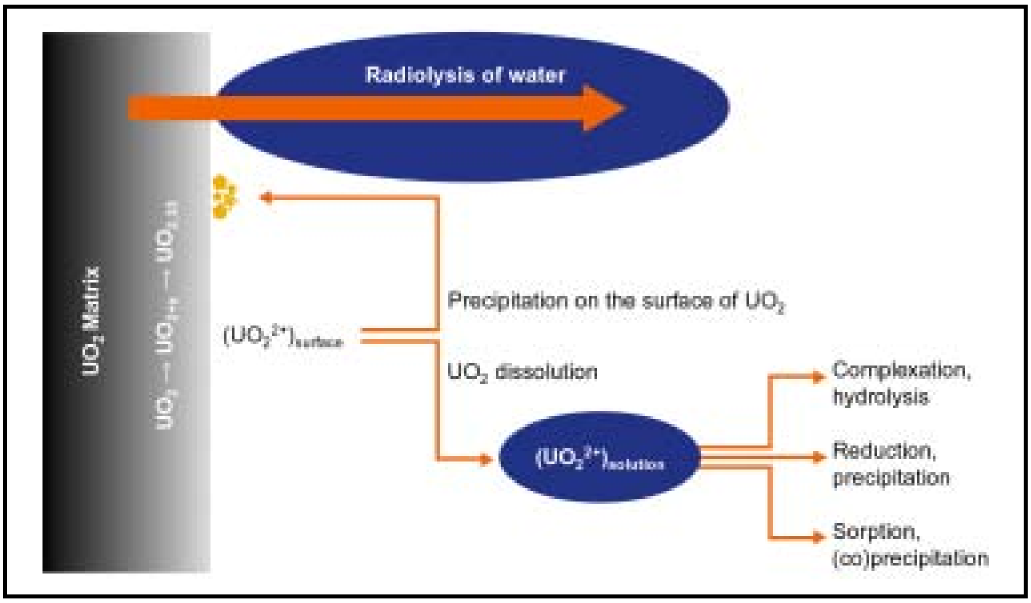


Figure 3.33 Representation of the dissolution mechanisms of the UO_2 matrix.

3.4.1.3 Hulls and endpieces

No study has yet been undertaken of the behaviour in the Boom Clay of hulls and endpieces and technological waste from reprocessing. This waste will not be immobilised in a cement-based matrix but simply compacted and placed in a primary packaging identical to that used for the vitrified waste. Because there is no overpack or waste matrix for this waste class, safety assessments apply the conservative assumption of an instantaneous release of radionuclides, an assumption that adds a safety reserve. Given its nature, this waste should not pose compatibility problems with the repository environment, e.g., it has only a marginal content of organic components. Nevertheless, the opportunity for conducting compatibility studies will be re-examined when acceptance criteria for this waste have been defined and its conditioning process has been qualified.

3.4.1.4 Bituminised waste

The two main types of bituminised waste earmarked for deep disposal are the MAGALC and MAGALE classes of waste. The MAGALC waste consists of coprecipitation sludge from the reprocessing of spent fuel by COGEMA, conditioned in a matrix of distilled bitumen (*soft bitumen*). The MAGALE waste consists of liquor with a high sodium nitrate content from the old Eurochemic facility, conditioned in a matrix of blown bitumen or *hard bitumen*. The organic nature of the bituminised waste and the volume it represents—some 3400 m^3—make it particularly important. The MAGALE waste will be studied as a matter of priority, as the number of packages of this waste (approximately 13400) far exceeds the number of packages of MAGALC waste (480).

Except for information about the generation of degradation products by radiolysis, the literature offers few data about the effect of the phenomena determining the impact of bituminised waste under disposal conditions on the repository performance. This is because the data do not exist or are not directly applicable to the Boom Clay, or because there are major uncertainties surrounding them, or again because they are contradictory. The reasons for these gaps in information are the very slow kinetics of the processes involved (except for the leaching of nitrates), the difficulty of carrying out tests on active packages under typical repository conditions, and the interactions between the various phenomena involved. Finally, there seems to be no example comparable with that of the MAGALE waste.

Nevertheless, a literature study indicates that the behaviour of the bituminised waste under disposal conditions will be mainly determined by five phenomena.

- The *leaching of some 750 tonnes of sodium nitrate* into the Boom Clay in the medium term. This could modify the geochemistry of the Boom Clay in the vicinity of the near field and influence the migration of radionuclides, especially of those that are sensitive to the redox potential.
- The *ageing* of the waste matrices, i.e., the change in their intrinsic characteristics (hardness, viscosity, softening point, density, etc.) over time under the influence of different factors. This will affect the nature and extent of other processes governing the behaviour of the matrices under disposal conditions.
- The *swelling* of the waste matrices following water diffusion into the bitumen matrix and the resulting pressure build-up (osmotic pressure). This may affect the performance of the engineered barriers.
- *Biodegradation* and *radiolysis* will entail the production of gas and soluble organic compounds, most of which have a complexing capacity. This could modify the speciation of the radionuclides and, hence, their behaviour in the Boom Clay.

The late 1980s and early 1990s saw the start of research work on the physico-chemical characterisation and leaching behaviour of the inactive salts and the radionuclides in the bituminised waste under a range of conditions. Studies relating to ageing, swelling, and biodegradation formed only a minor aspect of these programmes.

The information obtained so far about the MAGALE waste, and in particular about the rate at which it releases inactive soluble salts, indicates that the packages should make little contribution to the containment of radionuclides in a deep disposal system. Safety assessments ascribe no barrier function to the bitumen, and there are no plans for new studies of this subject at the present time. The issue may however need to be reviewed in the light of the results of related safety assessments.

More important than its durability is the compatibility of the bituminised waste with the repository environment. The complex phenomena of ageing and swelling are considered to be the most critical, and they will occupy a central place in future programmes, given that the data acquired to date cannot be used to assess the behaviour of an actual package under deep disposal conditions. The processes of biological and radiolytic degradation are accompanied by the production of gas and soluble organic compounds. With regard to gas production, estimates suggest an upper limit of around 1 m^3 per package over 1000 years.

This is a conservative figure calculated under standard conditions of temperature and pressure, while maintaining the initial biodegradation rate constant, whereas in reality the rate should fall drastically over time. (Gas production by radiolysis has little significance.) The main complexing agent generated in the environment by bitumen radiolysis is oxalate, although this has no major influence on the behaviour of radionuclides in the proposed near field, i.e., a cement-based backfill material. Initial results also suggest that the products of the radiolytic degradation of the MAGALE waste have no significant impact on the behaviour of plutonium and americium in the Boom Clay. These studies will be continued and deepened, as will investigations into the biodegradation processes (particularly in terms of gas production), the impact of changes in physico-chemical conditions in the near field, and the identification of the most likely microorganism populations to develop.

Certain results obtained for the MAGALE waste, and which are linked to phenomena that are relatively independent of the matrix type, such as radiolysis and, to a certain extent, biodegradation, could be extrapolated to the MAGALC waste. Other phenomena such as swelling will form the subject of specific studies, as will the task of defining the source term (if necessary) and the issue of the impact of the fluidity of the matrices of the MAGALC waste on its behaviour under disposal conditions. (An investigation into the potential influence of the migration of a sodium nitrate front on the retention properties of the clay began in 1999 as part of the programme devoted to radionuclide migration in the Boom Clay.)

3.4.1.5 Cemented waste

The durability of cemented waste is not a matter for investigation at the present time, given that safety assessments conservatively disregard the contribution of the cement matrix to radionuclide containment. As with the bituminised waste, the main issues raised by the disposal of cemented waste have to do with its compatibility with the Boom Clay. This is because it can generate an alkaline front, and some cemented waste streams also contain cellulose derivatives whose degradation products in an anaerobic and alkaline environment could have an impact on the solubility and sorption of radionuclides. However, results obtained so far from solubility measurements and sorption tests with plutonium and americium in the clay in the presence of isosaccharinic acid and other products of cellulose degradation indicate that these products, and isosaccharinic acid in particular, have only little impact on the behaviour of radionuclides in the Boom Clay. The issue of the contribution by waste matrices to the generation of an alkaline front in the clay is one that has not yet been investigated.

3.4.1.6 Data selected for modelling the near field

The parameters required for modelling the near field in safety assessments have been subject to critical review and have been compiled in data collection forms. These parameters are the solubility of radionuclides in the near field (backfill material and clay), the fracturation factor of the glass, and its mean dissolution rate.

3.4.2 Behaviour of materials used in the deep repository

The materials that constitute the principal components of a deep disposal facility must be selected, not only so that these components are able to perform the functions assigned to them, but also so that they are compatible with the other components. That is, they should have no adverse effect on performance. These materials are mainly metal packaging and overpack materials, and argillaceous backfill and sealing materials.

3.4.2.1 Packaging and overpack materials

The free enthalpy of the generic corrosion reaction in an anaerobic environment ($x\,M + y\,H_2O \Rightarrow M_xO_y + y\,H_2$) is generally negative for common metals, so the metals present in a deep repository are bound to degrade in time. This degradation is important in two respects; a thorough understanding of the mechanisms governing it is thus essential. Because corrosion involves the progressive degradation of the packagings and overpacks (if used), a good understanding and correct assessment of the mechanisms and kinetics controlling it must enable to make correct choices, which will ensure the physical containment of the radionuclides present in the vitrified waste and the spent fuel during the thermal phase of the repository, i.e., for several hundreds or several thousands of years respectively. As corrosion is also accompanied by the production of hydrogen gas, which may disturb the host formation, it must be investigated with a view to designing the repository in a way that keeps disturbances to acceptable levels (see Section 3.6.3). This can be achieved by minimising corrosion or by facilitating the escape of the gas formed.

The results of in situ corrosion experiments vary greatly depending on the type of material studied: stainless steels as used in existing packagings, and steels and alloys that have been proposed as overpack materials at European level (a carbon-based steel, stainless steels, pure titanium, a titanium alloy, and two nickel alloys), which were in five different initial states. Whatever the conditions of the experiment, the samples of *stainless steels* and *special alloys* show no trace of corrosion attributable to the experiment. (This observation seems to be confirmed by the fact that the many piezometers made from AISI 316 and used in direct contact with the Boom Clay in other parts of the research and development programme do not appear to have suffered any corrosion, although this has not been specifically investigated.) All of the *carbon steel* samples that have been tested, on the other hand, show marked traces of both generalised and pitting corrosion. The depth of the pits and the thickness of the corroded layer depend on the temperature and the exposure period. The polished samples are far less susceptible to pitting than the samples tested ‘as received’ since they present far fewer surface defects initially, while the latter samples display continuous pitting, with pits coalescing. This morphology is explained by a sequence of two mechanisms. In an initial aerobic phase, the oxygen that has dissolved in the interstitial water during the drilling into the clay of the boreholes needed for the sample-carrier tubes creates corrosion which is manifested mainly, but not only, by pitting. Once the mainly reducing conditions are restored after several months, the dominant mechanism becomes one of uniform corrosion, which tends to ‘smooth out’ the exposed surface. (Under actual conditions, the aerobic period following repository construction will be much longer, as the clay will have suffered greater chemical disturbances, and the depth of the pits could increase significantly.)

The unfavourable kinetics of pitting corrosion and uniform corrosion of carbon steel make it unsuitable for use as an overpack material. Hence, research is now being focused on the laboratory investigation of two materials that are relatively common and compatible with the waste packaging steel. These are the austenitic stainless steel grades AISI 316L hMo (which is regarded as the reference and is a grade of AISI 316 that has already been tested in situ) and UHB 904L (which is more highly alloyed and already tested in situ). This parametric study comprises two types of test and systematically investigates the impact of the surrounding material (Boom Clay or FoCa clay–sand–graphite backfill mixture), of temperature (from 16 to 140°C), and of representative concentrations of oxygen, chlorides, thiosulphates, and sulphates. The two latter compounds can be generated when the pyrite oxidises following the excavation of the Boom Clay. The electrochemical tests aim to determine the different characteristic potentials of pitting corrosion in order to assess its probability. The immersion tests involve placing samples of AISI 316L hMo that have been prepared in different ways in contact with the backfill material saturated in solutions of different compositions and placed in hermetically sealed containers. The different solutions simulate the changes in conditions expected in the near field over time (change from aerobic to anaerobic conditions, gradual decrease in the influence of the FoCa clay on the chemistry of the interstitial water giving way to a greater impact of the Boom Clay and a drop in temperature). Crevice corrosion and any galvanic corrosion favoured by the presence of graphite in the backfill material are also being examined. The tests will take a maximum of two years, with samples being taken at intermediate times.

Most of the results obtained so far are from electrochemical tests in an oxidised environment. The most striking of these are for the AISI 316L hMo at 90°C:

- an increase in chloride concentration enhances pitting corrosion;
- conversely, an increase in sulphate concentration inhibits pitting corrosion;
- the thiosulphates only appear to significantly enhance pitting corrosion at a concentration of 50 ppm and over.

The same tests conducted at 16°C only indicate pitting for chloride concentrations of 10 000 ppm, i.e., 1 000 times the chloride concentration in the interstitial water of the Boom Clay and 10 times the concentration in that of the Ypresian Clays. Finally, the UHB 904L systematically shows more resistance to pitting corrosion than the AISI 316L hMo in the tested media. (The first samples retrieved from the immersion tests show no corrosion.)

As well as continuing the studies already in progress, the future programme will aim to optimise the choice of overpack material. This will necessitate, first, conducting a more in-depth study of the different types of corrosion likely to occur so as to define the most probable and most harmful mode of attack, and, second, studying the aspects of practical implementation, especially the issue of weldability. This optimisation exercise will be part of an integrated approach that will take account of all of the parameters likely to affect corrosion and will, in particular, call for a better understanding of the evolution of the geochemistry of the environment over time.

3.4.2.2 Backfill and sealing materials

The principle of a robust design assumes that the presence of the *backfill material* contributes not only to the geomechanical stability of the disposal system and to the heat dissipation, but, if possible, to overall safety as well (see also Section 3.3.1 and Table 3.7). A judicious choice of the composition of this material is indeed likely to significantly enhance the performance of the engineered barriers and, as a result, of the repository as a whole. The backfill material can thus

- help create an environment that is geochemically favourable to limiting the corrosion of the watertight packagings;
- help create an environment that is geochemically favourable to limiting the leaching of the waste matrices;
- assist in the removal of the gases generated by anaerobic corrosion, by radiolysis, and by the biodegradation of the organic components;
- contribute to the containment and retention of the radionuclides in the near field.

The nature of the proposed backfill material varies according to the type of gallery to be backfilled and the type of waste to be contained.

- The backfill material for the disposal galleries for the vitrified waste and spent fuel will be required to have a thermal conductivity that is high enough to allow effective transport of the heat through its thickness. This will prevent an excessive temperature increase around the waste packages and around the waste itself. The material that is currently under investigation is a mixture based on FoCa swelling clay. This bentonitic clay quarried in the Fourges-Cahaignes region of the Paris Basin is chemically compatible with the Boom Clay and can easily attain a swelling pressure of between 4 and 5 MPa, i.e., roughly the value of the lithostatic pressure, depending on the compacting density. The mixture, which will be used in the PRACLAY demonstration experiment, consists of 60 % by weight of swelling clay, 35 % sand, and 5 % graphite. Adding sand makes it possible to limit total swelling to prevent the surrounding zone being excessively compressed. The graphite is used to increase the thermal conductivity of the mixture from 1.5 to 4 $W \cdot m^{-1} \cdot K^{-1}$. Finally, the addition of glass frit could reduce the dissolution rate of the vitrified waste matrix.
- The backfill material for the disposal galleries for the other types of waste in the geological group with cement-based matrices could be rather similar to the waste matrix itself, i.e., based on a hydraulic binder. This has the advantage that the many radionuclides in the waste, especially the actinides, are poorly soluble in an alkaline solution. This backfill material could, however, alter the retention properties of the surrounding clay by the diffusion of an alkaline front from the repository, and its mechanical strength could be lower than that of the mixtures based on swelling clay.
- The backfill material used for the connecting gallery, the main galleries, and the access shafts must have a rheological behaviour that can ensure mechanical stability and optimum chemical compatibility with the surrounding clay formation. A mixture of sand and FoCa clay could be an option.

The *sealing material* will be required to play an important part in the safety function of ‘delaying and spreading the releases’. The material currently being analysed is a mixture of pellets and powder made from FoCa swelling clay. As well as its excellent swelling ability, this clay has outstanding rheological properties, including the ability to self-heal by plasticity should it crack. Its properties of radionuclide retention and diffusion are similar to those of the Boom Clay. A hydraulic conductivity of $10^{-12}\ \mathrm{m{\cdot}s^{-1}}$ (the typical order of magnitude for the Boom Clay) can easily be achieved for the mixture considered.

Although, as yet, there has been no detailed research into backfilling and sealing the main galleries and shafts, several backfilling and sealing experiments have been carried out in the HADES underground research facility. The most recent one, the European RESEAL experiment, started in 1996, initially set out to theoretically determine the general development requirements for sealing an access shaft. Its experimental phase, which is still in progress, mainly aims to demonstrate that it is possible to seal a gallery of representative diameter, i.e., the small shaft, with a material made from a mixture of pellets and powder of FoCa swelling clay, as long as this material has a hydraulic conductivity low enough to prevent the preferential migration of water and gas along the shaft support or in the disturbed zone and as long as it is capable of retaining its mechanical stability in the event of an accidental surge in pressure induced, for example, by gas generation in the repository. In practice, the hydraulic conductivity of the seal is of the order of $10^{-13}\ \mathrm{m{\cdot}s^{-1}}$.

Finally, given the considerable volume of the excavations, it must be possible to manufacture and install the *backfill and sealing materials* on an industrial scale and at an acceptable cost. In addition, the installation techniques will have to be carefully chosen and correctly applied to avoid significantly increasing the geomechanical disturbances in the surrounding formation.

The work being done on the backfill and sealing materials is receiving added benefit from international studies into the behaviour of bentonites, as these are considered options in most foreign disposal programmes. The future programme will aim to optimise the choice of backfill and sealing materials according to the different functions that they are required to perform in the disposal system. For the backfill material, this optimisation exercise will take particular account of the need to establish an environment capable of preventing the corrosion of the overpacks, and will benefit directly from the lessons learned from the construction of the OPHELIE mock-up.

3.5 Behaviour of radionuclides in the Boom Clay

The theoretical and experimental study as well as the understanding and modelling of the migration of radionuclides in the Boom Clay, and of retention processes in particular, have been of crucial importance ever since the start of the ONDRAF/NIRAS research and development programme into deep disposal. As long-term safety assessments have repeatedly shown (see Chapter 4), the Boom Clay represents indeed the main barrier to radionuclide migration from the waste emplaced in the repository towards the biosphere. The need for a better understanding of the migration mechanisms has, however, become imperative following the realisation that it is impossible to satisfactorily interpret the migration tests or describe the behaviour of certain classes of species in the Boom Clay using the existing models. These models assumed, among others, reversible sorption and thermodynamic equilibrium with no solubility limit, and had produced in some cases an incorrect assessment of the migration parameters, especially of the retardation factor *R*.

Species A general term describing the particles, atoms, defined compounds, or molecules present in a medium.

Speciation Description of the amounts and kinds of the species, forms, or chemical phases that are present.

Sorption A generic surface phenomenon, independent of the mechanisms involved, that may be either absorption or adsorption, or a combination of both.

Solubility Maximum concentration of an element measured in solution for the system considered, under well-defined physico-chemical conditions. The concentration in solution of the ions forming the solubility-limiting phase is determined by the equilibrium constant of dissolution (solubility product) and the equilibrium constants for the formation of all the other species (complexation constants).

The main two objectives of the 1990–2000 research and development programme as regards migration were, therefore, to understand and predict the radionuclide behaviour in the Boom Clay and, specifically,

- to identify the basic mechanisms governing migration;
- to reassess the migration parameters needed for long-term safety assessments.

Two classic tests can be used to study the migration of radionuclides in clay and to determine the values of their migration parameters, i.e., the diffusion-accessible porosity η, the retardation factor R, and the apparent diffusion coefficient D_{app}. These are, first, diffusion tests, in which the driving force is a concentration gradient, and, second, percolation tests, in which solutions are hydraulically forced through the pores of the clay. A new technique, electromigration, i.e., forced migration under an electric field, which can also be used to gather information about the speciation of diffusing species in solution, is currently being developed. Its applicability has already been tested successfully in a number of cases. It is a useful complement to the classic tests as it can be used to obtain migration parameters by a method based on an entirely different approach, thereby reducing the risk of experimental artefacts.

Retardation factor A term used to refer to phenomena of physisorption and surface complexation on functional groups of the clay, including in particular reversible and non-reversible linear sorption, ion exchanges and exchanges of ligands.

Diffusion-accessible porosity For the species considered, the fraction of total porosity saturated in water that is available for migration by diffusion.

Research on migration is conducted both in the surface laboratories and in the HADES underground research facility. The tests carried out in the underground facility aim

- to confirm the applicability of the migration parameters determined in the surface laboratory, both for the weakly sorbed or non-sorbed species and for the strongly sorbed species;
- to test the migration models on a large scale (linear increase in the scale by a factor of 50 between the tests in the surface laboratory on clay cores and the in situ tests performed in the underground facility). This aspect of the programme concerns the weakly sorbed or non-sorbed species (tritiated water or HTO, I^-, HCO_3^-, mobile organic matter); it does not concern the strongly sorbed species, given the very long periods of time that would be needed for their migration.

Research into migration is supported by conceptual and numerical modelling exercises and by involvement in international projects. The international studies mainly aim to test and compare the models used and to create quality databases. Geochemical modelling also contributes to the interpretation of migration tests (determining the speciation and the solubility of species in clay).

The species used in migration experiments are selected mainly on the basis of the results of long-term safety assessments. At the beginning of the 1990s, they fell into two categories:

- *the critical radionuclides*, i.e., those with the greatest radiological impact: ^{14}C, ^{99}Tc, ^{129}I, ^{135}Cs, and ^{237}Np.
- *the potentially critical radionuclides*: ^{79}Se, ^{93}Zr, and ^{107}Pd, and the isotopes of uranium, plutonium, americium, and curium.

Radium (^{226}Ra) and protactinium (^{231}Pa) were added later to the programme following the conclusions of an initial assessment of the direct disposal of spent fuel into the Boom Clay. Uranium, which was already part of the programme, has become highly important.

Studying the organic matter is just as important as studying the critical radionuclides, given the potential influence of the organic matter on the migration of radionuclides in general and on that of actinides in particular. A study looking specifically at the role of organic matter in actinide migration began in 1995. This includes migration tests with organic matter labelled with ^{14}C (single-labelled migration experiments) and with organic matter labelled with ^{14}C and contacted with ^{241}Am (double-labelled migration experiments).

Migration experiments are also being conducted with other species, however:

- species being studied to acquire a better understanding of the migration mechanisms at work in the clay. This applies to weakly sorbed and non-sorbed species such as tritiated water, strontium (Sr^{2+}), calcium (Ca^{2+}), halogen anions (Br^-, Cl^-), and organic molecules labelled with ^{14}C (sucrose, lactose, etc.);
- species that are used as analogues. Europium is used as an analogue of trivalent actinides, and small organic synthesis molecules are used as analogues of mobile organic matter.

3.5.1 Characteristics of the Boom Clay related to migration

Apart from the fact that radionuclides in the Boom Clay migrate mainly by diffusion, i.e., their migration is controlled by concentration gradients and is therefore very slow, the Boom Clay possesses a number of geochemical and physico-chemical characteristics that are very favourable to the retention of radionuclides:

- *it is a reducing and slightly alkaline medium* favouring the reduction of species sensitive to the redox potential to species of low solubility;
- *it has a high capacity for cation exchange*;
- *it acts as an ultrafilter for colloids*, especially organic colloids with which certain radionuclides are partially associated, thus restricting their mobility.

3.5.1.1 Dominance of diffusion

The Boom Clay beneath the Mol–Dessel nuclear zone is characterised by a very low vertical hydraulic conductivity ($K_v \approx 10^{-12}\ m{\cdot}s^{-1}$) and a very low natural hydraulic gradient (2 metres of water over 100 metres of clay thickness). Radionuclide migration is therefore controlled essentially by diffusion, with advection having only a secondary role. Two tests carried out in situ in the underground research facility illustrate this property very well. One of them, the test with tritiated water, involves large scales of space and time.

- A migration test on the metre scale, begun in 1988, clearly shows that the migration of tritiated water is a diffusive process. This makes the results of experiments obtained so far very consistent with the theoretical predictions calculated from a strictly diffusive model using the parameters determined in tests in the surface laboratory (Fig. 3.34). Tritium activity is currently being detected in filters at distances of 1 and 2 metres on either side of the injection filter, whereas no activity has yet been recorded in the filters that are at 3 and 4 metres from the injection filter.

- A percolation test with ^{134}Cs conducted over 7 years under a very high hydraulic gradient (600 to 1 300, whereas the natural gradient is 0.02) indicates an insignificant percolation effect (the activity profile in the clay core is virtually symmetrical relative to the initial position of the source), demonstrating that even under this extreme hydraulic gradient, the migration of the caesium is still mainly determined by diffusion (Fig. 3.35).

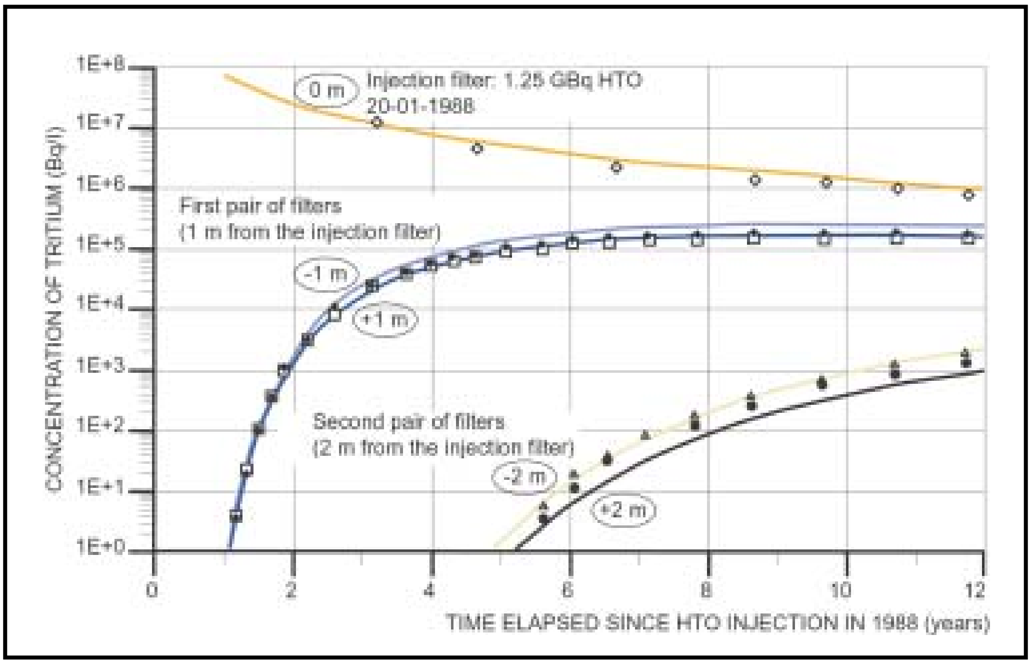


Figure 3.34 Comparison between experimental results and theoretical curves for the in situ migration test with tritiated water.

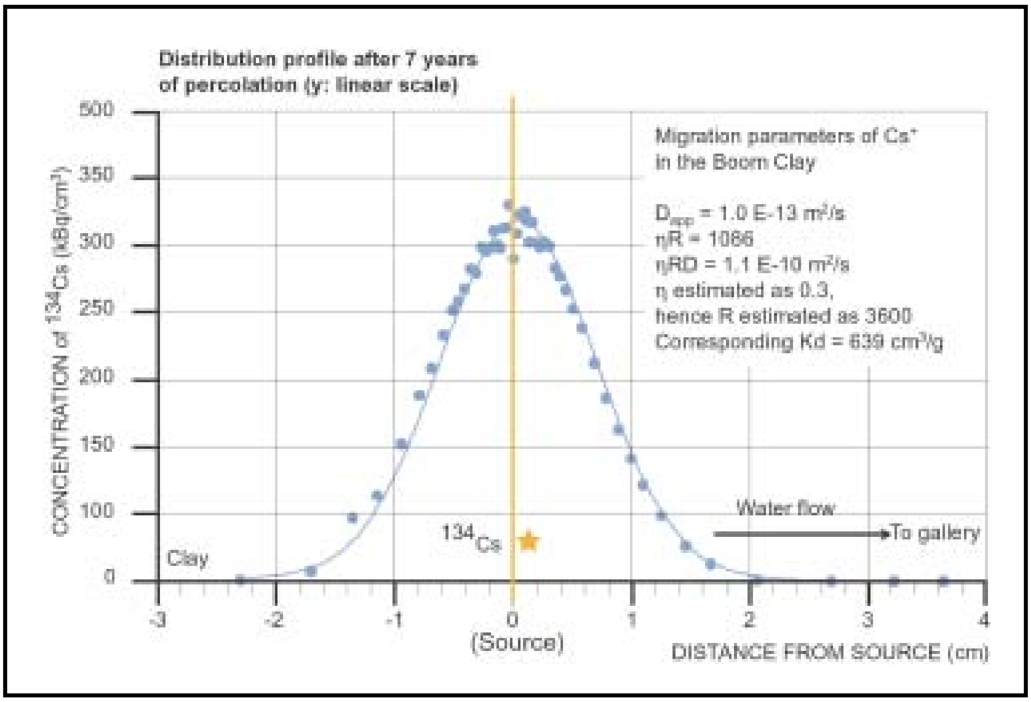


Figure 3.35 Activity profile of ^{134}Cs in the clay core for the in situ percolation test.

3.5.1.2 Geochemical characteristics

The Boom Clay is a reducing and slightly alkaline medium; this favours the reduction of species that are sensitive to the redox potential to species of low solubility. It has significant buffer capacities in terms of pH and E_h owing to the presence of minerals such as calcite, siderite, and pyrite at concentrations between 1 and 5 % by weight (Table 3.8). Its interstitial water has been in equilibrium with the minerals of the solid phase (dissolution/precipitation equilibrium) for a very long time, although it is currently impossible to determine exactly how long. The redox equilibria have been in place since the very beginning of sedimentation and were attained very early on due to the activity of sulphate-reducing and methanogenic bacteria, which quickly produced pyrite and then methane.

Table 3.8 Characteristics of the interstitial water in the Boom Clay.

Anions ($mol \cdot l^{-1}$)	
HCO_3^-	$1.36 \cdot 10^{-2}$
Cl^-	$7.61 \cdot 10^{-4}$
F^-	$1.89 \cdot 10^{-4}$
HPO_4^{2-}	$3.96 \cdot 10^{-5}$
Br^-	$6.13 \cdot 10^{-6}$
SO_4^{2-}	$2.08 \cdot 10^{-6}$
Cations ($mol \cdot l^{-1}$)	
Na^+	$1.77 \cdot 10^{-2}$
K^+	$2.81 \cdot 10^{-4}$
Mg^{2+}	$1.19 \cdot 10^{-4}$
Ca^{2+}	$9.98 \cdot 10^{-5}$
Fe (II/III)	$1.61 \cdot 10^{-5}$
Al (III)	$2.96 \cdot 10^{-6}$
Neutral species ($mol \cdot l^{-1}$)	
$B(OH)_3$	$6.93 \cdot 10^{-4}$
$Si(OH)_4$	$1.78 \cdot 10^{-4}$
Organic carbon in solution (DOC) (mg of $C \cdot l^{-1}$)	41.3 to 144
Physico-chemical parameters	
pH*	8.2 ± 0.05
E_h (V/SHE**)	– 0.250
Ionic conductivity ($mS \cdot cm^{-1}$)	1.8
Total quantity of dry matter ($mg \cdot l^{-1}$)	≈ 1500
Cation exchange capacity (CEC) for strontium (meq per 100 g)	24 ± 3
Cation exchange capacity (CEC) for calcium (meq per 100 g)	23 ± 3
Redox capacity ($meq \cdot g^{-1}$)	2

*: measured in situ without loss of CO_2 with an optode

**: redox potential relative to the standard hydrogen electrode

The Boom Clay is very sensitive to oxidation however (the oxidation of pyrite results in the production of sulphates and, depending on the calcite content in the environment, in acidification of the medium). This phenomenon, which was observed especially during the excavation of the underground facilities, is accompanied by a modification of the geochemical characteristics of the clay, which could lead to changes in the speciation and solubility of the radionuclides and modify the behaviour of the organic matter. In most cases, the oxidised form of the radionuclides sensitive to the redox potential (Se, Sn, Tc, U, Np, Pu) is characterised by a significantly higher solubility. The oxidation of the pyrite also involves the formation of insoluble hydrous ferric oxides, which have a very high sorption capacity. Should the thickness of the geochemically disturbed zone be significant, then the migration of species in the clay would have to be reassessed.

3.5.1.3 Interactions between clay and solutes

The constitutive minerals of the clay carry a permanent negative electrical charge on their surface, causing anions to be electrostatically repelled and cations to be sorbed. The diffusion-accessible porosity of the cations and neutral species ($\eta \approx 0.30$) such as tritiated water or dissolved silica ($Si(OH)_4$) is therefore greater than that of non-sorbed anions such as the iodide ion (I^-, $\eta \approx 0.12$). The sorption of cations depends not only on their affinity with the ligands on the surface, but also on their hydrated radius and their net electrical charge. The cationic radionuclides—Cs (I), Pd (II), Eu (III), Am (III), Cm (III), and Zr (IV)—and the species sensitive to the redox potential and easily reduced to weakly soluble species (Se, Tc, U, Np, Pu) are strongly retarded on the solid phase. A diffusion-accessible porosity of 0.30 is postulated for those anions for which a sorption process is observed (by exchange of ligands).

3.5.1.4 Presence of organic matter

The Boom Clay contains approximately 1 to 3 % by weight of organic matter, a very small proportion of which is in solution and is considered to be mobile (≈ 0.05 %). About half of this organic matter in solution, which consists of 70 % humic acids and 30 % fulvic acids and other small molecules, is characterised by a molecular weight of less than 1000.

While the formation of humic complexes (radionuclides–humic acids) can lead to an increase in the solubility of certain radionuclides, it can also involve a reduction in their mobile concentration. The Boom Clay, whose mean pore diameter is around 5 nm, acts indeed as an ultrafilter for the organic colloids with which the complexed radionuclides are partly associated, thereby limiting their mobility. The organic matter sorbed on the surface of the minerals and retarded by the filtration effect of the clay has a high sorption capacity for the actinides. As this capacity seems to be highest for those fractions with the highest molecular weight, the sorption of radionuclides on the immobile fraction should be encouraged. The organic matter at the surface of the clay minerals in the form of argillo-humic complexes would act as a kind of film that is highly complexing to metal cations. Several processes contribute to the formation of these complexes: exchanges of ligands, hydrophobic interactions, cation bridging, and even ultrafiltration by the clay.

3.5.2 Behaviour of radionuclides in the Boom Clay

The Boom Clay's potential for retaining radionuclides during their migration by diffusion and advection depends on the nature of the dominant retention processes and on the ability of the natural materials to retain the radionuclides, sorption generally being the first step in immobilisation (Table 3.9). Thus, if precipitation is the dominant process, the capacity of the natural barrier to impose and maintain reducing conditions will determine its retention properties. If sorption is the principal process, then the total concentration of sorption sites is the key factor. Finally, if the formation of solid solution and co-precipitation are the dominant processes, then the calcite content and other secondary mineral phases are the key parameters.

Table 3.9 Solid–solution interactions that may assist radionuclide retention in the Boom Clay, arranged in ascending order of reaction time.

Processes of radionuclide retention
Processes of migration
Anion exclusion
Molecular filtration
Processes of reversible and fast sorption
Physisorption like Van der Waals' sorption
Surface complexation on functional groups of the clay (linear and non-linear sorption, ion exchange, ligand exchange, etc.)
Processes of immobilisation (processes by which the solutes are incorporated into immobile solid phases over periods of time of relevance for safety assessments)
Formation of solid solution
Surface precipitation
Precipitation
Phase transformation (processes of ageing or alteration under the action of external factors, etc.)
Processes believed to have a very slow kinetics
Isotopic fractionation, etc.

Because of its high content in the Boom Clay, the organic matter can also induce specific interactions that affect the migration of certain radionuclides (Fig. 3.36).

The many tests conducted in the surface laboratory are used to differentiate radionuclide behaviours within the Boom Clay, of which there appear to be three groups (Fig. 3.37).

- The *fission products (Se, Tc, and Pd)* seem to be characterised by a weak sorption. Their concentration in solution, about 10^{-8} mol·l^{-1}, appears to be solubility limited.
- The *actinides (An) that are weakly sorbed (U and Np)* could be present in the Boom Clay in a neutral form ($An(OH)_4$) and/or as negatively-charged carbonated complexes, and this would explain their poor sorption. Their concentration in solution is in the range of 10^{-10} to 10^{-9} mol·l^{-1}.

- The behaviour of the *strongly sorbed trivalent actinides (Am and Cm) and trivalent or tetravalent plutonium* is determined by their interactions with the organic matter, which are the dominant processes. (For plutonium, this is an assumption inferred from the similarity of the behaviour of the three actinides, that must still be confirmed.) Their concentrations in solution range from 10^{-14} to 10^{-12} $\mathrm{mol \cdot l^{-1}}$. With the exception of hydrolysis reactions, the solution chemistry of the actinides in the Boom Clay may be seen as a competition between carbonates and humic and fulvic acids (complexation).

The factors and/or processes determining the behaviour of the studied species in the Boom Clay are shown in Table 3.10.

Table 3.10 Factors and/or processes determining radionuclide behaviour in the Boom Clay.

	I	Cs	C (HCO_3^-)	Se	Tc	Pd	U	Np	Pu	Am	Cm
E_h				+	+		+	+	+		
Organic matter									+(?)	+	+
Anion exclusion	+		+								
Molecular filtration									+	+	+
Sorption		++	+(?)				+	+	++	++	++
Immobilisation (solubility limits)				+	+	+	+	+			

?: to be confirmed

+: weakly or moderately retarded species

++: strongly retarded species

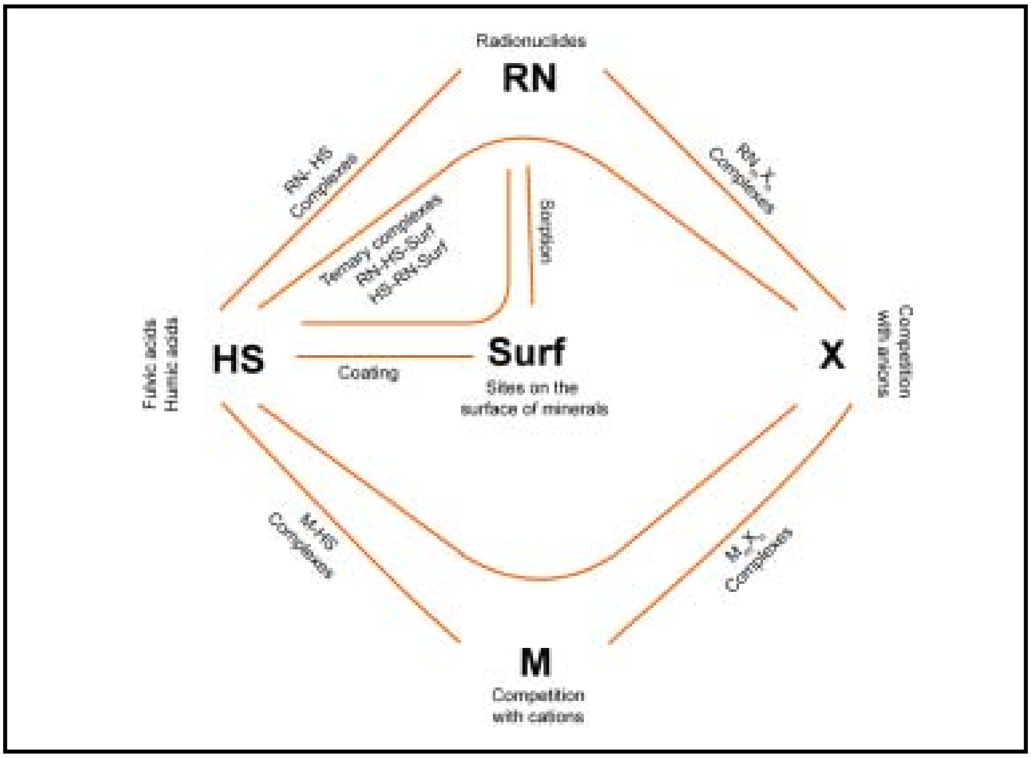


Figure 3.36 The possible interactions between the radionuclides and the organic matter.

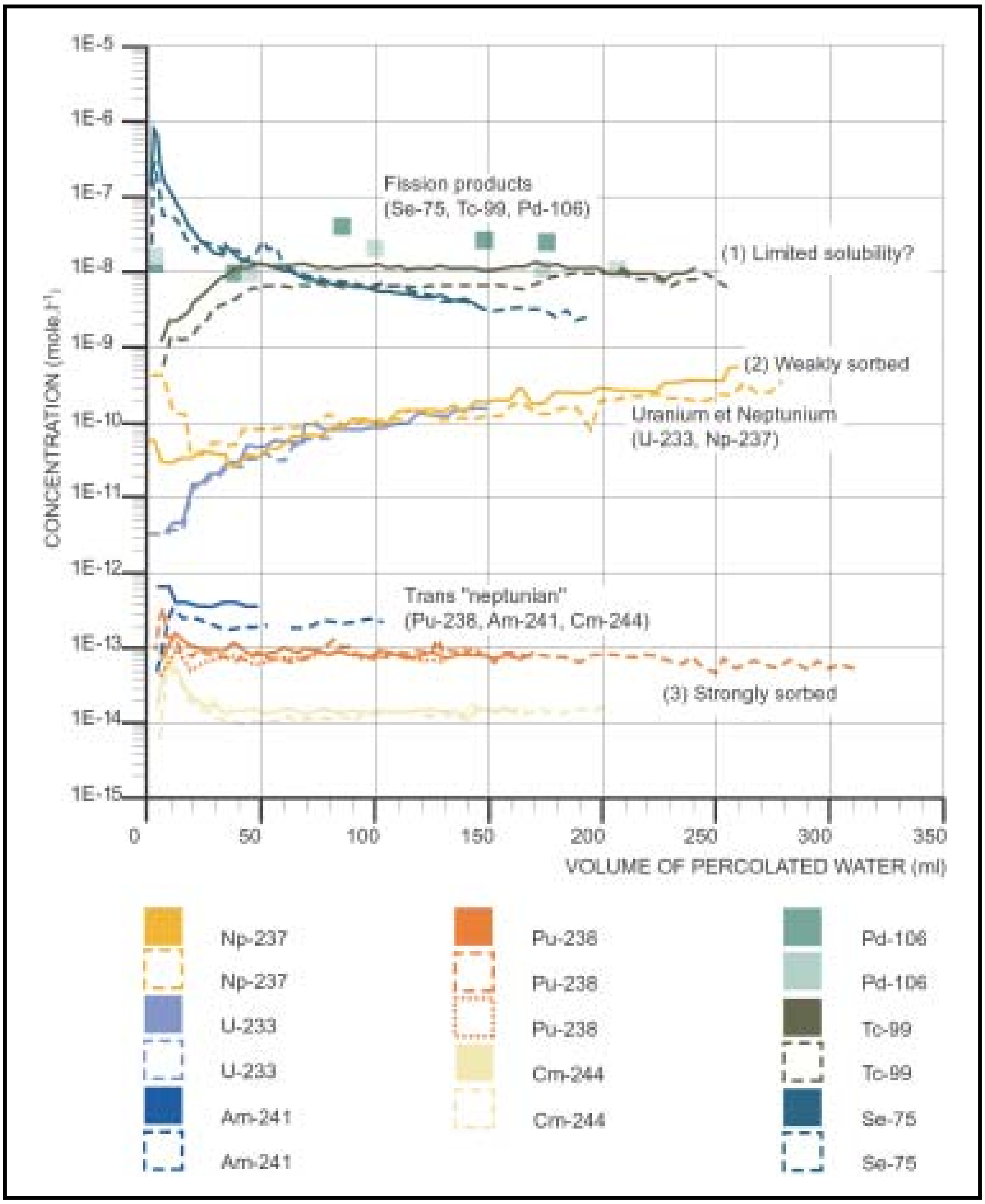


Figure 3.37 Distribution of radionuclides according to their concentrations in the percolation solutions as a function of time, for various migration tests.

3.5.3 Migration parameters

The level of uncertainty inherent to determining the key parameters that describe radionuclide migration in the Boom Clay (η, R, and D_{app}) and that form the basis for long-term safety assessments in particular varies widely according to the nature of the studied species.

There is no particular problem in determining the migration parameters of *species not sensitive to the redox potential*—weakly sorbed or non-sorbed (HCO_3^-, I^-) and strongly sorbed (Cs^+). In these cases, the validity of the models used has been demonstrated by large-scale in situ tests (I^-, HTO) and very long-term in situ percolation tests (Cs^+) (see Section 3.5.1.1). The level of confidence that can be given to the values selected for caesium and iodine is regarded as satisfactory. The value of the retardation factor R for the species HCO_3^- remains uncertain, however; it would be very low ($R \approx 1.5$).

Interpreting migration tests for the *elements that are strongly sorbed and/or sensitive to the redox potential* (Se, Tc, U, Np, Pu, Am, Cm) presents certain difficulties. Their resolution will require the adaptation of the migration models and, if necessary, of the experimental procedures used for preparing and conditioning radionuclide sources (source term). The models that have been specifically developed for determining the products ηR and the diffusion coefficients D_{app} from the experimental results, and which allow for diffusion and advection and assume linear and reversible sorption, are indeed perfectly suitable for elements characterised by a well-defined oxidation state and a high solubility under the experimental conditions encountered. They cannot, however, account for the precipitation of elements sensitive to the redox potential which are reduced to a form that is usually far less soluble. A rigorous interpretation of the experimental results must consider not just migration processes, but also the chemical processes of oxidation-reduction (kinetic aspects), the precipitation of insoluble phases and, if necessary, a process of irreversible sorption. The procedures for preparing and conditioning the radionuclide sources used in certain types of experiment will be adapted in order to introduce the elements in a chemical form close to their chemical equilibrium with respect to the Boom Clay. This will reduce the complexity of the experiments, especially for the elements sensitive to the redox potential, and assist the interpretation and modelling of experimental results. (Only pure diffusion tests have been conducted so far for certain elements, and these do not allow to determine the product ηR.)

3.5.4 Role of the organic matter

The presence of organic matter in the Boom Clay is a potentially important factor for radionuclide migration as its capacity to complex radionuclides (especially trivalent actinides) is high, and as a very small fraction of the organic matter is mobile. The study of its behaviour in the Boom Clay and of the behaviour of actinide–organic matter complexes has thus become a major topic of the migration research programme.

3.5.4.1 Ultrafiltration capacity of the Boom Clay

Fundamental lessons have been learned from the migration tests conducted in the surface laboratory on organic matter labelled with ^{14}C: the capacity of the Boom Clay to retain organic molecules increases with their molecular weight, i.e., with their size. The clay acts as an ultrafilter for molecules with a molecular weight above 100 000 (Fig. 3.38), the higher values of the distribution coefficient K_d (ratio of the sorbed fraction to the fraction in solution) reported in this case being ascribed to hydrophobic interactions with the solid phase. However, it has not yet been possible to explain the percolation of small molecules during tests on the fraction with a molecular weight over 100 000. Either these molecules were present in the initially injected sample or they have been generated in the medium by a continuous scission process of larger organic entities.

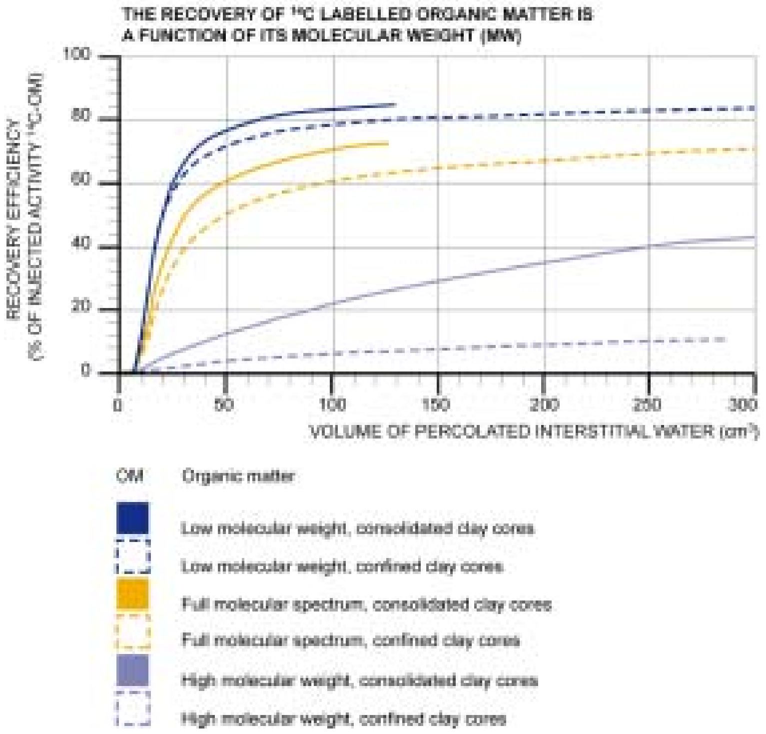


Figure 3.38 Elution profiles obtained with organic matter of different molecular weights labelled with ^{14}C (constant applied pressure in consolidated conditions; constant clay core volume in confined conditions).

The results of migration tests performed with organic matter have been modelled using a simple diffusion–advection migration model without taking into account the colloidal aspects. The values obtained for the diffusion coefficients D_{app} are comparable whatever the organic fraction considered, and are consistent with those reported previously ($D_{app} \approx 3 \cdot 10^{-11}$ $m^2 \cdot s^{-1}$). This could mean that they are all related to the same fraction of molecules, i.e., the small ones. Similarly, relative constant values of between 0.38 and 0.71 are obtained for the product ηR, except for the organic fraction with a molecular weight over 100 000. A first in situ test started in 1997 (piezometer parallel to the plane of sedimentation of the clay) and a second in 1998 (piezometer perpendicular to the plane of sedimentation of the clay). These are to confirm the applicability of the migration parameters determined in the surface laboratory and to test the migration models on a large scale.

3.5.4.2 Behaviour of americium

The study of the role played by the organic matter in the migration of the actinides in the Boom Clay has so far concentrated on the behaviour of americium, which is well known to interact strongly with organic matter. This study, carried out with organic matter labelled with ^{14}C and contacted with ^{241}Am, has already provided significant results on the behaviour of americium and has made it possible to confirm certain hypotheses.

- The americium, which is initially associated with the organic matter in solution, is then redistributed between the liquid and solid phases (mobile and immobile organic matter).
- The complexes formed by americium with the organic matter in solution are the principal vectors of its migration.
- The complexes formed by americium with the fractions of organic matter with the highest molecular weight are characterised by slower dissociation kinetics than their smaller counterparts.
- The molecular spectrum of the organic matter influences the migration of americium, with the different fractions making different contributions.

However, additional studies will be needed for a precise explanation of the difference observed between the results of tests with double tracers (^{14}C + ^{241}Am) and the results of percolation tests so as to permit a thorough selection of values of migration parameters for use in safety assessments. For the tests with double tracers, in which the americium is introduced in solution in a form complexed with the organic matter, the americium concentration measured in the solutions at the exit from the columns after an initial rapid *breakthrough* varies from 10^{-12} to $5{\cdot}10^{-12}$ $mol{\cdot}l^{-1}$ depending on the organic fractions considered. For the percolation tests, however, which use a filter impregnated with americium placed between two clay cores, the values obtained are in the range of 10^{-14} to 10^{-13} $mol{\cdot}l^{-1}$.

The differences in concentration observed between the results of the two types of tests are in all likelihood due to differences in the kinetics of the mechanisms involved, directly linked to the differences between the characteristics of the source terms used. It will be necessary to demonstrate that, in all cases, a steady state will be achieved within the transit time of the americium through the first metres of clay and that the mobile concentration of americium will effectively be from 10^{-14} to 10^{-13} $mol{\cdot}l^{-1}$.

3.5.4.3 Behaviour of uranium, neptunium, and plutonium

Although it is generally expected that the complexation of the actinides by the organic matter and/or the carbonates increases their solubility, the results obtained so far show that the organic matter in solution has little impact on the solubility of plutonium or of UO_2, and preliminary studies indicate that the carbonates have no significant effect on the solubility of neptunium or plutonium under the in situ Boom Clay conditions.

3.5.5 Variability of migration parameters over the thickness of the clay

A preliminary study designed to assess the vertical homogeneity of the Boom Clay in terms of its migration properties has already succeeded in demonstrating uniform migration properties for non-retarded species (Fig. 3.39). The retarded species still have to be studied. Specifically, migration tests with non-retarded or weakly retarded species were performed on samples taken over the whole thickness of the formation during the Mol-1 drilling campaign (see Section 3.2.2.2). The fifty tests on HTO and $^{131}I^-$ and the dozen tests on $H^{14}CO_3^-$ (about one measurement every two metres for the former and one every ten metres for the latter) have indicated values falling within the range of minimum and maximum values used for the long-term safety assessments.

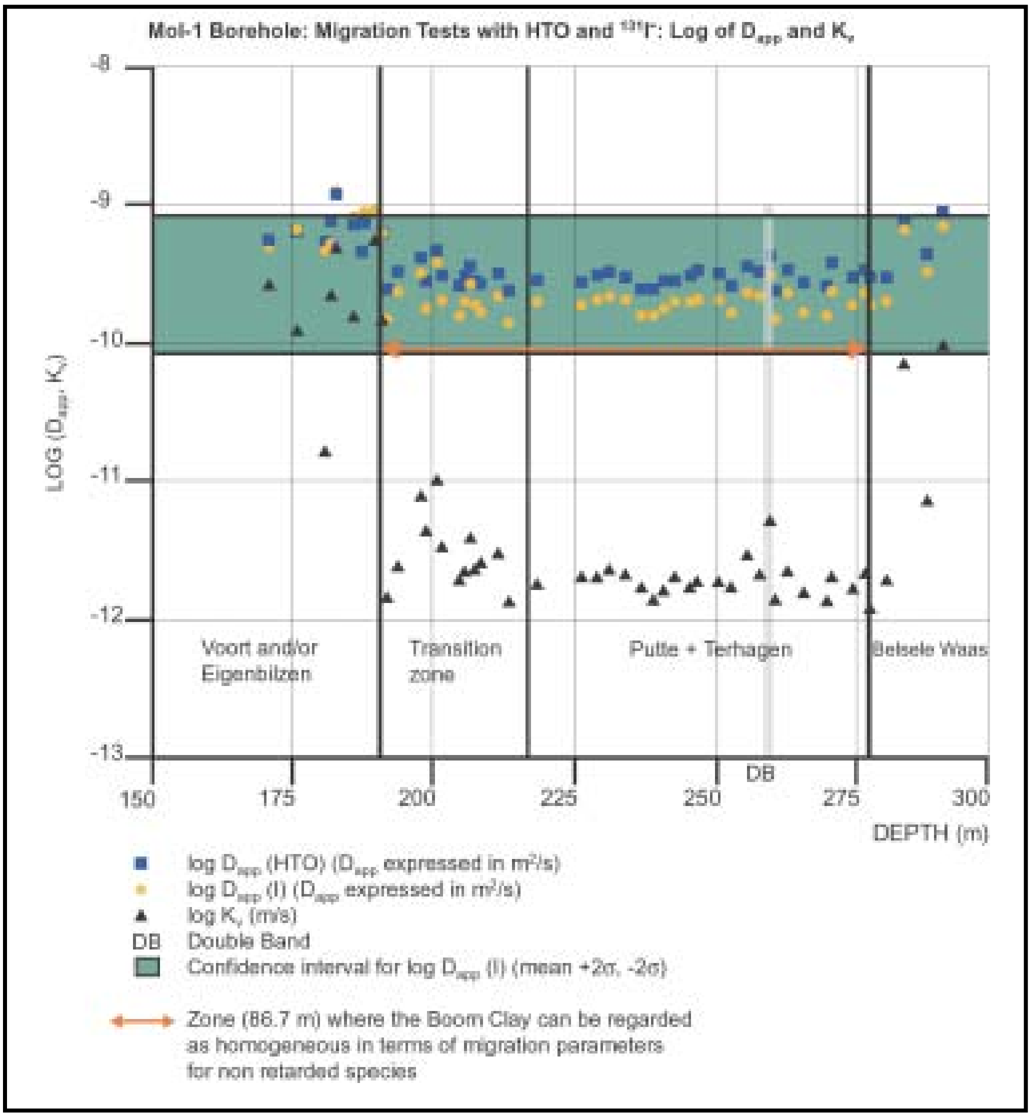


Figure 3.39 Variation in migration parameters for the species HTO and I^- and in hydraulic conductivity over the thickness of the Boom Clay at the site of the Mol-1 borehole.

3.5.6 Data used for the long-term safety assessments

The considerable progress achieved in recent years in understanding the chemistry of the elements in the Boom Clay has led to a significant revision of the values of the migration parameters of some of those elements. This is because the data that have been gathered have made it possible to better define the various processes controlling the behaviour of the elements in the clay and to take fuller account of their specific contribution. For elements characterised by a complex chemistry, especially those sensitive to the redox potential, the use of a source not in equilibrium with the medium in migration tests induces a number of reactions before a steady state is established. Using existing models to interpret these test results has therefore produced incorrect values in several cases.

The main advances that have led to a significant revision in the values of migration parameters (by several orders of magnitude in some cases) are as follows:

- *Distinction between processes of immobilisation (precipitation) and sorption* Initial confusion between these two phenomena led to believing that Se, Tc, U, and Np are strongly sorbed. It now appears, however, that it is the limited solubility of selenium and technetium that is very probably responsible for the retention observed in the Boom Clay. For uranium and neptunium, the process of immobilisation by precipitation remains dominant, although moderate sorption also appears to occur ($R = 40$).
- *Influence of the organic matter* The concept of operational solubility has been introduced to simulate the migration of a small mobile fraction for the trivalent elements (Sm, Ac, Am, Cm) and the tetravalent or trivalent plutonium that migrate without any apparent retardation. It is inferred from the values of concentrations measured in percolation solutions at the exit of columns, and is assumed to represent the non-retarded mobile fraction of the element considered. To calculate the migration of these elements in the Boom Clay, it is postulated, first, a concentration in solution equal to the operational solubility, and, second, a retardation factor R of 1. For uranium and neptunium, the values for solubility and for the retardation factor R have been calculated by modelling the elution profiles of percolation tests (parameter fitting). Although this is a different case ($R \neq 1$), because these values are indirectly inferred from values of concentrations measured at the exit of columns, the term ‘operational solubility’ is also used for these two elements by extension.

The validity of the approach based on the concept of operational solubility has not yet been justified for all the elements considered. It seems realistic for the actinides and trivalent lanthanides (Sm, Ac, Am, Cm), and preserves a wide safety margin. This is because the major fraction of these elements is very strongly sorbed on the clay surface (sorption by surface complexation on the organic matter associated with the argillaceous minerals and immobilised by ultrafiltration), and this greatly reduces their concentration in solution, with only a small fraction being mobile. For reasons of caution, the mobile species masked by the organic matter in solution are assumed to have difficulty interacting with the immobile organic component. The operational solubility approach must be used with caution for plutonium, however, as not enough is known about its behaviour, and is even more uncertain for uranium and neptunium. Conservatively, molecular diffusion coefficients D_p equal to that of mobile organic matter are used for Sm, Ac, Am, Cm, and Pu, and coefficients equal to that of tritiated water are used for U and Np.

Despite the progress made in understanding the mechanisms controlling the behaviour of the radionuclides in clay, it still seems too early to create a single reference database for the values of the key migration parameters, given the uncertainties still surrounding some classes of elements. Consequently, three data sets reflecting the development in the understanding of the element chemistry in the clay have been used in safety assessments:

- *set 1*: strong sorption considered for Se, Tc, U, and Np and for the actinides and trivalent lanthanides (the mobile fraction is disregarded);
- *set 2*: *R* is assumed to be equal to 1 for Se and Tc (and a solubility limit is taken into account);
- *set 2'*: application of the concept of operational solubility for Ac, Pu, Am, Cm, and Sm ($R = 1$), and a solubility limit and moderate sorption for U and Np ($R = 40$) are taken into account.

The database created for the different elements concerned is compiled in the form of *data collection forms*, based on a critical in-depth review both of the results obtained by programmes carried out by SCK•CEN and of the values extrapolated from data reported in literature. It is regularly updated as new results are obtained.

3.5.7 Outlook

The future migration programmes will form part of ongoing research work and will aim to increase the understanding of the element chemistry in the clay. This will improve the selection of the values of the migration parameters, the interpretation of tests, and the adaptation of the related models. In particular, these programmes will be required to

- determine the oxydation state of Pu and U;
- study the influence of the organic matter on the migration of Pu, U, Np, Am, Cm, Se, Tc, Pd, and Zr;
- demonstrate the relevance of the conservative approach based on the concept of operational solubility for Pu, Am, and Cm;
- determine the mechanisms responsible for the retardation of U, Pd, and Zr;
- study the speciation of U, Np, Pd, Zr, Se, and Tc;
- determine the solubility of Se and Tc;
- determine the behaviour and migration parameters of elements recently considered following the results of safety assessments, such as Sn and Pa, the latter being known to be strongly sorbed on a large number of materials;
- confirm or disprove the assumed weak retardation of the bicarbonate ion and, if appropriate, identify the mechanism responsible for this retardation;
- investigate the impact of the migration of chemical fronts and/or complexing species generated by the near field on the retention properties of the clay;
- reduce the uncertainties related to the parameters pH and E_h;
- continue to study the vertical homogeneity of the migration properties of the Boom Clay with elements representing the various families of elements concerned, and retarded species in particular (sensitive to the redox potential and/or to the presence of organic matter and/or strongly sorbed);

- characterise the organic matter, mainly in terms of its mobility in solution, the exchanges between mobile and immobile fractions, and the ageing processes governing its evolution over time. Ultimately, the characterisation of the organic matter must answer the fundamental question of whether it is continuously released in solution from the immobile pole or whether the dissolved organic matter is immobile.

The migration parameters will also be determined using the technique of electromigration as an alternative and independent control of the current methods. Finally, migration tests with the strongly retarded elements (long-term tests) will be continued.

3.6 Disturbances induced in the Boom Clay and its environment

The disturbances in the Boom Clay and its environment are induced by the radioactive waste itself, by the excavation of the repository, and by the presence of the underground facility.

3.6.1 Thermal disturbances

Over the past decade, the thermal effects of heat-emitting waste, that is, mainly the vitrified waste and spent fuel, have been the subject of experimental and theoretical studies. This is because this waste will continue to generate significant levels of heat for a period lasting from several centuries to several millennia after the cooling-down period preceding their disposal; this cooling-down period is currently fixed at 50 years but could be extended to 60 years. The resulting temperature increase will have an impact on both the near field and the far field. The strength of this impact, which will depend on the amplitude of heat emission and its duration, could have repercussions for the entire design of the repository, if it is shown to prematurely compromise the integrity of the engineered barriers or of the natural barrier. Based on present knowledge, however, the heating effects due to the presence of the waste do not cast doubt on the feasibility of the repository design and are compatible with the dimensions proposed for the repository and the selected materials. The thermal impact of the waste on the far field can, in any case, be reduced by modifying the geometry of the repository, if required. The PRACLAY demonstration experiment should supply valuable additional information in this field.

3.6.1.1 Experimental studies

Determining the thermal properties of the host formation is essential to assess the disturbances that may be induced by the presence of heat-emitting waste. Experiments conducted in situ indicate a thermal conductivity of 1.7 $W \cdot m^{-1} \cdot K^{-1}$ maximum for the saturated Boom Clay. Thus, it has only a low capacity for heat dissipation. (By comparison, the conductivity of carbon steel is around 50 $W \cdot m^{-1} \cdot K^{-1}$.) This characteristic is one of the major requirements on the design of the disposal facilities (see Section 3.3).

The CERBERUS experiment, which ran from 1987 to 1998, is the principal in situ study of the effects of disposal of a vitrified waste package on the Boom Clay and on various potential materials for the near field. Such a package was simulated by a group of ^{60}Co sources designed to create a representative field of gamma radiation, and by electrical heaters which increased the temperature in the argillaceous formation to over 100°C in places (Fig. 3.40). (This experiment was very conservative since, according to the reference design, the radiation field will be very strongly attenuated by the engineered barriers—see Section 3.6.4.) The main results of the CERBERUS experiment are as follows:

- *glass* The corrosion rate of the glass used as a matrix appears to decrease in a gamma radiation field.
- *packaging materials* The austenitic stainless steels, nickel alloy, titanium alloy, and pure titanium show no signs of corrosion; however, carbon steel, which is no longer considered as an overpack or packaging material, is severely corroded.
- *concrete* Concrete, which would be used as a lining material, is locally enriched with iron at the sample / clay interface.
- *Boom Clay* The mineralogical composition of the Boom Clay is not significantly modified by heating and radiation, the pH of the interstitial water remains approximately neutral, and its electrochemical potential remains reducing. The system of interstitial water pressures responds quickly to heating, and the thermal cycles induce mild consolidation of the clay.

3.6.1.2 Implications for the repository design

The properties of the materials proposed in the reference repository design and the interpretation of the experimental results have been used to establish an initial set of quantitative criteria. These define the maximum temperatures that are tolerable at various points in the disposal system and its environment.

In the *near field*, the heating may alter the physicochemical properties of the waste, the backfill material, and the structural material of the disposal galleries, as well as increase the corrosion rate of the packaging materials. The following maximum allowable temperatures have been selected:

- for the *vitrified waste*: 400°C; for safety reasons, this is 100°C below the temperature above which the structure of the matrix alters and its mechanical properties change;
- for the *spent fuel assemblies*: 350°C, to prevent an excessive pressure build-up by the helium present in the fuel rods;
- for the *backfill material*: 100°C, to prevent any physico-chemical alteration of the material and, in particular, to prevent any significant disturbance of the local hydraulic system following the increase in interstitial pressure. It is this temperature requirement on the backfill material that is the most decisive for the near field.

In the *far field*, the heating may modify the geochemical, geomechanical, and hydrogeological conditions in the clay as well as its mineralogy, and so alter its containment and retention properties. It can also modify the hydrogeological regime in the aquifers. The maximum allowable temperature increases are as follows:

- for the *clay*: about 85°C, in order not to exceed 100°C, given the fact that the initial temperature of the formation is 16°C. 100°C is the maximum temperature observed during the CERBERUS experiment, at which no significant change in the properties of the clay could be demonstrated.
- for the *Neogene Aquifer*: a maximum increase of 6°C on average over the thickness of the aquifer has been selected in the absence of any regulations governing the maximum acceptable temperature increase in the underground;
- for the *biosphere*: a maximum increase of 0.5°C has been selected.

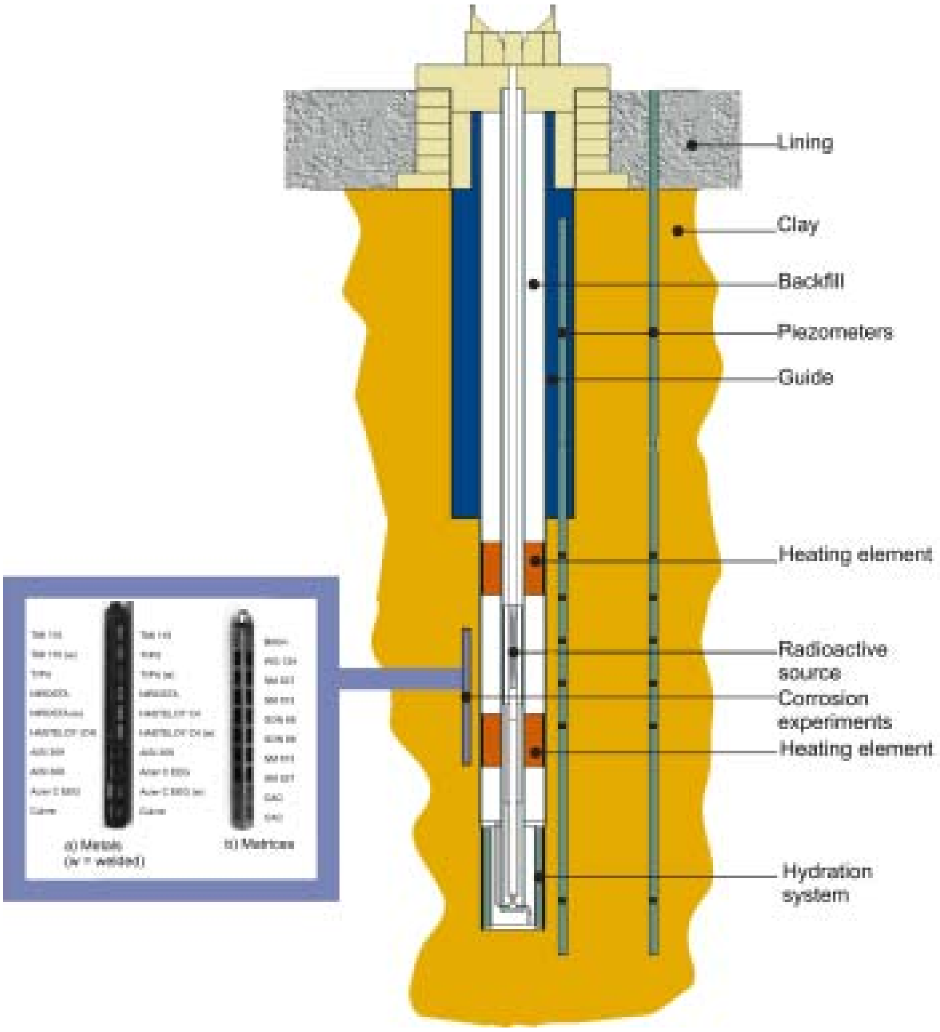


Figure 3.40 Schematic of the CERBERUS in situ experiment that combines a radiation field with a thermal field.

3.6.1.3 Thermal impact of the repository

Thermal calculations designed to quantify the maximum increases in temperature in the disposal system and its environment have been carried out using three burn-up rates for the spent fuel. (These temperature increases are defined as the difference between the local temperature due to the presence of the waste and the initial temperature of the argillaceous formation, which is approximately 16°C.)

After 50 years of interim storage on the surface, the maximum temperature increase in the vitrified waste packages that have been disposed of is between 160 and 200°C, depending on the value of thermal conductivity attributed to the backfill material, and occurs after about three years. This temperature increase drops in the void interfaces, i.e., between the primary package and the overpack, and between the overpack and the disposal tube, and is no more than about 80°C on the internal face of the gallery lining.

The disposal galleries for vitrified waste will have to be spaced at 40-metre intervals to achieve the criterion for the overlying aquifer. The result would be a maximum increase in temperature at the clay / aquifer interface of approximately 15°C. The maximum temperatures reached in the disposal system and its environment in such case are given in Figure 3.41 for various characteristic time frames. For the spent fuel, the minimum interval between disposal galleries varies from 80 to 110 metres, depending on the burn-up rate.

Future research work will initially focus on redefining criteria for an acceptable temperature increase for the various components of the disposal system and its environment. For the engineered barriers, these criteria could influence the choice of overpack and backfill materials. In particular, the options for a more efficient removal of the heat by alternative backfill materials that are more conductive than in the reference design should be studied. Defining criteria for the aquifers and the biosphere should take account of any regulatory requirements which apply, and include an examination of the chemical, mineralogical, and biological effects that could be induced by a temperature increase. If necessary, the geometry of the disposal facilities (distances between disposal galleries and between the waste packages within these galleries) could be reviewed to reduce the thermal impact on the aquifers and the biosphere.

3.6.2 Disturbances due to excavation

The evaluation of the disturbances induced in the Boom Clay by excavation implies necessarily as thorough an evaluation as possible of its geomechanical properties.

3.6.2.1 Geomechanical characterisation and modelling

The construction of the existing underground facility has been accompanied by intensive investigation programmes, with a view to optimising the excavation and lining techniques, and to gaining a better understanding of the geomechanical behaviour of the clay during and after excavation. Although a fair amount of confidence has been achieved in the quality

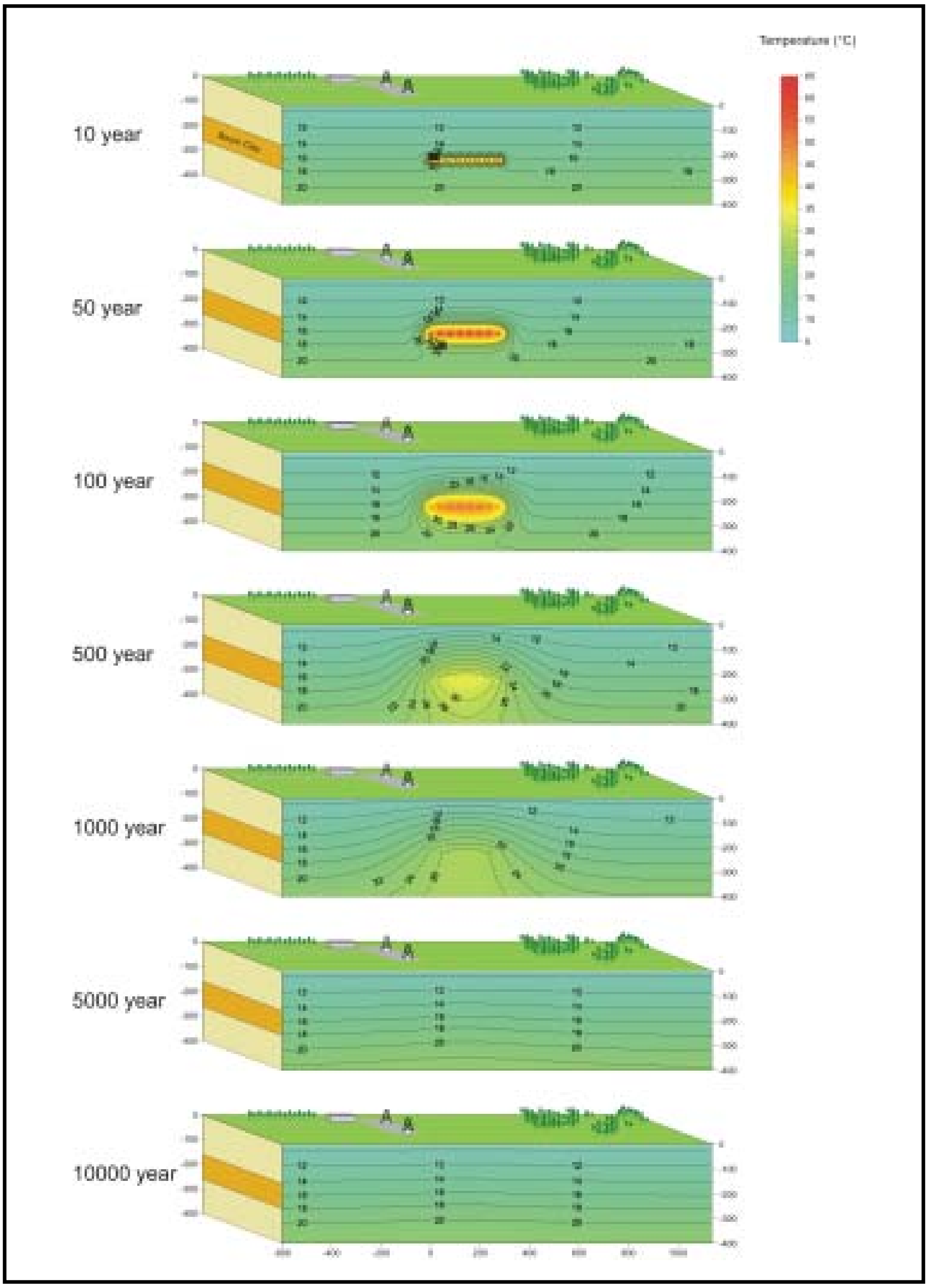


Figure 3.41 Maximum temperatures [°C] reached around a repository of vitrified waste.

of measurements of movements and interstitial pressures, measurements of total pressures are still difficult. These investigation programmes have been simulated many times by modelling teams in a number of countries. Different in situ experiments with and without a thermal load, some of which have included a study of the engineered barriers and their interactions with the host formation, have also made it possible to develop or verify (thermo)hydromechanical calculation codes.

The Boom Clay layer beneath the Mol–Dessel nuclear zone can be likened to a saturated porous medium with a solid phase (the argillaceous skeleton) and a fluid phase. The mechanics of continuous porous media can be used to describe its global behaviour from

- the behaviour of each phase (solid and liquid) taken separately;
- coupling relationships between the phases, i.e., relationships describing the effects of phases on one another.

Contrary to the initial notion that attributed qualities more typical of 'soils', i.e., unconsolidated rocks, to the Boom Clay, its behaviour lies actually on the borderline between soils and rocks. At the depth of the HADES facility, the lithostatic pressure is 4.5 MPa and the hydrostatic pressure is 2.2 MPa. This latter figure was recently measured in situ within the CLIPEX programme in a piezometer outside the zone of hydraulic influence of the underground facility. It corresponds perfectly with the pressure of a water column to the depth of the facilities. A slight anisotropy was noted between the vertical and horizontal effective stresses. The data given in Table 3.11 correspond with the undrained geomechanical characteristics of the Boom Clay around the existing facilities, assuming that the rock has a perfect elastic-plastic behaviour.

Table 3.11 Undrained geomechanical characteristics of the Boom Clay around the existing underground facilities (depth of 223 metres), assuming the clay has a perfect elastic-plastic behaviour.

Young's modulus, original tangent	E	200 to 400 MPa
Poisson's ratio	ν	0.4 to 0.45
Angle of friction	φ	4°
Cohesion	c	0.5 to 1 MPa
Plastic limit		23 to 29 %
Liquid limit		55 to 80 %
Plastic index		32 to 51 %
Coefficient of pressure of soils at rest	K_0	0.9

Measuring instruments installed in and around the Test Drift are used to assess the hydraulic responses (piezometers) and mechanical responses (inclinometers) of the rock during and after excavation. The results obtained have been used to calibrate numerous models of the behaviour of the Boom Clay. These demonstrate the importance of viscous effects that are not allowed for in conventional elastic-plastic models, which underestimate the movements and variations in interstitial pressure compared with the in situ measurements. Other, more sophisticated models allowing a smoother transition between the elastic and plastic states have been used. The results obtained with them are closer to actual observations but are still unable to account for the significant drops in interstitial pressure recorded during the excavation of the Test Drift. This excavation was not mechanised and proceeded at a slow pace, however, and this exacerbates the difficulties in understanding the excavation parameters, especially the over-excavation, and prevents proper calibration of the models (superimposition of instantaneous and delayed effects in the rock).

The process of allowing for the dependence of the behaviour of the Boom Clay on time has also been developed to take account of the delayed effects induced by the dissipation of the interstitial pressures and those due to the solid skeleton (viscosity). It has been shown that allowing for these effects leads to larger variations in interstitial pressures. However, identifying the parameters of these models from existing test results is still very difficult and will require a substantial effort in the future.

The CLIPEX experimental programme has been developed on the basis of the above findings. It will investigate the hydromechanical response, i.e., the movements and variations in total and interstitial pressure, of the formation during the excavation of the connecting gallery (between the second shaft and the Test Drift—Fig. 3.25) by instrumenting (in particular from the Test Drift end) the zone that will be excavated. Thus, for the first time in the Boom Clay, the parameters in the rock ahead of the working face will be measured directly, and there will also be direct measurement of the instantaneous convergence during excavation work (behind the cutting head of the tunnel boring machine—see Section 3.3.2.1). Compared with previous investigations, the CLIPEX programme will benefit from a better control over the excavation parameters thanks to the use of a tunnel boring machine, and from the ability to separate instantaneous effects from delayed effects. At the end of the programme, a comparison of experimental results with the 'blind' predictions of hydromechanical models should enable to improve the understanding and modelling of the behaviour of the Boom Clay and, in particular, the understanding of its response to excavation.

In the longer term, the study of the delayed effects will be intensified, in particular the change over time of the stresses exerted by the rock on the gallery linings and the deformation of the linings. From a hydromechanical point of view, understanding the distribution of stresses at the intersection of two galleries will require three-dimensional investigations; the information gathered during the excavation of the gallery needed for the PRACLAY experiment will be very useful in this regard. As well as studying hydromechanical behaviour, understanding and modelling such a demonstration experiment will have to take account of thermal couplings and of effects associated with the degree of saturation of the engineered barrier. This will require a major effort to comprehend the non-saturated behaviour of the materials used over the anticipated temperature ranges.

3.6.2.2 Excavation-disturbed zone

As described in Section 3.3.2.1, fractures appeared during the excavation of the starting chamber of the future connecting gallery at the base of the second shaft, causing large slabs of clay to slip. The rock was already decompressed at this point by the excavation of the shaft. As well as the obvious implications for mining safety, these fractures pose a series of questions about the understanding of the geomechanical behaviour of the Boom Clay and about its potential impact on the properties of the host formation and, hence, on the long-term safety of the repository.

The assumed continuity of the medium in the disturbed zone may have to be reconsidered to explain the significant drops in interstitial pressure (10 %) recorded during the excavation and observed in instrumented boreholes in the CLIPEX programme.

In plastic clays, the changes in hydraulic conductivity associated with fractures have a tendency to be ‘repaired’ by a phenomenon known as self-healing. In this respect, no significant variation in hydraulic conductivity was noted around the Test Drift a decade after it was excavated. Moreover, the initial conditions of hydrostatic pressure are rapidly restored after piezometers used for experiments on migration, gas injection, etc. are installed in the Boom Clay (see also Section 3.6.3.2). These observations are supported by the large-scale measurements of hydraulic conductivity carried out around the small shaft in the HADES facility (see Section 3.2.3.4), which give results comparable with the value for the undisturbed clay. All these observations indicate that the self-healing process occurs relatively soon after excavation. To confirm these observations, a number of studies have been launched with a view to

- estimating the intensity and extent of the zone disturbed by the excavation of the second shaft and the starting chamber of the connecting gallery (cored boreholes, geophysical measurements);
- confirming the restoration of the initial conditions of hydraulic conductivity in the disturbed zone (installation of piezometers);
- establishing the origins of the fissures and fractures (induced solely by the excavation or induced by the reactivation of previous natural discontinuities);
- interpreting the drops in hydraulic pressure observed during the construction of the second shaft;
- assessing the secondary disturbances due to fracturing (oxidation of the clay and in particular of the pyrite);
- acquiring a more in-depth understanding of the phenomena controlling the self-healing properties of the clay under conditions representative of those found around the deep repository (theoretical and experimental studies and modelling of the fracturing and healing processes).

Finally, it will be necessary to assess the impact of this fracturing and its long-term evolution on the repository design and on safety. In particular, it will be necessary to define criteria for acceptable disturbance in the Boom Clay during excavation, especially in terms of radionuclide migration parameters. It could also prove necessary to reconsider the thickness of the disturbed zone used in safety assessments. Currently, it is conservatively estimated that construction work and the presence of the repository could lead to long-term perturbations of migration parameters in a 5-metre-thick zone around the disposal galleries.

3.6.3 Disturbances due to gases

The assessment of disturbances which could be induced by the production, accumulation, and migration of gases in the disposal system has undergone a large number of developments over the past ten years, mainly as part of joint international projects. The information gathered by the Belgian programme accounts for a significant portion of the knowledge that is now available. These developments relate mainly to experimental and modelling aspects of the processes involved, while the impact on long-term radiological safety has only received relatively basic consideration through the assessment of an altered-evolution scenario (see Section 4.3.3).

3.6.3.1 Gas generation

For the category C waste (vitrified waste and spent fuel), anaerobic corrosion and radiolysis are the main mechanisms of gas generation. The radiolysis of the Boom Clay will be greatly limited, however, by the presence of the engineered barriers and the retention of alpha-emitting radionuclides in the backfill material (see Section 3.6.4).

The rate of generalised anaerobic corrosion of stainless steels in the presence of Boom Clay is very slow, even zero, as has been found by experiments and during the day-to-day operation of the HADES underground research facility. This rate has been cautiously fixed at 0.05 μm per year for assessments relating to gas generation. Such a rate is all the more conservative as it is localised corrosion processes, which generate little gas, that predominate in such steels (pitting corrosion, stress corrosion, intergranular corrosion, etc.).

For the category B waste, apart from the fact that the existing steels are of the carbon steel type and far more susceptible to generalised anaerobic corrosion, the microbial degradation and radiolysis of organic matter must also be considered as mechanisms of gas generation. Here again, the production of hydrogen by anaerobic corrosion of metals is the most important process. Laboratory and in situ experiments indicate that, in the presence of Boom Clay, carbon steel suffers generalised corrosion estimated conservatively at 1 μm per year. As an initial assessment, it has been shown experimentally that the production of gas by microbial degradation could be disregarded given the small volumes that are generated.

The gas produced by anaerobic corrosion of metals is initially hydrogen, but all of the experiments indicate a rapid conversion (over a period lasting several days to several months) of the hydrogen (H_2) to methane (CH_4), due probably to the action of methanogenic bacteria in the Boom Clay. This conversion reduces the amount of gas produced by a factor of 4, although this is cautiously disregarded in safety assessments.

The future programme will concentrate on the availability of water in the near field and the evolution over time of its geochemistry, with a view to assessing the kinetics of gas generation. Continuing research into the corrosion of the metals proposed as components of the disposal facilities should also make it possible to dispense with the ultra-conservative rates of generalised corrosion used up to now for the stainless steels. It will be necessary to define the importance and consequences of the specific phenomena of gas generation for the bituminised waste, such as the microbial activity, internal radiolysis and, in the particular case of the Eurobitum waste, the generation of nitrogen from nitrates in the presence of nitrate-reducing bacteria.

3.6.3.2 Gas transport

Both the diffusion and advection of hydrogen and methane through the Boom Clay have been studied experimentally (in situ and in permeameter, oedometer, isostatic, and triaxial cells) and by means of models.

The opportunities for transport by diffusion in the host formation (i.e., as gas dissolved in the interstitial water) are very limited, especially for hydrogen. (The apparent diffusion coefficient of hydrogen is close to that of tritiated water.) The continuous conversion of hydrogen to methane makes it difficult to interpret the experimental data. Because it is more soluble, methane displays a higher diffusive flux, though this remains to be confirmed.

The low capacity for diffusion of the generated gases poses a risk of accumulation of a gas phase and, hence, of a pressure build-up in the near field. Such a pressure build-up could lead to the expulsion of the interstitial water in the Boom Clay on the one hand and to the creation of preferential migration pathways in the host formation (fracturing) on the other hand. Since only a small fraction of the interstitial water in the Boom Clay is mobile, it is mainly the latter advective mechanism that needs to be considered. Experiments carried out in situ and in the laboratory have shown the strong coupling between the distribution of geomechanical stresses in the argillaceous rock and the pressure above which the rock would fracture under the pressure from the gas. Preferential migration pathways would, thus, be created when the gas pressure exceeds the minimum total stress; the fracture plane is at right angles to that stress. The degree of desaturation of the clay during fracturing is only a few per cent of the total porosity, suggesting that the resulting movement of interstitial water is minimal. The fractures created in this way are very permeable to gas, and so the initial pressure would quickly drop. Experiments clearly show a process of self-healing of the preferential pathways when gas injection ceases or the pressure is reduced. Thus, the gas migrates episodically as a function of the cycles of opening and closing of the preferential pathways controlled by balance between the gas pressure and the distribution of effective stresses.

A migration test with tritiated water has shown that after fracturing and self-healing, the clay had recovered its initial properties. In this in situ experiment, the preferential pathway created by fracturing was kept open for one year before the injection of gas and tritiated water was halted.

Several conceptual models have been developed to gain a better understanding of the phenomena at work in the transport of gas in the Boom Clay, on an experimental scale. The discontinuous variation in the conductivity of the clay relative to the gas (creation of preferential pathways) makes it impossible to use conventional models based on the simple laws of two-phase flow. Given the initial encouraging results that have been obtained, it will be necessary to continue the work on modelling the couplings between the geomechanical conditions controlling gas propagation, fracturing, and the evolution of fractures. In future, it will also be necessary to study the temporal and spatial extrapolation of the conceptual model or models, and to explore their simplification with a view to their incorporation into long-term safety assessments. There has been a recent initiative at European level in this field.

It will also be interesting to analyse the impact of the excavation-disturbed zone on the creation and evolution of fractures potentially induced by gas pressure, and to determine the properties of the preferential migration pathways.

The current understanding of gas transport in the Boom Clay can be summarised as follows:

- if the generation of gas is below the diffusion capacity of the clay, then only dissolved gas is present;
- if gas generation exceeds the diffusion capacity, then the partial pressure of the gas increases until it exceeds the local interstitial pressure (2.2 MPa); when this happens, a gas phase is created and the gas bubbles that are formed displace the interstitial water in the clay to a limited extent (two-phase flow);
- when the gas pressure exceeds the lithostatic pressure locally (4.5 MPa), fracturing occurs, and a preferential migration pathway is created.

3.6.3.3 Impact on the Boom Clay

In the reference repository design for the vitrified waste, the anticipated rate of gas generation by generalised anaerobic corrosion (of the steel in the primary packages, the overpacks, and the disposal tube) is sufficiently low for the hydrogen that is generated and converted to methane to be dissipated by diffusion through the Boom Clay. A gas phase could form if this conversion is not effective, but the pressures should still be below the level at which the host formation would fracture.

With the category B waste, the generation of both hydrogen and methane will result in the formation of a gas phase; the creation of preferential pathways by fracturing is probable if the hydrogen is not converted to methane.

The weakness of the two-phase flows and the capacity for self-healing of the preferential migration pathways potentially generated by gas pressure should restrict the overall impact of the gases on the host formation, despite their minimal capacity to diffuse through the Boom Clay.

3.6.4 Disturbances due to radiation

A large proportion of the gamma radiation produced by the high-level waste (category C) will be absorbed within the engineered barriers: only a negligible fraction will reach the Boom Clay. The radiation levels at the interface between the gallery lining and the Boom Clay will be too low to significantly affect the geochemistry and mineralogy of the environment.

Even so, the impact on the Boom Clay of a field of intense gamma radiation combined with a thermal field has been studied during the CERBERUS in situ experiment. For this experiment, sources of ^{60}Co with a total activity equivalent to that of a package of vitrified waste were installed in situ in the immediate vicinity of the clay for 5 years (see Section 3.6.1). The experiment has shown that, even for much higher dose rates than will occur under repository conditions (several orders of magnitude higher, because of the direct contact between the sources and the clay), gamma radiation has no significant effect on either the mineralogy and geochemistry of the Boom Clay or on the migration of americium (a radionuclide sensitive to complexation with organic matter) and technetium (a radionuclide sensitive to the redox potential). A process of coalescence of the organic matter and the formation of oxalate, sulphate, and thiosulphate ions was noted however. The corrosion of the metals could be adversely affected by the presence of thiosulphates, and so their influence has been studied (see Section 3.4.2.1).

Alpha radiation will be insignificant in the far field for a number of reasons:

- the solubility of the actinides is very low and this limits their migration through the interface between the engineered barriers and the clay;
- the activity of the alpha emitters with a short half-life—those with a high specific activity—will have decreased significantly in the near field following sorption on the engineered barriers and on their degradation products.

It can therefore be concluded that disturbances of radiochemical origin will be negligible for the host formation.

3.6.5 Geochemical disturbances

The long-term maintenance of the favourable geochemical conditions of the Boom Clay, especially where the retention of radionuclides is concerned, is an important aspect in the assessment of the performance of the host formation. The phenomena involved are mainly

- the oxidation of the pyrite and organic matter by the atmospheric oxygen in the galleries;
- the migration of chemical fronts generated by the near field (alkaline plume resulting from the use of cement or concrete, leaching of sodium nitrate);
- the impact on the solubility and sorption of radionuclides of degradation products of organic compounds, especially cellulose.

To these disturbances can be added the migration of potentially chemotoxic species.

3.6.5.1 Migration of chemotoxic species

As well as the radiological risk, the radioactive waste may pose a risk of chemotoxicity to humans and the environment. Since the publication of the SAFIR report, this aspect has been the subject of a preliminary analysis to assess the impact on the environment of toxic compounds present in category B and C waste. This was done by comparing the maximum levels of toxic elements in the aquifers with the standards that apply to drinking water. This study, completed in 1995, examined mainly the migration of metals (pure chemical elements) for the normal-evolution scenario of the repository (see Section 4.2.2.1). It showed that, subject to certain accepted hypotheses, the chemotoxicity of the waste in the geological group does not compromise the safety of the repository. This is not surprising given that most of the metals are present in solution in a cationic form and that positively charged species are strongly sorbed on the Boom Clay. The methodology used to assess the chemical toxicity of a repository involved the following:

- characterising the source term, i.e., drawing up a quantitative inventory of the metal elements in the waste likely to eventually reach the aquifers;
- from this inventory, selecting the elements to be included in a study of migration in the Boom Clay;
- studying the migration of these elements in the Boom Clay.

Of the 54 elements identified, the elements to be used in migration studies were selected on the basis of three types of criteria (the *comparison of chemical toxicity and radiological toxicity*, the *similarity of the chemical properties of the lanthanides*, and *solubility*). The final selection comprised 24 elements: B, Cr, Mn, Co, Ni, Zn, Ge, As, Br, Rb, Sr, Y, Mo, Tc, Cd, In, Sb, Cs, Ba, Sm, W, Hg, Pb, and U.

The initial migration assessments were conservative, based on diffusion with no solubility limits (i.e., the elements are fully soluble in the interstitial clay water). In a second phase, which only considered the elements whose concentrations at the clay / aquifer interface were above one milligram per litre, solubility limits were applied where known.

A comparison of concentrations at the clay / aquifer interface with Flemish drinking water standards (1992 legislation, in accord with European recommendations) suggests that the chemotoxicity of the waste disposed of into the Boom Clay is not a safety-limiting factor. The four elements whose calculated maximum concentrations in the aquifers are closest to the maximum permitted levels and which thus have the greatest potential for chemotoxicity, namely, boron, nickel, molybdenum, and uranium, actually have concentrations that are systematically a factor of 100 below the relevant standards. (So far as possible, standards governing elements having close chemical properties were used for the metals not covered by these regulations. In the case of samarium and uranium, for which there were no standards at the time, their maximum concentrations in the aquifers, $1.7 \cdot 10^{-9}$ $g \cdot l^{-1}$ and $2.5 \cdot 10^{-8}$ $g \cdot l^{-1}$ respectively, are significantly below the most severe standard, in this case the limit for mercury, which is 10^{-6} $g \cdot l^{-1}$).

Given the quantities of metals associated with the waste, however, it is not impossible for the sorption sites within the clay to be saturated in the immediate environment of the repository. This would lead to a reduction of the retardation factors and an increase in the maximum concentrations in the aquifers.

The chemotoxicity of the waste that is to be emplaced in the deep repository will have to be reassessed as part of the future programme, especially on the basis of a confirmation of the inventories that are present. The potential for, and consequences of, a competition between sorption of radionuclides and sorption of metal elements in the near field and in the Boom Clay will also have to be analysed.

3.6.5.2 Migration of chemical fronts

The oxidation of the 1 to 5 % pyrite present in the Boom Clay takes place on contact with air in three stages. First, the pyrite is oxidised, with the release of protons (acidification);

then, the calcite present in the clay is dissolved (neutralisation); finally, calcium ions are replaced by sodium ions from the clay minerals. As a result, the interstitial water of the Boom Clay becomes of the sodium sulphate type. Apart from sulphates, the oxidation of the clay also produces thiosulphate ions, whose significance for the pitting corrosion of the metal barriers has been demonstrated. It is important to stress, however, the very localised nature of the oxidation of the pyrite, and that no acid fluid has ever been collected in the underground facility around the various piezometers in operation.

The oxidation of the clay on contact with air and the progression rate of the oxidation front will have to be quantified in order to define the maximum periods allowed for the various operational phases of the disposal facility. Given that a lining will be installed rapidly during excavation of the galleries and that oxygen transport in the clay will be controlled by diffusion, a limited oxidation is expected. A study has recently begun to investigate the oxidation of the clay along fractures induced by the excavation of the underground facilities.

An alkaline front could be generated by the degradation of the concrete and cement used, for instance, for the gallery lining, as a waste matrix, or as backfill material. Such an alkaline plume could alter the geochemistry and mineralogy of the clay (dissolution/ precipitation of minerals, cation exchanges, etc.) and, hence, its migration properties and the speciation of the radionuclides.

An initial assessment indicates that the thickness of the host formation likely to be disturbed by an alkaline front induced by the degradation of the lining of the disposal galleries for vitrified waste should be of the order of several tens of centimetres. This assessment is based on the reactivity of the minerals that make up the clay (hydrolysis of the alumino-silicates in an alkaline environment). In addition to these reactions, the clay will help neutralise the alkalinity of the concrete by the permanent supply of bicarbonates. For disposal galleries for category B waste that are backfilled with a hydraulic cement, the extent of the alkaline disturbance in the clay should be more significant. As yet, however, neither the extent of the disturbance nor its possible impact on the migration of radionuclides has been quantified. These issues will be examined in a number of research programmes that have recently begun. A low alkaline cement could be used for the linings and backfill, should this prove necessary.

Another recently launched study will investigate the influence of the migration of a sodium nitrate front, of which there are some 750 tonnes in the bituminised waste produced in Eurobitum.

Organic compounds, especially cellulose derivatives, are present in certain waste streams. Given the potential impact of the products of cellulose degradation in an anaerobic and alkaline environment on the solubility and sorption of the radionuclides, priority has been given to this task. The partial results that are available suggest that the products of cellulose degradation have little effect on the speciation and solubility of plutonium and americium in the clay.

3.7 Biosphere modelling

Biosphere modelling aims to obtain an assessment of the radiological impact of the release of radionuclides from a disposal system into the biosphere. The estimated individual radiological impact corresponds to the annual effective dose for an individual of the reference group (see also Sections 2.1 and 4.3.1.1).

Reference group
A group comprising individuals whose exposure to a source is relatively homogeneous and representative of that of individuals who, among the population, are more particularly exposed to that source.

Since the SAFIR report was published, large-scale international projects (the BIOMOVS and BIOMASS programmes of the IAEA) have developed a systematic methodology for developing conceptual and mathematical models of the biosphere. This methodology has been applied to the local context of the Mol–Dessel nuclear zone. Practically, the model of the biosphere starts from consideration of the normal-evolution scenario, in which the biosphere is assumed to be unchanging. It is used in safety assessments to calculate the doses to an individual of the reference group on the basis of radionuclide flows and concentrations in the aquifers. Given the long periods of time over which the radionuclides are released, it assumes that the ratios of concentrations in the various compartments of the biosphere remain constant, or can be considered as an average over time for the parameters that vary. It is therefore an equilibrium model.

The radionuclides eventually released by the disposal system will be transported by the groundwater until they reach different types of *receptors* that will give them access to the biosphere (Fig. 3.42). For the biosphere modelling of the Mol–Dessel nuclear zone, the radionuclides can enter the biosphere via the following three types of receptor:

- the *wells*, which are assumed to have been drilled into the aquifer around the periphery of the disposal facility and downstream of it, at the point of maximum radionuclide concentrations;
- the *water courses*, which will disperse the contamination;
- the *soil* layer that is penetrated by the roots of plants.

Once in the receptors, the radionuclides will continue to disperse into the biosphere by *transfer* to other media, either naturally or as a result of human intervention, and it is these media which will form the sources of exposure for humans. The principal modes of transfer are as follows:

- contaminated well water may be used as a source of drinking water, for irrigating crops and pastures, and for watering livestock;
- contaminated water in water courses can, if they are large enough, be ingested by fish or contaminate the sediments deposited on their beds;
- the radionuclides contained in the contaminated soils, whether directly by groundwater or by irrigation by the contaminated water, can be ingested by livestock or absorbed by the roots of plants which grow, or which are cultivated there, and subsequently ingested by livestock or by humans.

Finally, the main *pathways of radiological exposure* due to the use of receptors and supports by humans, or even due to their mere presence, are the following:

- the *ingestion* of contaminated drinking water and foods (fruit, vegetables, milk, meat, fish);
- the *inhalation* of dust in suspension in the air above contaminated fields and of radon exhaled by the soil and coming from radium-bearing waste;
- the *external irradiation* of the soil to individuals who would be on the contaminated fields or on the banks of rivers whose sediments are contaminated.

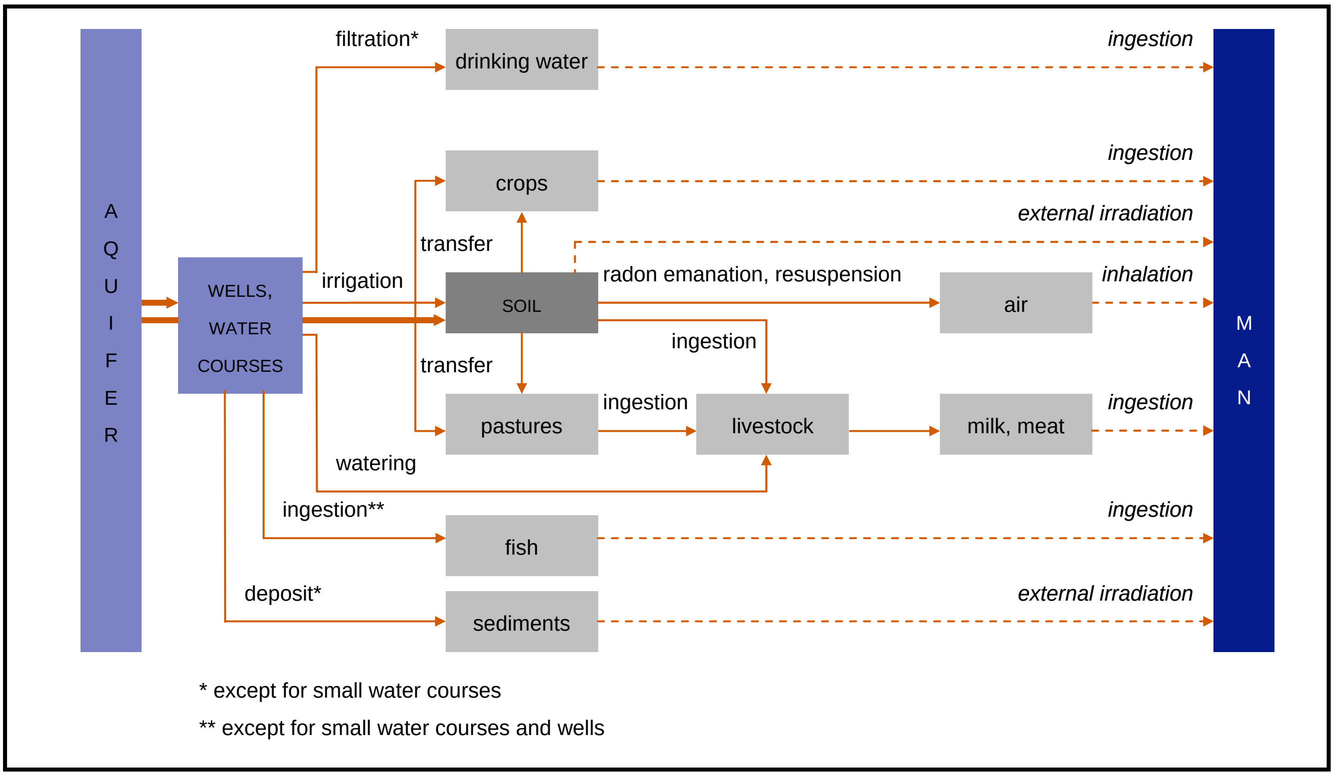


Figure 3.42 Model of the biosphere. The different exposure pathways of humans to ionising radiation for the Mol–Dessel nuclear zone following the transfer of radionuclides from the aquifer to the biosphere receptors, and from there to the other media of the biosphere.

The concentrations of radionuclides in the compartments of the biosphere can be used to calculate the resulting exposure and the individual dose.

By using transfer factors between the various compartments of the biosphere (e.g., soil to pasture, cow to milk, etc.), it is possible to calculate the concentrations of radionuclides in the exposure media as a function of the concentrations in the receptors. Thus, it is possible to inter-relate the concentrations in the various compartments.

The calculation of anticipated annual individual doses then assumes that all of the potential exposure pathways that can significantly contribute to the exposure of individuals of the reference group are taken into consideration. Doses are thus calculated from the concentrations of radionuclides in all the biosphere compartments that are relevant.

The doses to individuals of the reference group can be divided into three main categories. They are calculated using the dose coefficients recommended by the ICRP.

- The *dose by ingestion* is the product of the concentrations in drinking water and food multiplied by the quantities consumed annually and by the dose coefficients for ingestion.
- The *dose by inhalation* is only used for farmers in their fields. It is the product of the concentrations in the air multiplied by the quantities of contaminated air inhaled annually and by the dose coefficients for inhalation.
- The *dose by external irradiation* is used for farmers in their fields and fishermen on riverbanks. It is the product of the concentrations in the soil or sediments multiplied by the annual exposure times and by the dose rate coefficients for external irradiation.

The final results of these calculations are expressed as dose conversion factors, i.e., the annual maximum dose for a given concentration in the wells, water courses, or soils.

3.8 The Ypresian Clays as an alternative host formation

3.8.1 Overall context

As mentioned in Section 3.2.1, ONDRAF/NIRAS has conducted a study of an alternative host formation at the request of the SAFIR Evaluation Commission (1990). This is with a view to providing an alternative solution, should the Boom Clay prove to have a prohibitive flaw, i.e., one that would prevent it from performing its long-term safety functions without it being possible to use engineered barriers to overcome this.

As with the Boom Clay, the research and development programme for the Ypresian Clays is methodological, and considers a reference site—the Doel nuclear zone—without prejudging the actual location where the proposed disposal solution would be implemented. This programme aims to assess the potential of the Ypresian Clays as a host formation in terms of safety and feasibility. It mainly involves geoscientific characterisation and migration studies but has not, so far, considered aspects relating to the design of the disposal facilities.

The knowledge acquired by ONDRAF/NIRAS about the Ypresian Clays has been sourced from an inventory of data on the argillaceous formations of the Ieper Group. It is also based on the results of a series of boreholes drilled at Doel in order to

- obtain undisturbed samples of Ypresian Clays and their surrounding sands for the purpose of general characterisation and for migration tests;
- conduct a major programme of high-resolution wireline logging;
- carry out hydraulic injection tests;
- install piezometers.

In terms of lithology and geometry, the Kortrijk Formation seemed to be the most favourable within the Ieper Group, and research has therefore focused on this formation. As regards terminology, the ONDRAF/NIRAS programme uses the term ‘Ypresian Clays’ to refer to the most argillaceous layers in the Ieper Group, i.e., the Saint-Maur, Moen, and Aalbeke Members in the Kortrijk Formation, and the Kortemark Member, which belongs to the Tielt Formation.

The results obtained in the boreholes are still being interpreted. Thus, it is not yet possible to make full use of the data or to draw any specific conclusions as to the potential of the Ypresian Clays as a host formation.

3.8.2 Geographical and geological framework

The Doel nuclear zone is to the north of the city of Antwerpen on the left bank of the River Schelde (Fig. 3.2); the landscape consists mainly of Schelde polders. The topography is very flat, with no point rising higher than 10 metres above sea level. The region is part of the Flemish Valley, an important system of valleys of Pleistocene age, which have been infilled by heterogeneous sediments (fluvial sands, peats) and are, in turn, overlain by a layer of aeolian sands seldom more than 5 metres thick. The whole region is part of the Schelde drainage area and is characterised by the presence of a dense network of ditches and canals used for artificial drainage.

Lithostratigraphy

The term ‘Ypresian Clays’ refers to the clays that were deposited during the Ypresian period, which is part of the Eocene and lasted from 54 to 49 million years ago. In terms of lithostratigraphy, the Ypresian Clays belong to the Ieper Group, specifically to the Kortrijk Formation, which is divided into four members. From the oldest to the youngest, these are the Mont-Héribu, Saint-Maur, Moen, and Aalbeke Members. The Mont-Héribu Member consists of alternating layers of silty clays and very fine sands, which are overlain by the clays of the Saint-Maur Member. The Moen Member is a heterogeneous complex of clays, silts, and very fine sands containing a number of shell-rich and glauconitic strata. This complex is overlaid by the Aalbeke Member, which is mainly argillaceous. Due to its almost total lack of sand, the Aalbeke Member is the purest deposit of marine clay in the Belgian Tertiary. The Kortemark Member, which actually belongs to the Tielt Formation that overlies the Aalbeke Member, is also argillaceous, consisting of compact clays that are rich in silt.

The Kortrijk Formation outcrops in the region of the same name and thickens towards the north and the west (Fig. 3.43). Owing to its low northward dip, the top of the formation in the northern part of the Province of Antwerpen is at a depth of over 400 metres. The most homogeneous member of the Kortrijk Formation is the Saint-Maur Member. This argillaceous band is the only one to have been deposited throughout the whole of the sedimentary basin; the occurrence of other members depends on their location within the basin.

Tectonic context

The Doel nuclear zone is part of a region whose geology is dominated by the presence of the Brabant Massif, which is of Paleozoic age. In contrast with the Campine Basin, the Cretaceous formations directly overlie the Paleozoic.

The whole of northwest Belgium is subsiding at a rate of some 0.5 mm a year relative to the reference point (Uccle). Subsidence may be greater locally due to intensive groundwater pumping.

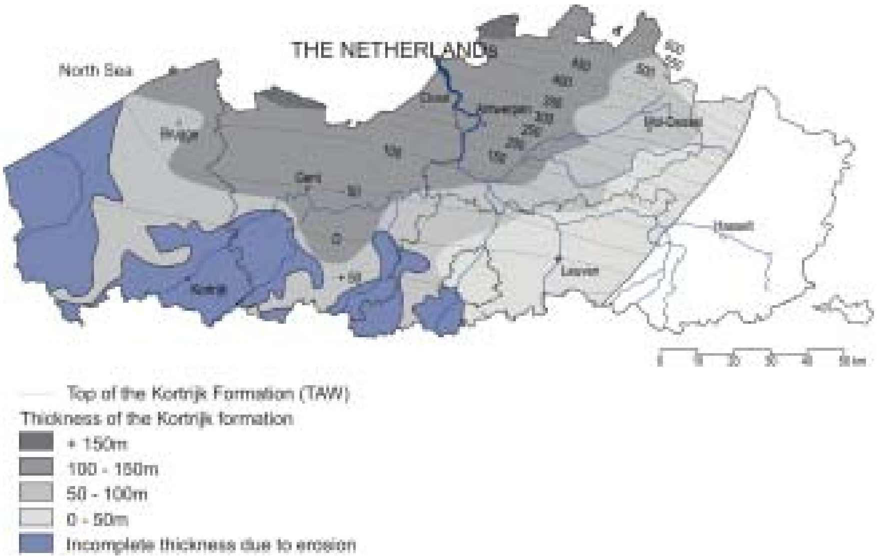


Figure 3.43 Thickness of the Kortrijk Formation and depth to its top surface.

The Brabant Massif is cut by a series of faults trending northeast and west–northwest, which do not normally extend upwards into the Cretaceous or Tertiary formations. This massif is tectonically active, as demonstrated by the Oudenaerde earthquake of 1938, which was associated with an intensity of VII around its epicentre. On a map of the maximum recorded intensities (isomacroseismic map), Doel lies in a zone where intensities reach between VI and V.

Seismic reflection surveys carried out in the North Sea have given evidence of extensive faulting within the Kortrijk Formation. Such structures are also found in a number of clay pits. These faults are thought to have been induced by the expulsion of water during the gradual burial of this formation. Their impact on present-day groundwater flow is not known.

Hydrogeology

Aquifers are found above and below the Kortrijk Formation. The groundwater flow within them is highly influenced by intensive groundwater pumping, to the extent that the overall movement of groundwater is downwards. Without pumping, groundwater flow would be upwards. This shows the sensitivity of the hydrogeological system, not just to anthropogenic disturbances, but also to disturbances that may be induced by climatic change.

3.8.3 Characteristics of the Ypresian Clays at Doel

The preliminary results reported below are based on an interpretation of the wireline loggings in the Doel boreholes, hydraulic tests conducted both in situ and in the laboratory, and laboratory tests on cored sections. Importantly, difficulties encountered during drilling made it impossible to obtain ideal borehole conditions for the wireline loggings.

Beneath the Doel nuclear zone, the Ypresian Clays, i.e., the Kortrijk Formation and the Kortemark Member, represent a total continuous thickness of 114 metres.

Mineralogy

The carbonate content in the Kortrijk Formation is generally below 2 %, except for the central part of the Moen Member, where it can attain 5 %. The base of the Kortemark Member is also richer in limestone. The organic matter content in the formation is low and evenly distributed. The sandy fraction consists mainly of quartz, feldspars, opaque minerals, and small fossil fragments. The non-clay minerals of the silty fraction are predominantly feldspars as well as quartz and carbonates. The mineralogy of the clays in the silty fraction is dominated by illite and kaolinite. (The base of the Saint-Maur Member contains up to 30 % kaolinite.)

The swelling clays (smectite) account for over half the argillaceous fraction of the Kortrijk Formation, illite being the other dominant mineral. The Saint-Maur Member is characterised by having more than 75 % of clay minerals and a high kaolinite content. The percentage of smectite increases in the Moen Member at the expense of kaolinite. The clay of Aalbeke consists almost exclusively (89 %) of clay minerals.

Physical and geomechanical properties

The water content (as a percentage of dry weight) decreases as depth increases, from 34 to 16 %, with a mean of 27 %. The total porosity shows a parallel decrease from 48 to 32 %.

The thermal properties of samples representative of the different stratigraphical units of the Ieper Group have been determined. The thermal conductivity of the wet samples is low, and varies between 0.7 and 1.1 $W \cdot m^{-1} \cdot K^{-1}$.

The Aalbeke Member has a very high plasticity index and swelling pressure (150 % and 1.72 MPa respectively) as was to be expected from its high clay content. The difficulties experienced with borehole stability suggest a low mechanical strength for these clays and, hence, potential problems in the excavation of underground facilities.

Hydraulic conductivity

The hydraulic conductivity of the Ypresian Clays is comparable with the values measured locally for the Boom Clay (between 10^{-11} $m \cdot s^{-1}$ and 10^{-12} $m \cdot s^{-1}$). The Saint-Maur and Aalbeke Members present the lowest values.

The in situ injection tests indicate values of hydraulic conductivity that are systematically higher (by one or two orders of magnitude) than the laboratory measurements. This could be the result of an anisotropy in the hydraulic conductivities, although this alone could not explain the extent of the observed differences, which are probably linked to the measurement methods themselves. The in situ tests influence the host formation over a diameter of several metres around the boreholes, whereas the laboratory measurements are confined to just a few cubic centimetres.

Geochemical and migration properties

The interstitial water of the Kortrijk Formation is saline to brackish (between 6000 and 13500 $mg \cdot l^{-1}$ of Cl^-).

Migration tests with tritiated water and iodine have been conducted on cores from the Doel-1 borehole in order, first, to determine the migration parameters of the Ypresian Clays for non-retarded radionuclides, and, second, to assess the homogeneity of this formation in terms of migration. The migration parameters (ηR and D_{app}) obtained for HTO and $^{131}I^-$ are comparable with those of the Boom Clay. Within the limitations of the data, the Ypresian Clays intercepted by the Doel-1 borehole appear to be relatively homogeneous from the point of view of the migration parameters of non-retarded radionuclides.

3.8.4 Outlook

Future work on the characterisation of the Ypresian Clays will concentrate first on interpreting and applying the data which have been acquired so far and which are still being obtained. An initial assessment of the performance of the natural barrier should be carried out on this basis.

Although the degree of knowledge to be acquired for the alternative solution need not yet be on a par with that which is available for the reference solution, it will be important to give detailed consideration to the specifics of the Ypresian Clays as opposed to the Boom Clay, especially with a view to assessing the scope for transferring information between one formation and the other. The specifics that are likely to have a direct impact on the feasibility or safety of the repository include

- the low mechanical strength: this raises issues about the feasibility of underground excavations;
- the presence of saline interstitial water, the impact of which on the choice of materials for the engineered barriers and on the design of the disposal facilities will have to be

investigated (corrosion of metals, behaviour of swelling clays, etc.). In addition, the speciation and migration of certain radionuclides, especially those sensitive to the redox potential and to the presence of complexing agents, may well be altered;

- the low thermal conductivity: this raises issues about the dissipation of the heat generated by the heat-emitting waste;
- the possible presence of preferential migration pathways (faults) in the formation: their role in the transfer of fluids will have to be investigated.

Given the significant lateral variability of the lithological characteristics of the Ypresian Clays, it will also be essential to examine the representative character of the Doel nuclear zone towards the properties that can be expected from this host formation.

4 Assessing long-term radiological safety: normal-evolution scenario and altered-evolution scenarios

The primary objective of assessing the long-term radiological safety of a deep disposal system is to show in an indirect, yet convincing, manner that, whatever the timescales considered, the potential radiological consequences of such a system remain within limits that are deemed acceptable. The assessments involve testing the performance of such a system for all of the possible relevant evolution scenarios, by using different models and calculation codes as well as different quantitative and qualitative arguments. To make the calculations possible, however, they are based on a simplified system with a simplified functioning. The simplifying assumptions, including those that relate to the evolution of the system over time, are always carefully selected, so that they result in principle in an overestimate of the actual future radiological impact. The results of safety assessments must therefore be seen as purely indicative: they are not predictions.

Assessing the long-term safety of a deep repository is a lengthy iterative process. The assessments presented in the SAFIR 2 report, most of which were begun in early 1997, are based on the five safety assessments conducted in the first phase of the methodological research and development programme of ONDRAF/NIRAS and SCK•CEN (1974–1989) and in the first half of its second phase (Table 4.1). These assessments were undertaken as part of European Commission projects, except for the third one. They have gradually evolved from initially exploratory and highly simplified assessments towards assessments that are increasingly better argued and more detailed, as they are able to make use of increasingly more accurate and reliable experimental data and increasingly efficient calculation codes.

Generally speaking thus, since the SAFIR report, the methodology of long-term safety assessments, especially the development of scenarios, has been developed and systematised on the basis not just of data from previous studies, but also of international developments in the field. Today, this methodology is an efficient tool for testing and understanding the functioning of the disposal system as a whole and of its different components taken separately. This has made it possible to better identify the processes and characteristics that determine the safety of the system and the different types of uncertainty that cannot be eliminated and their relative importance. These uncertainties, and above all the fact that they increase rapidly as the disposal system evolves over time, can now be allowed for more effectively thanks to the introduction of alternative modes of reasoning and calculation and the use of different safety indicators for the different phases in the evolution of the system.

Whereas the SAFIR report only considered the long-term radiological safety of a deep repository for the vitrified waste, the subsequent safety assessments have examined the radiological impact of virtually every class of waste in categories B and C that will have to be placed in a deep repository. The emphasis, however, has been placed on the three waste classes with the highest specific activities: the vitrified waste, the spent fuel, and the hulls and endpieces. The inventory of the other waste classes still remains to be specified, and the repository design for these waste classes has not yet been developed. Moreover, the long-term safety assessments undertaken so far have focused on the normal-evolution scenario; only preliminary and partial assessments have been performed for the altered-evolution scenarios. Finally, given the difference in the extent of existing knowledge about the Boom Clay and the Ypresian Clays, these assessments relate only to a reference disposal facility constructed in the Boom Clay beneath the Mol–Dessel nuclear zone.

This chapter devoted to the assessment of the long-term radiological safety of a deep repository explains the methodology that has been developed, including the methodology for scenario development, justifies the introduction of additional safety indicators as a complement to conventional indicators of radiological safety, and presents the principal results of the assessments. Specifically, all of the assessments carried out for all of the scenarios considered confirm the predominant role of the geological barrier. Finally, this chapter deals very briefly with the issue of the sub-criticality within a deep repository.

Table 4.1 Overview of safety assessments for the deep repository conducted prior to 1996 as part of the Belgian programme.

	PAGIS (1988)	PACOMA (1990)	Updating 1990 (1992)	Spent fuel (1995)	EVEREST (1996)
Objectives	To develop a methodology for assessing the safety of a deep repository and make an initial assessment of its long-term radiological impact	To supplement the results of PAGIS	To update the results of PAGIS and PACOMA based on new data from the Belgian nuclear programme and from research	To make a first safety assessment of the direct disposal of spent fuel by applying the methodology of the Updating 1990 study	To determine systematically and quantitatively the different sources of uncertainties and their relative importance in a safety assessment
Basic data					
source term	vitrified waste	category B waste	vitrified and category B waste	spent fuel	vitrified and category B waste
inventory	← 8180 tU →		← 4895 tU →		
indicators	← dose and risk, individual and collective →			← individual dose →	
scenarios	← 1 of normal evolution, 3 of altered evolution →			1 of normal evolution	several, more realistic
calculations	← deterministic and stochastic →				
models	← highly simplified →			revised	more complex
Principal results	■ development of a systematic methodology ■ identification of the determining components for safety (esp. clay) ■ indications that the studied solution can be safe ■ the most critical RN: ^{237}Np, ^{99}Tc, and ^{135}Cs (^{129}I and ^{36}Cl were not studied)	■ confirmation of the main results of PAGIS ■ indications that the studied solution can be safe ■ the most critical RN: ^{14}C, ^{129}I, ^{79}Se, and ^{99}Tc	■ confirmation of the results of PAGIS and PACOMA: the maximum radiological impact is well below the acceptable radiological impact	■ the maximum annual dose is approx. 100 × below that due to natural radioactivity and increases with the burn-up ■ confirmation of the importance of migration and the solubility limit of the RN ■ the most critical RN: ^{129}I, ^{14}C, ^{237}Np, ^{226}Ra, and ^{231}Pa	■ the doses are 2 to 100 × below the doses of the Updating 1990 study ■ demonstration of the potential importance of the Darcy velocity in the aquifers, and of parameters describing migration through the clay
Recommendations	To study in depth the mechanisms of migration of the main RN in the Boom Clay		To prepare a detailed inventory of the critical RN (esp. ^{129}I), study the near and far fields, and accurately assess the role of the aquifers and the biosphere	To study the decay of fuel pellets	To systematise the definition of the scenarios, specify the solubility limit of the critical RN, and study their complexation and the effects of gas migration in greater depth

4.1 Methodology of long-term safety assessments

The methodology of long-term safety assessments, the aim of which is to test the performance of the disposal system, has become much more systematic since the SAFIR report was published. This methodology is based on a broad consensus at international level, especially within the European Commission, the IAEA, and the NEA, and is both stepwise and iterative (Fig. 4.1). It is *stepwise*, because each phase of the implementation of the disposal system is required to undergo an intermediate safety assessment. This helps define the priorities for future research and identify any modifications that must be made to the system to enhance its safety during a subsequent phase of the project. This process is one which lasts several decades; it began with the methodological research and development work and will eventually end with a decision to leave the repository site unsupervised, that is, to release the site for unrestricted use. It is *iterative*, because the different steps of each safety assessment are carried out in a 'loop' until the accuracy of the results related to the level of safety achieved is deemed to be sufficient. This level of safety then becomes the subject of a statement, which is not just a comparison of the calculated radiological impact with the safety requirements or criteria, such as the dose constraint, but also and primarily an assessment of the reliability of the results and of the margin that exists for optimising the solution. This statement is then submitted for independent critical review, for example by the safety authorities or by an appropriate commission, who decide whether or not the process may move on to the next phase of the programme.

During each of the phases leading up to the implementation of the disposal system, the safety assessment is based on three types of information:

- the *safety strategy*, which guides the entire approach used to reach the implementation of a safe disposal solution and to argue that this solution is safe;
- the *intrinsic characteristics of the disposal system* that determine its safety, in other words, the properties of the disposal system and the contribution they are expected to make to the safety functions, the quality of the disposal system, as well as the method of construction, operation, closure, and control of the disposal facility;
- the *information that allows a scientifically correct and convincing assessment of the long-term safety* offered by the disposal system, in other words, the methodology of the safety assessments, accompanied by the necessary quality assurance and quality management.

The methodology of the safety assessments is based on a 'scenario' approach and comprises two major steps: scenario development and scenario assessment.

4.1.1 Scenario development

The process of scenario development (see Section 4.2), which involves identifying and describing the major types of evolution which the disposal system could undergo, is carried out in two steps. The first step is to identify the features of the deep disposal system and the events and processes (features, events, and processes or FEPS) that can influence its

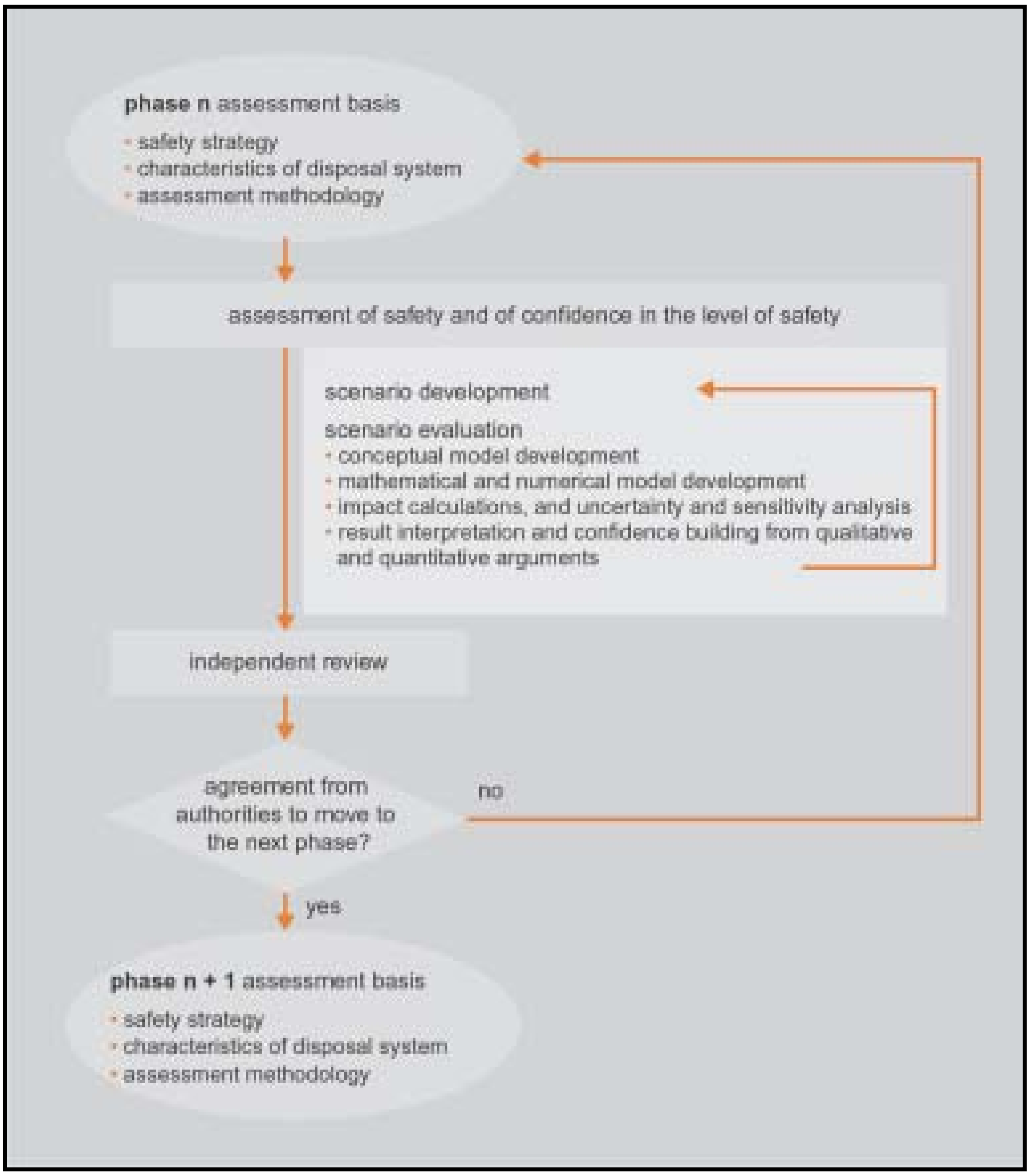


Figure 4.1 The iterative process of long-term safety assessments, which form part of the stepwise and flexible process of implementation of the disposal system.

long-term evolution, and to arrange them in scenarios, after first eliminating the FEPs that have no relevance for safety. The second step consists of describing the scenarios to allow their subsequent assessment.

The evolution scenarios reflect different possible futures of the disposal system relevant for safety assessments, but they are not predictions. They are divided into two families.

- The *normal-evolution scenario*, or reference scenario, considers all the FEPs that are certain or almost certain to occur, and so describes the expected sequence of events and processes following the closure of the disposal facility, events that will inevitably lead to radiological exposure in the very long term.

- The *altered-evolution scenarios* deal with the possible disturbing events or processes that, although they are usually unlikely, are nonetheless capable of significantly altering the disposal system if they do occur, and which therefore may give rise to radiological exposure.

4.1.2 Scenario assessment

There are four steps to the process of scenario assessment (see Section 4.3): conceptual modelling, mathematical and numerical modelling, impact calculations, including uncertainty and sensitivity analyses, and, finally, the interpretation of results and the building of confidence (Fig. 4.1).

Each of the scenarios obtained is described as fully and accurately as possible by applying reasonable simplifying hypotheses about the behaviour and functioning of the disposal system. The complexity of such a system makes it impossible to simulate all of its details. Provided the system is robust (see Section 2.2.2), however, *conceptual modelling* can be confined to a description of the components and processes that may have a significant impact on its functioning, and this makes the modelling more reliable than if a more complex system was represented. The normal-evolution scenario is modelled under the assumption that each barrier performs the safety function that is ascribed to it. The altered-evolution scenarios are modelled assuming that one or more barriers function poorly or not at all. The different elements underlying the conceptual models are

- the *characteristics* of the disposal system (made up of the waste, its packaging and overpack, if any, the other engineered barriers, and the natural geological barrier) and its environment (the aquifers and the biosphere);
- the numerous *processes* (physical, chemical, biological, radiological, etc.) that take place in the various components of the disposal system and in its environment and at the various interfaces. This includes processes like diffusion and advection, which contribute to radionuclide migration towards and in the biosphere, and processes affecting the condition and functioning of the components of the disposal system. The latter includes processes such as the corrosion of the waste packagings and overpacks, which will ultimately lead to their perforation, and processes that will take place in the geosphere and biosphere and will result in a radiological impact on humans;
- *external events* (glaciations, earthquakes, etc.) that can alter the characteristics and the functioning of the disposal system and of its environment.

The functioning of the disposal system assumed in each conceptual model is then translated into one or more *mathematical models* for simulation purposes. All of the major processes that have been identified are described by means of mathematical equations. This includes the migration equation, which is by far the most frequently used general equation in safety assessments. Numerical solutions to these equations are then converted into an algorithmic form in order to create calculation codes.

Simulations of the long-term behaviour of the disposal system, called *impact calculations*, are then carried out for each of the identified scenarios. The complexity of the disposal system and of the processes to be considered, as well as the scales of space and time, are usually such that it is almost impossible to simulate its functioning with a single calculation code. Thus, a number of codes are used one after the other, each simulating the release or migration of radionuclides in a component or group of components of the system. Even so, interpreting the results of impact calculations is complicated by three types of uncertainties. These are often inevitable but their influence on the functioning of the system must be assessed:

- *uncertainties in the description of the scenarios*, i.e., uncertainties as to whether all of the FEPS and all of the relevant scenarios have been included. In assessments of the normal-evolution scenario, these uncertainties can be greatly reduced by the presence of elements of robustness in the disposal system, but they may remain particularly substantial in the case of the altered-evolution scenarios.
- *uncertainties in the conceptual and mathematical models*. These include uncertainties about processes, the spatial definition of models, the representation of the natural environment, and initial and boundary conditions.
- *uncertainties in the values of the parameters* of models. These are largely due to a lack of knowledge about, or the random nature of, the values of the parameters considered, and to uncertainties about measurements.

Uncertainty analyses and *sensitivity analyses* are an integral part of the impact calculations, their aim being to discover to what extent the results obtained are sensitive to the residual uncertainties. Uncertainty analyses aim to establish an upper limit of the calculated impact by assessing the uncertainty about that impact. Sensitivity analyses aim to determine which processes or components most influence the safety of the disposal system. They represent an important tool for identifying research priorities and defining the components that must be reinforced. Sensitivity analyses relating to uncertainties in the description of scenarios and in the conceptual models often apply a deterministic approach in which the parameters have fixed values. Sensitivity and uncertainty analyses relative to uncertainties in the values of parameters often use a stochastic approach. In this approach, the calculations are repeated many times, while sampling the values of input parameters from their respective statistical distributions, which reflect the uncertainties about those values.

Finally, the *interpretation of the results* of safety assessments at the end of the uncertainty and sensitivity analyses and the *confidence* in those results are based not only on a comparison of different safety indicators with the radiological standards in force and the radiological reference characteristics of the disposal medium and its environment, but also on a series of qualitative arguments. Such arguments include the quality of the assessment methodology (method of scenario development, methods of reasoning, conceptual models, calculation codes, etc.) and the quality of all of the basic information and data about the waste, the disposal site, and the engineered barriers (see Section 4.3.1). This confidence is an essential aspect of safety assessments, as it is a prerequisite for moving on from one step in the progressive implementation process of the disposal system to the next. The main elements that can help enhance confidence are as follows:

- *treatment of uncertainties in the description of the scenarios*: the use of catalogues of FEPS drawn up and verified at international level, the establishment of a method of constructing scenarios that is structured and traceable and verified by other experts, an analysis of the disposal system in the different time periods considered, and the use of different types of calculation, methods of reasoning, and safety indicators for each of these periods.
- *treatment of uncertainties in the conceptual and mathematical models*:
  - the use of several conceptual models if there is uncertainty about the precise nature of the mechanisms at work.
  - verification of the calculation codes that are used (i.e., checking that they are correct mathematical representations of the conceptual models and that they calculate correctly): comparison of the results of each code with the results of a code developed independently, the use of a quality assurance procedure, comparison exercises on an international scale, and the checking of calculations by other experts.
  - building confidence in the models (i.e., demonstrating that the models or codes used reflect reality with the desired degree of accuracy, bearing in mind the desired goal): validation of the models used for the different components of the disposal system by means of experiments whose results can be compared with the results of simulations (a strict validation of the models is generally impossible given the scales of time and space that are considered in the assessments), use of natural analogues, use of different methods of reasoning, and demonstration that the calculations are based on a sound scientific foundation.
- *treatment of uncertainties in the values of parameters*: conducting the additional measurements and experiments that are necessary, establishing statistical probability distributions for the values of parameters, and carrying out stochastic and deterministic calculations for the uncertainty and sensitivity analyses.

4.2 Scenario development

As with the methodology of long-term safety assessments, the methodology for scenario development was systematised during the period 1990–2000 in order to minimise the risk of important features, events, or processes being omitted from safety assessments. The selection of FEPS and of the scenarios and variants to be analysed has become a transparent and traceable process. This methodology, which has gained international consensus, comprises two steps: scenario identification and scenario description.

4.2.1 Scenario identification

The process of identifying scenarios that are representative of the possible different long-term evolutions of the deep disposal system under study starts by identifying the FEPS that can, in theory, affect it. The catalogue of the FEPS which may have an impact on the long-term safety of a repository in clay has been drawn up from the NEA catalogue, one of the generic catalogues developed and regularly reviewed at international level. The Belgian catalogue narrows the 134 generic FEPS down to 60 FEPS by eliminating those that can be regarded as not relevant and those that only concern the biosphere. (FEPS that only affect the biosphere are considered in the biosphere modelling rather than in the scenario development.) The catalogue gives a definition of each FEP and a brief discussion of its relevance or potential impact on the disposal system considered and the reasons which have led to its inclusion or otherwise. It is divided into three main categories that are, in turn, split into sub-categories (Table 4.2).

Table 4.2 Classification of the FEPS.

Categories and sub-categories of FEPS, with examples

Natural phenomena

- *of extraterrestrial origin*: meteorite strike
- *geological*: diagenesis, rise or fall of ground level, earthquakes, tectonics
- *climatic*: extreme precipitation, melting of snow and flooding, change in sea level
- *geomorphological*: erosion, displacement of riverbeds, transport and deposit of marine sediments
- *hydrological*: infiltration of groundwater, changes in characteristics of groundwater flows
- *of migration and geochemical*: advection and dispersion, formation, dissolution, and migration of colloids
- *effects of radionuclides on the ecology*: uptake by plants, pedogenesis

Human activity

- *design and construction*: material defects, chemical effects, excavation effects
- *operation and closure*: poor backfilling, heterogeneity of waste, poor sealing
- *intrusions*: exploratory drilling, archaeological research, groundwater pumping
- *post-closure activities*: loss of information about the repository, irrigation

Effects directly linked to the presence of waste and the disposal facility

- *thermal effects*: hydrological modifications, physicochemical modifications
- *chemical and biological effects*: metal corrosion, addition of complexing agents
- *mechanical effects*: deformation of waste packages, changes in in situ stresses
- *radiological effects*: radiolysis, changes in the properties of materials

The selected FEPS are then systematically combined to form scenarios that reflect different possible and safety related futures of the disposal system. This process takes place after the main possible states of the system have been identified. These states are obtained by assuming that each of the system's three main components—the engineered barriers, the geological barrier, and the aquifers—either remains able to perform its initial function (it is intact), or is disturbed and can no longer do so (it is 'short-circuited'). This approach results in 8 main states, one of which is the normal-evolution scenario of the system (Table 4.3). Groundwater plays a central part because of its role in the progressive degradation of the engineered barriers and in the migration of radionuclides to the biosphere. All of the FEPS that are not included in the normal-evolution scenario are then associated with one or more of the other seven states of the system. So far as possible, FEPS which can bring about the same state of the system are combined in the same altered-evolution scenario, each of the eight altered-evolution scenarios being able to have a number of variants. (The probability of occurrence of two of these FEPS—the occurrence of a glaciation and transport by gases—depends largely on their extent, and so is dealt with in two altered-evolution scenarios.)

Table 4.3 Classification of FEPS as a function of the state of the disposal system and its environment (1 = component intact; 0 = component 'short-circuited').

No. of the state of the system	State of the barrier or component			Examples of FEPS (These FEPS are those giving their name to the eight altered-evolution scenarios.)
	Engineered barriers	Geological barrier	Aquifers	
1	**1**	**1**	**1**	**normal state of the system**
2	1	1	0	exploitation drilling, greenhouse effect
3	1	0	1	activation of a fault, transport by gases, poor sealing
4	1	0	0	severe glaciation
5	0	1	1	premature failure of an engineered barrier
6	0	1	0	(no FEP)
7	0	0	1	activation of a fault, transport by gases
8	0	0	0	severe glaciation, exploratory drilling

4.2.2 Scenario description

There are two parts to the description of scenarios: first, there is the description of the evolution over time of the disposal system and of its environment according to the scenario considered; second, there is the description of the main processes involved in the migration of radionuclides to the biosphere, which is simplified in the case of a robust disposal system. The evolution of the system and its environment over time is of course one of the main sources of uncertainty in the description of scenarios and, hence, in the conceptual models and parameter values. It is, therefore, essential to identify different periods in the safety assessments and, also, to estimate the robustness of the various components of the disposal system that perform a safety function. That is, it is necessary to estimate the extent to which their future behaviour may be reliably assessed (Fig. 4.2).

4.2.2.1 Normal-evolution scenario

The normal-evolution scenario describes the slow and progressive degradation of the containment capacity of the disposal system due to natural processes, and assumes that the current characteristics of the environment of the disposal system remain constant over time. This inevitable degradation enables radionuclides to be released into the biosphere, eventually leading to the radiological exposure of individuals of the reference group.

Specifically, the *waste packages* and the *backfill materials* will inevitably degrade over time. The estimated durability of the waste matrices ranges from a few hundred years (bitumen and cement matrices) to several tens of thousands or even several hundreds of thousands of years (glass and uranium oxide matrices respectively). The durability of packagings/overpacks can vary from about 1000 years to several tens of thousands of years for corrosion resistant materials. Finally, a clay-based backfill material may theoretically perform its barrier function for several thousands of years, provided that it does not undergo any mineralogical or chemical transformations due to an excessive temperature increase.

Moreover, the current theories of long-term climate change, based on the orbital theory of Milankovitch, forecast a moderate glacial period after approximately 24000 years and a more severe one after about 56000 years. These glacial periods will induce major modifications in the upper part of the geosphere and, hence, changes in the *aquifers*. Thus, the detailed models of the hydrogeology developed for the present geographical and climatic conditions will probably cease to be representative of the conditions prevailing in 15000 to 20000 years time. However, the *geological barrier* should remain relatively unchanged for at least 100000 years. From 100000 to one million years, major changes in the topography induced by alternating glacial and interglacial periods and movements in the Earth’s crust could alter the depth at which the argillaceous formation lies. Beyond one million years, its characteristics could also change following movements in the Earth’s crust and tectonic, metamorphic, diagenetic, and geomorphological processes, with the result that its behaviour will become highly uncertain. Recent calculations that make allowance for the influence of the greenhouse effect on the climate, however, indicate that the temperature falls anticipated under Milankovitch’s theory will be greatly mitigated by the greenhouse effect (see Sections 4.2.2.2 and 4.3.3).

Finally, and well before any of this happens, probably within a few decades, continual changes in farming practices and eating habits as well as other future human activities, which are by definition impossible to predict, will probably have brought about major changes in the *biosphere*.

One of the most difficult aspects of assessing the safety of a deep disposal system is therefore to decide how the calculations of the radiological impact (quantitative or semi-quantitative calculations, or qualitative reasoning methods) should be adapted as a function of the timescale, so as to ensure that they have the maximum relevance. Whereas it would seem possible to quantify the impact of a disposal system over several thousand years, it becomes increasingly difficult to do this beyond that period. What is important, however, is for safety assessments to provide arguments that make it credible that the radiological impact of the disposal system will not increase significantly in the very long term, for example because the radiological inventory will have been depleted before then. As a result, calculations are sometimes extended up to as much as 100 million years.

To overcome the difficulty posed by the unpredictable nature of most of the changes that will affect the disposal system, and to be able to justify the quantitative hypotheses made to assess its long-term radiological impact, safety assessments must have recourse to certain expedients. More specifically, they use a *reference hydrogeology*, which is modelled on the present-day hydrogeology and assumed to be constant over time. In addition, they use one or more *reference biospheres*, each of which is defined by a set of hypotheses based on current practices and habits, and again assumed to be constant over time. They also use *alternative safety indicators*, which take no account of the uncertain behaviour of the environment of the disposal system (see Section 4.3.1).

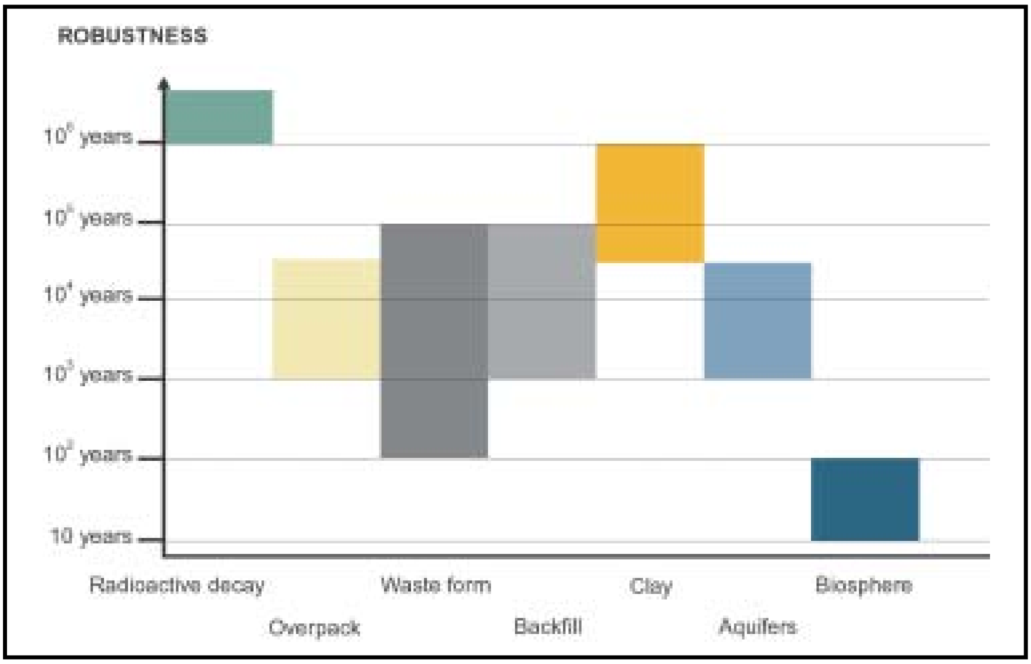


Figure 4.2 Robustness of the main components of the disposal system and of its environment.

The normal-evolution scenario provides a qualitative description of the anticipated functioning of the disposal system based on the components included in safety assessments (Fig. 4.3).

- The only *waste matrices* that have sufficiently high resistance to leaching to be included in safety assessments are the glass, UO_2, and UO_2–PuO_2 matrices. The cement matrices can sorb certain radionuclides that are not sorbed by the clay and so can be included in certain cases. Finally, the potentially negative effect of swelling and of the degradation products of the bitumen matrices on the migration properties of the clay must also be taken into consideration.
- The *watertight packagings/overpacks* physically contain the waste for at least 300 years for the vitrified waste and at least 2000 years for the spent fuel.
- The contribution of the *backfill material* to delaying and spreading the releases of radionuclides is negligible compared to that of the Boom Clay in most impact calculations; it can, however, be significant in the case of radionuclides that are not sorbed by the clay but are sorbed by the backfill material.
- The *excavation-disturbed zone* is taken into account in the estimation of the effective thickness of the clay barrier.

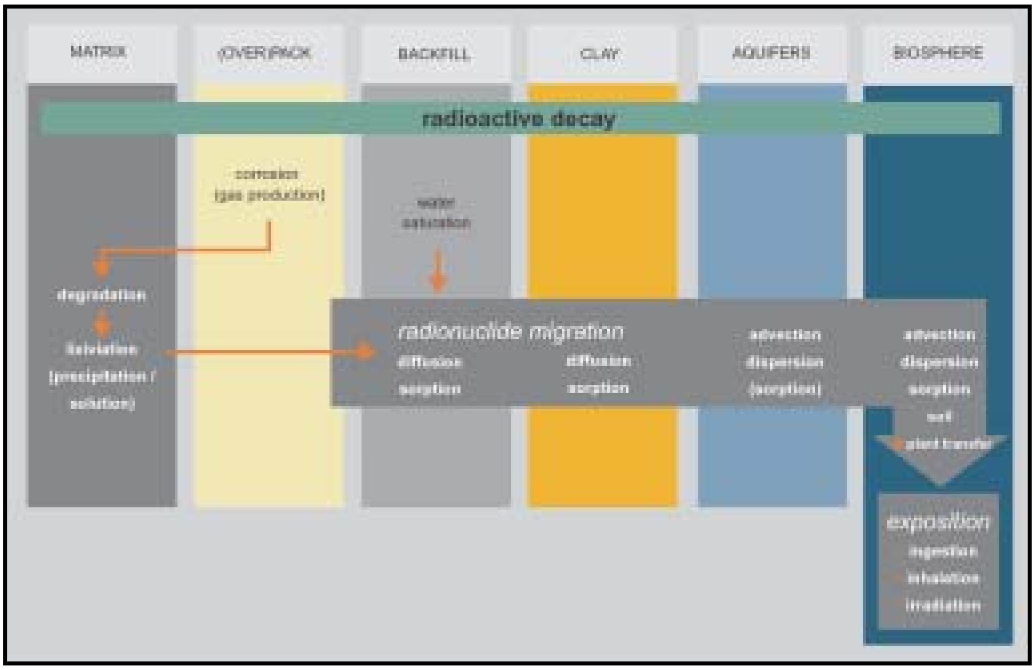


Figure 4.3 Main components of the disposal system and of its environment and main processes considered in the description of the normal-evolution scenario.

- The *undisturbed clay* layer is the principal barrier to the migration of the radionuclides present in the interstitial claywater. Migration through the clay is mainly by molecular diffusion and to a very limited extent by advection; during migration, many radionuclides are sorbed by the clay minerals or by the organic materials occurring in the clay. Modelling is complicated by the possible complexation of certain retarded radionuclides by mobile organic materials—complexation can accelerate their migration—and the possible exchange of radionuclides between mobile and immobile organic materials. (The problem of transport by gases which mainly affects the category B waste is dealt with in the corresponding altered-evolution scenario because the transport mechanisms are very different from the process of diffusion.)
- After their migration through the Boom Clay, the radionuclides reach the *aquifers*, which have no barrier function but instead dilute and disperse the radionuclides that have not been retained by the geological barrier. The main migration mechanisms here are advection under the influence of groundwater flows, and dispersion, with diffusion being negligible in most cases. The radionuclides can also be sorbed by the minerals present in the aquifers.
- Finally, radionuclides that have reached the aquifers may eventually reach the *biosphere* by three mechanisms: the drainage of groundwater towards rivers or possibly towards other water expanses, the pollution of soil by groundwater, and the pumping of groundwater. In the latter case—the only one in which the radionuclides reach the biosphere due to human intervention—the normal-evolution scenario considers the pumping of water from the Neogene Aquifer only, the pumping of water from the underlying Lower-Rupelian Aquifer being considered in the exploitation scenario (see Section 4.2.2.2). The normal-evolution scenario assumes that this

pumping is localised in a particularly unfavourable way, i.e., deep in the aquifer, on the perimeter of the disposal facility and ‘downstream’ relative to the natural direction of groundwater flow (Fig. 4.4). It also assumes that the pumping rate is relatively small (5 000 m^3 per year), so that the pumped water is not diluted by uncontaminated water drained from the overlying strata.

4.2.2.2 Altered-evolution scenarios

The eight altered-evolution scenarios considered in long-term safety assessments are described as follows.

- *The exploitation drilling scenario* (State 2, Table 4.3; Fig. 4.4) posits that a pumping well is drilled into the Lower-Rupelian Aquifer beneath the Boom Clay and in immediate proximity to the repository, and that the pumped water is used for irrigation and as drinking water. This scenario is not included in the normal-evolution scenario because the quality of this water makes it unfit for human consumption unless treated, and the hydraulic conductivity of this aquifer is so low that it is impossible to pump large quantities of water from it. (The drilling of a well in the overlying Neogene Aquifer is considered in the normal-evolution scenario.)
- *The greenhouse effect scenario* (State 2, Table 4.3) envisages changes in the Neogene Aquifer following an increase in the Earth’s temperature that could be produced by the greenhouse effect in the coming centuries.
- In the *fault activation scenario* (States 3 and 7, Table 4.3), a tectonic fault appears through the Boom Clay and the disposal facility following the reactivation of an old fault by an increase in tectonic activity. Such a fault would decrease the containment capacity of the geological barrier; although the barrier would not suffer a clean fracture thanks to its high plasticity, the hydraulic properties in the plane of the fault would indeed be likely to change relative to those of the intact clay.
- *The severe glaciation scenario* (States 4 and 8, Table 4.3) postulates that during a future glacial period, more severe than the last three glacial periods of the Quaternary, the ice cap that would form in Scandinavia would extend as far as the Mol–Dessel region, inducing erosion phenomena likely to affect the Boom Clay and even the engineered barriers. (The occurrence of a glacial period comparable with the last three glacial periods of the Quaternary is covered within the normal-evolution scenario.) For a repository at a depth of around 200 metres, these phenomena could affect the geological formation to the point where fragments of waste would appear on the surface. This could then have a direct radiological impact on humans if they returned to dwell near to the repository location at the end of the glacial period.
- *The poor-sealing scenario* (State 3, Table 4.3) hypothesises that the main galleries and an access shaft have been poorly sealed off, providing a preferential migration pathway for radionuclides, and that the hydraulic conductivity in the main galleries and the access shaft exceeds that of the Boom Clay by several orders of magnitude. The galleries would then behave like huge filters, draining the groundwater out of the argillaceous formation and inducing advection through the galleries and the shaft. To

reinforce the possible effect of filtration even further, this scenario also posits an inversion of the hydraulic gradient in the Boom Clay, which would become ascendant.

- *The scenario of the premature failure of an engineered barrier* (State 5, Table 4.3) has several variants whose outcomes will be greatly limited as long as the clay layer remains intact. The most serious variants are the premature failure of the watertight packagings/overpacks, which would allow the released radionuclides to come into contact with the groundwater while there are still high thermal gradients in the near field, and the rapid degradation of the matrices of the vitrified waste and the spent fuel.

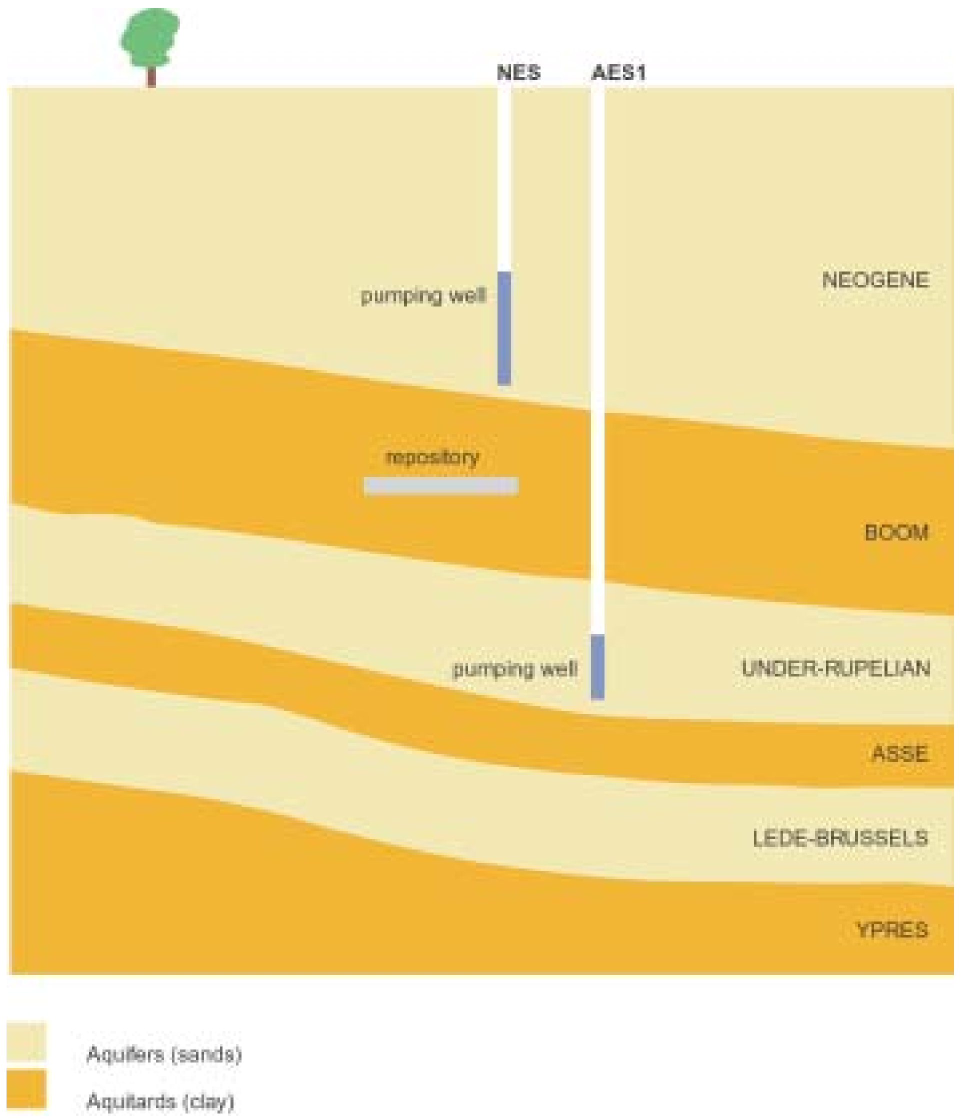


Figure 4.4 Schematic representation of the normal-evolution scenario (NES—pumping of water in the Neogene Aquifer) and of the altered-evolution scenario that considers the pumping of water in the Lower-Rupelian Aquifer (AES1).

- *The scenario of transport by gases* (States 3 and 7, Table 4.3) envisages the generation in certain disposal galleries of a greater volume of gas than can escape by diffusion. This process would lead to the formation of a gas phase capable of expelling potentially contaminated water through the near field. The gas pressure in the near field would continue to increase until it induced a preferential migration pathway to appear in the argillaceous formation, allowing the gas to escape. It would then increase again until more gas escaped, and so on. This gas could, in part at least, consist of radioactive molecules and could accelerate the migration of radionuclides in solution through the argillaceous barrier. (The effects of a moderate production of gas are considered in the normal-evolution scenario.)
- In the *exploratory drilling scenario* (State 8, Table 4.3) is hypothesised that a survey borehole drilled on the site of the repository penetrates the disposal facility. This scenario has two main variants. The first, which is a drastic case of intrusion, assumes that cores are taken which contain fragments of radioactive waste and that they are analysed in a surface laboratory by persons who are unaware of their radioactivity. In the second variant, the borehole drilled through the disposal facility is not backfilled, and so fills up with groundwater that comes into contact with the radioactive waste and causes the radionuclides to leach and possibly contaminate the aquifer.

4.3 Scenario assessment

The safety assessments reported in the SAFIR 2 report are more refined than those reported in the SAFIR report. The simulations carried out since 1997 have benefited from the significant progress made in the development of models and calculation codes, while the interpretation of results now also considers safety indicators additional to the conventional indicators. While the SAFIR report presents mainly very simplified assessments, in particular using one-dimensional approaches, a two-dimensional migration model and new commercial calculation codes can now be used to take fuller account of the principal processes at work in the migration of radionuclides in the Boom Clay and, especially, of the solubility of radionuclides. (Three-dimensional simulations are also now possible but are judged to be unnecessary.) The calculations are of course based on a simplified description of the disposal system and of its functioning; this simplification is possible primarily because the disposal system is robust (see Section 2.2.2).

4.3.1 Quantitative and qualitative arguments

The interpretation of the results of the long-term radiological safety assessments for a deep disposal system must be based not only on quantitative indicators but also on qualitative arguments. More specifically, the interpretation of results is based both on a comparison of the values of two groups of indicators with the relevant standards or threshold values and also on an assessment of the quality of the reasoning. These indicators and the bases of reasoning which accompany them have a certain relative importance or ‘weight’ that may vary, depending on which phase in the evolution of the disposal system is being considered (Fig. 4.5).

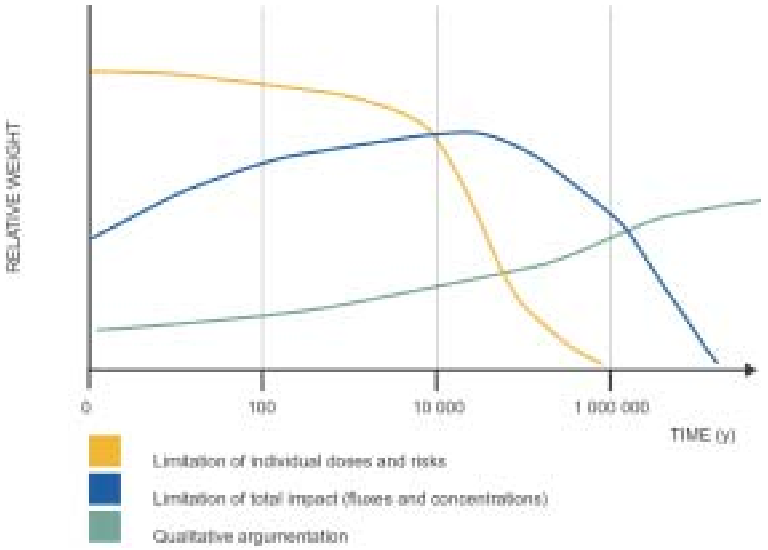


Figure 4.5 Relative weights of the two groups of safety indicators and of the qualitative arguments.

4.3.1.1 Conventional safety indicators

There are three conventional safety indicators: the individual effective dose, the individual radiological risk, and the collective effective dose. Only the first two have any real value as indicators for a deep repository, however. They must be below the dose and risk constraints applicable to this practice. These constraints take into account the fact that the individuals of the reference group may be exposed to more than one source or practice, and must therefore be set at a fraction of the individual dose and risk limits, respectively (see also Section 2.1). The safety assessments given in the SAFIR 2 report use the recommendations made by the ICRP on this matter.

- The *effective dose* (in mSv per year) to an individual of the reference group due to the gradual release of radionuclides is used for the normal-evolution scenario. It must be below the dose constraint which, according to the ICRP, must not exceed 0.3 mSv per year for the disposal of radioactive waste. (Most countries require a value of between 0.1 and 0.3 mSv per year.)
- Potential exposures are assessed using two indicators, the individual effective dose and the probability of exposure to a given dose, which are the two factors of the calculated *individual radiological risk* R_i. In the altered-evolution scenarios, this risk is used in place of the individual effective dose, since the possibility that these scenarios will induce an exposure greater than the dose constraint cannot be entirely ruled out, although their probability of occurrence is low. The level of safety of a disposal system must therefore be such that the radiological risk run by an individual of the reference group in one year due to disturbing events that are not covered by the dose constraint is below the risk constraint. The individual radiological risk is defined as follows:

  R_i = probability of exposure to a given dose × probability of death from this exposure
  = probability of exposure × individual effective dose × risk factor

For doses below 100 mSv, the ICRP considers that the probability of death is proportional to the dose, the factor of proportionality or risk factor which it uses being $5{\cdot}10^{-2}$ Sv^{-1} for the whole population and $4{\cdot}10^{-2}$ Sv^{-1} for the sub-group of workers. If non-fatal cancers are included as well, then the risk factor is $7{\cdot}10^{-2}$ Sv^{-1}.

- The *collective effective dose* is an indicator of the total radiological impact of a given practice on the entire exposed population, as it takes account of the total number of exposed persons and the mean dose that they receive. For a deep repository, the uncertainty about calculated collective doses increases more rapidly over time than the uncertainty about individual doses, as it becomes more and more difficult to estimate the total number of exposed persons. The collective dose is therefore of limited value as a safety indicator; this is confirmed by the latest recommendations of the ICRP (ICRP 81) on radiological protection in the case of deep disposal. Specifically, the use of collective doses must be limited to a period of a few hundred to a few thousand years after the closure of the repository and must be interpreted as a relative value and not as an absolute indicator of the total radiological impact. Its use in the optimisation of radiological protection, mainly during the operational phase, will have to be considered however.

4.3.1.2 Alternative safety and performance indicators

Although the conventional safety indicators of ‘dose’ and ‘risk’ are the main indicators of the radiological impact of controlled practices on an individual of the reference group, their use must be supplemented by alternative indicators for assessing the safety of a deep repository. This is because, first, radiological protection controls will no longer be in place when the maximum anticipated radiological impact occurs and, second, uncertainty about the estimated radiological impact increases as this impact occurs later in time, i.e., paradoxically, the more efficient the disposal system is, the more uncertain the results. This uncertainty stems mainly from a lack of knowledge about the evolution of the environment of the disposal system. This environment is relatively less robust than the disposal system itself, being particularly sensitive to changes brought about by humans and, in the case of hydrogeology, to climate changes. This uncertainty is thus not directly linked to the system’s main safety functions. If possible, therefore, the conventional safety indicators should be backed up by complementary indicators of radiological impact, preferably indicators that are less sensitive to the uncertainties that increase with time. Safety indicators for the safety functions performed by the barriers of the disposal system are examples of such indicators (see Section 2.2.1).

The main safety indicators for safety functions are those which relate to the function of delaying and spreading the releases. These are the *radionuclides flux densities* (in $\mathrm{Bq{\cdot}m^{-2}}$ per year) or the *total radionuclide flux* (in Bq per year) *between the disposal system and its environment*, and the *resulting radionuclide concentrations* (in $\mathrm{Bq{\cdot}m^{-3}}$) *in the aquifers and in different parts of the biosphere*. These indicators are sensitive to the robustness of the disposal system because they relate to a safety function that is provided by robust barriers. Their values can be compared with the quantities of naturally-occurring radionuclides in the geosphere and, more particularly, with the concentrations of radionuclides naturally occurring in the interstitial water. Two other variables can also give an indication of the performance of the disposal system. These are, first, the *containment factor*, i.e., the ratio of the total activity placed in the repository to the cumulative activity released by the disposal system, and, second, the *total inventory of uranium* placed in the repository, which can be compared with the alpha activity naturally present near to the disposal facility.

4.3.1.3 Qualitative arguments

Qualitative arguments are used to interpret the results of safety assessments and to build confidence in the way in which these assessments have been carried out (see also Section 4.1.2). Such arguments are about the quality of reasoning methods, which must be logical and transparent and have been assessed by outside experts, about the quality of the models, which must be consistent with the available scientific knowledge, and about the quality of the calculation codes and the values used for the parameters. The qualitative approach therefore sets out to answer a series of questions, such as ‘Have all of the relevant processes been considered?’, ‘Have the disposal system and its functioning been simplified correctly?’, or ‘Are the hypotheses cautious enough?’.

4.3.2 Assessment of the normal-evolution scenario

The safety assessments of the normal-evolution scenario lead to the calculation of the dose to an individual of the reference group and, also, of alternative safety and performance indicators, which are the intermediate results of the dose calculation. These assessments are based primarily on deterministic calculations known as *best estimates*, which means that they use the best possible estimates of parameter values. They are sometimes supplemented by stochastic calculations, which take account of the uncertainty in parameter values and whose results are used as a basis for uncertainty and sensitivity analyses.

4.3.2.1 Calculations of doses

Doses are calculated in three steps.

- The radionuclide migration in the near field and the Boom Clay is simulated to calculate the activity flux at the interface between the clay and the Neogene Aquifer. These calculations are based on different source term models for each of the three waste classes considered, namely, vitrified waste, spent fuel, and hulls and endpieces.
- Radionuclide migration in the Neogene Aquifer is simulated to calculate the concentrations of radionuclides in the water taken from a well that pumps water from just above the disposal facility, and the activity fluxes towards the rivers. These calculations are identical for the three waste classes considered.
- The transfers of radionuclides in the biosphere and the exposures are calculated to obtain the actual doses.

Activity flux in the disposal system and at the interface between the Boom Clay and the Neogene Aquifer

The basic data and simplifying hypotheses used to calculate radionuclide migration in the disposal system relate to the repository design, the characteristics of the near field and host formation, the dominant migration processes and the values of the parameters which govern them, the evolution of the disposal system over time, and the inventory of the waste that is placed into the repository.

The repository design that is considered in the safety assessments for vitrified waste and spent fuel is virtually identical to the reference design (see Section 3.3.1); for the hulls and endpieces, which are not explicitly considered in this reference design, the safety assessments assume that they are disposed in a single gallery. The total area of the repository considered in the safety assessments is 0.224 km^2 or 1.17 km^2, depending on whether reprocessing of spent fuel is continued or halted.

For the purposes of modelling, the disposal galleries are treated as infinitely long cylinders, since they are very long relative to the thickness of the argillaceous layer. This makes it possible to calculate migration through the near field and the clay in two dimensions in a plane perpendicular to that of the galleries. The area to be modelled around each gallery can also be limited by the existence of two, and usually three, planes of symmetry (Fig. 4.6): the horizontal symmetry plane passing through the axis of the gallery and that results from the fact that migration by advection can be disregarded compared with migration by diffusion because of the low hydraulic conductivity of the clay and the small hydraulic gradient over the thickness of the argillaceous layer, the vertical symmetry plane passing through this axis, and, except for the hulls and endpieces, the vertical plane equidistant from two identical disposal galleries.

In the robust disposal system, the model used to simulate radionuclide migration through the near field and the Boom Clay is based on the diffusion equation and disregards migration by advection and dispersion. The Boom Clay layer beneath the Mol–Dessel nuclear zone is, moreover, assumed to be homogeneous over its full thickness (90 metres). This makes it possible for the main parameters that are used in migration calculations—diffusion-accessible porosity η, diffusion coefficient D_p, and retardation factors R—to be kept constant. In an initial approximation, however, the thickness of clay that can make an effective contribution to delaying and spreading the releases of radionuclides is only 40 metres. This is the thickness of clay above or below the repository less the thickness of the zone that is potentially disturbed by excavation and less a thickness to allow for the fact that the median plane of the disposal facility might not perfectly coincide with that of the clay layer. The sealing of the galleries and shafts is assumed to possess the same migration properties as the Boom Clay (see Section 4.3.3 for the poor-sealing scenario). Since the migration of radionuclides in the near field is conditioned by their solubility limits and by the slow migration rate through the Boom Clay, it is usually modelled together with migration through the clay.

Although the uncertainties increase greatly in the very long term, the assessments reported in the SAFIR 2 report assume that the geological barrier remains unchanged for

100 million years. Migration calculations can thus be continued until the radionuclide fluxes at the interface between the Boom Clay and the Neogene Aquifer attain their maximum; these flux peaks correspond to the maximum risk. Of course, these values only give an indication of the size of the radionuclide fluxes that might be expected, and must be qualified by other safety indicators and other arguments.

Finally, migration calculations must be based on accurate data and hypotheses as regards the source terms concerned. For each of the three waste classes considered, the source terms take account of the assumed durability of the watertight packagings and overpacks, the corrosion rate of the waste matrices and their durability, the solubility limit of the radionuclides, the migration properties of the backfill material, and the least favourable quantitative inventory (Table 4.4). For the vitrified waste and the hulls and endpieces, the least favourable inventory is the one that corresponds to the continuation of reprocessing, i.e., 3920 and 6410 containers of waste, respectively. For the spent fuel, it is the inventory that corresponds to cessation of reprocessing, i.e., 4160 tU (2180 tUO$_2$ with a burn-up of 45 GWd·tHM^{-1} and 1980 tUO$_2$ with a burn-up of 55 GWd·tHM^{-1}) and about 70 tHMMOX. This inventory, which was drawn up in 1997 and is used for the SAFIR 2 safety assessments, is almost identical to the most recent inventory made in 1999 (Table 3.2; Table 3.3 for the radiological inventories). When calculating activity fluxes at the interface between the Boom Clay and the Neogene Aquifer, however, the inventories are divided by 2. This acknowledges the horizontal plane of symmetry due to the fact that migration through the Boom Clay occurs primarily by diffusion.

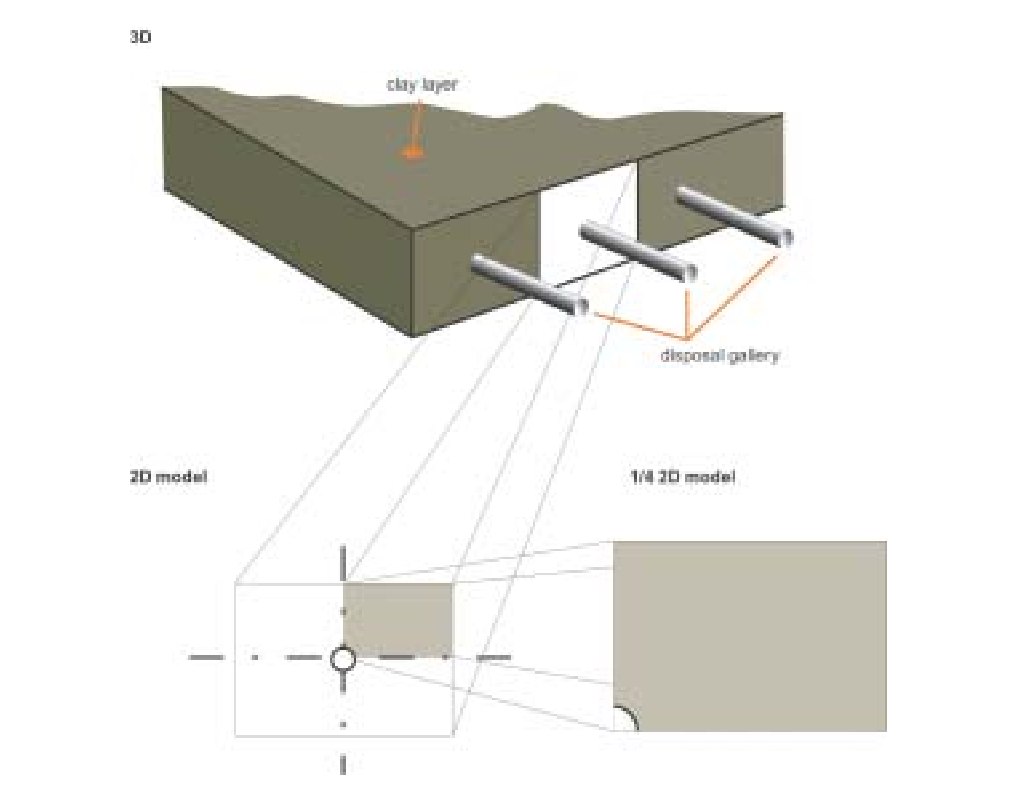


Figure 4.6 Configuration and simplifications used for calculating migration in the near field and argillaceous layer.

To avoid carrying out detailed migration calculations for all of the radionuclides in the radiological inventories, only the radionuclides which have a long enough half-life or which migrate fast enough to reach the Neogene Aquifer are selected. For simulations of the migration of activation and fission products, the list of radionuclides which meet the selection criteria is as follows: ^{14}C, ^{36}Cl, ^{59}Ni, ^{79}Se, ^{93}Zr, ^{94}Nb, ^{99}Tc, ^{107}Pd, ^{126}Sn, ^{129}I, ^{135}Cs, and ^{147}Sm. The heaviest actinides (Cm, Am, and Pu) do not normally need to be considered in simulations, as they are strongly retarded by the clay and most of their isotopes are relatively short-lived. The decay chains considered in the calculations are therefore as follows:

- $^{248}\mathrm{Cm} \rightarrow {}^{244}\mathrm{Pu} \rightarrow {}^{236}\mathrm{U} \rightarrow {}^{232}\mathrm{Th}$
- $^{237}\mathrm{Np} \rightarrow {}^{233}\mathrm{U} \rightarrow {}^{229}\mathrm{Th}$
- $^{242}\mathrm{Pu} \rightarrow {}^{238}\mathrm{U} \rightarrow {}^{234}\mathrm{U} \rightarrow {}^{230}\mathrm{Th} \rightarrow {}^{226}\mathrm{Ra}$
- $^{235}\mathrm{U} \rightarrow {}^{231}\mathrm{Pa}$.

The parent radionuclides which are not considered in radiological calculations are still used for calculating the solubility of radionuclides in the near field.

Table 4.4 Principal characteristics of the source terms used in calculations of migration in the near field and the Boom Clay.

	Vitrified waste	**Spent fuel**	**Hulls and endpieces**
Inventory	3 920 containers, i.e., 420 containers + 3 500 if reprocessing is continued	4 160 tU and about 70 tHMMOX, i.e., the inventory if reprocessing ceases	6 410 containers, i.e., 820 containers + 5 590 if reprocessing is continued
Watertight packagings / overpacks: durability	300 years	2 000 years	(no overpack)
Source term: models	dissolution of the matrix at a constant rate during its considered durability: ■ reference = 72 000 years ■ variant 1 = 20 000 years (lower limit) ■ variant 2 = 10^6 years (upper limit) ■ variant 3 = instantaneous dissolution of the matrix as soon as it comes into contact with water	1. immediate dissolution of part of the radionuclides, then dissolution at a constant rate of the matrix for 1 million years and of the hulls and endpieces for 1 000 years 2. model of alpha auto-oxidation: as 1, but matrix dissolution is influenced by the oxidation, due to alpha radiolysis, of uranium oxide when placed in contact with water in a reducing medium	immediate dissolution of the radionuclides, limited only by their solubility (no waste matrix)
Backfill material	mixture of 60 % FoCa clay, 35 % sand, and 5 % graphite: possible contribution to containment is largely disregarded by assuming, arbitrarily but conservatively, $D_{\mathrm{p\ backfill}} = 5$ to $10 \times D_{\mathrm{p\ clay}}$, $\eta_{\mathrm{backfill}} = \eta_{\mathrm{clay}}$, and for all radionuclides, $R_{\mathrm{backfill}} = R_{\mathrm{clay}}$.		concrete: possible contribution to containment is disregarded by assuming, very conservatively, $D_{\mathrm{p\ backfill}} = 10 \times D_{\mathrm{p\ clay}}$, and for all radionuclides, $R = 1$.

Vitrified waste The exact durability of the glass matrix, and hence the potentially high related uncertainties, have practically no influence on the overall performance of the disposal system; this represents a major element of robustness. For ^{129}I, for example, a radionuclide that is very long lived (16 million years) and that is not retarded in the Boom Clay, the durability of the matrix has almost no effect on the peak value of the radionuclide flux reaching the Neogene Aquifer. This durability also has only a minimal effect on the time when this peak occurs, insofar as this durability is less than 100 000 years (Fig. 4.7). As regards the retarded activation and fission products (^{93}Zr, ^{99}Tc, ^{107}Pd, and ^{135}Cs), the durability of the matrix has no notable influence on either the value of the flux peak or the time when it occurs.

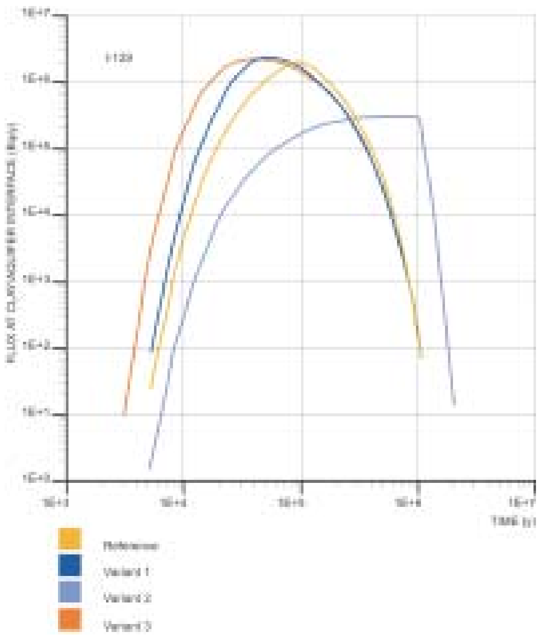


Figure 4.7 Flux of ^{129}I at the interface between the Boom Clay and the Neogene Aquifer for the vitrified waste.

The anticipated evolution of the radiological impact of the total calculated activity release for the vitrified waste shows two peaks: the first, which is also the highest, is produced by the activation and fission products; the second is due to the actinides (Fig. 4.8). The principal *activation* and *fission* products are—in descending order of importance—^{79}Se, ^{99}Tc, ^{129}I, ^{107}Pd, ^{126}Sn, and ^{93}Zr (Fig. 4.9). The change in the flux of ^{99}Tc clearly shows the influence of the solubility limit: the value of the ^{99}Tc flux peak at the interface between the Boom Clay and the Neogene Aquifer, which is approximately 10^7 Bq per year and occurs after approximately 200 000 years, remains more or less constant up to 2 million years, after which ^{99}Tc disappears by radioactive decay. The fluxes of ^{79}Se and ^{107}Pd are also affected by the solubility limits of these elements. The maximum flux peak, that of ^{79}Se, is around $2{\cdot}10^7$ Bq per year and comes after 150 000 to 200 000 years. Considering the *actinides*, the flux comes mainly from the chain $^{237}\mathrm{Np} \rightarrow {}^{233}\mathrm{U} \rightarrow {}^{229}\mathrm{Th}$ (Fig. 4.10). This is moreover the only chain for which any significant increase appears in the fluxes if the mobile organic fraction is included in the assessments. In this case, the maximum peak is for ^{233}U and is around $2{\cdot}10^4$ Bq per year as against about $5{\cdot}10^3$ Bq per year if the mobile organic fraction is neglected. In both cases, the peak occurs after approximately 15 million years; these radionuclides only start to reach the Neogene Aquifer after about 100 000 years with the mobile organic fraction taken into account and one million years otherwise. The mobile organic fraction thus has no significant impact on the containment capacity of the geological barrier.

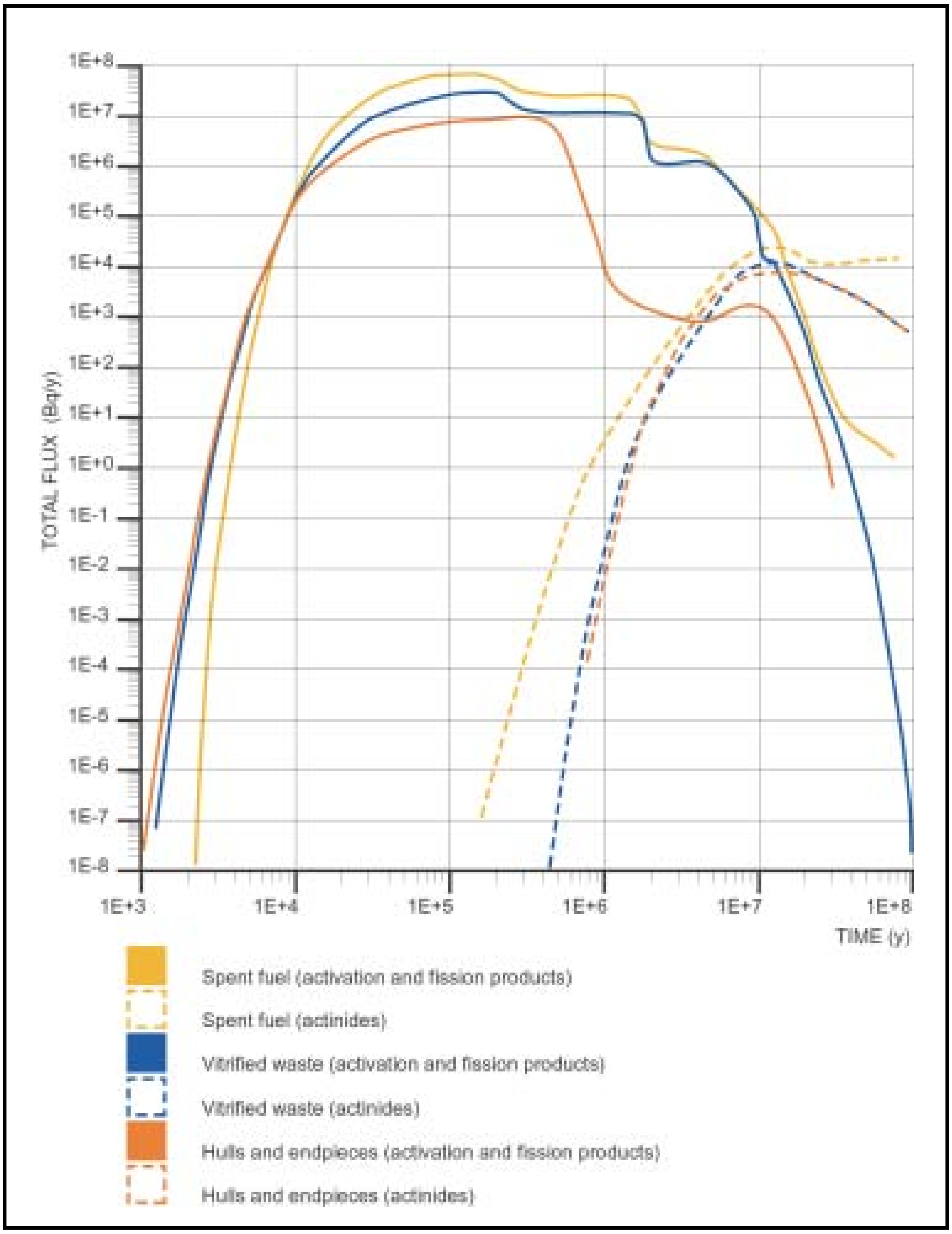


Figure 4.8 Activity flux at the interface between the Boom Clay and the Neogene Aquifer for the vitrified waste, the spent fuel, and the hulls and endpieces.

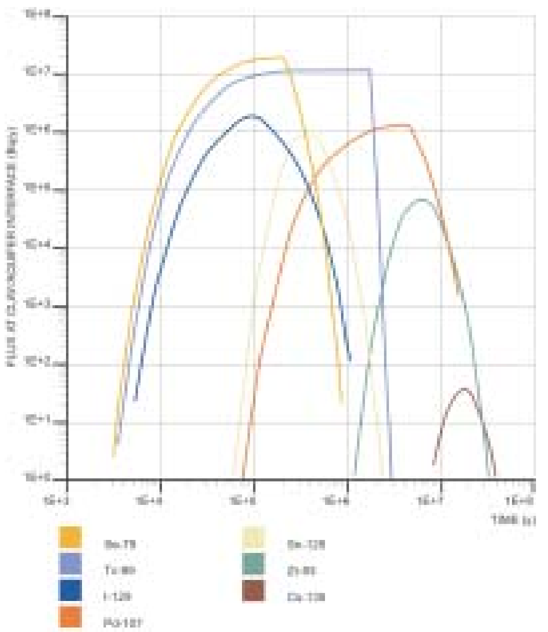


Figure 4.9 Activity flux at the interface between the Boom Clay and the Neogene Aquifer of the activation and fission products in the vitrified waste.

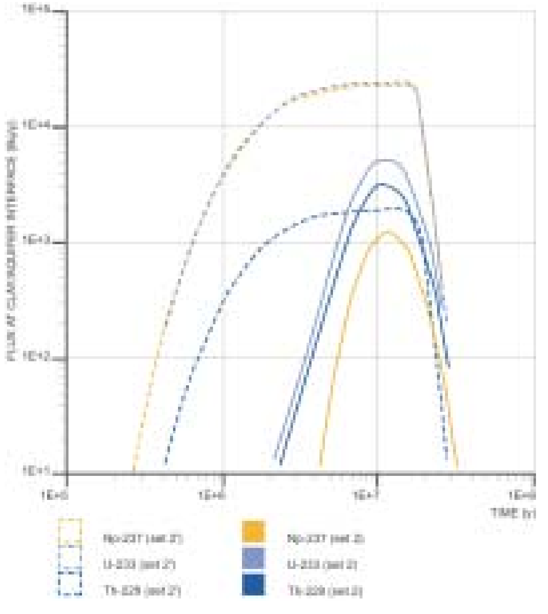


Figure 4.10 Activity flux at the interface between the Boom Clay and the Neogene Aquifer of the actinides in the chain $^{237}Np \rightarrow {}^{233}U \rightarrow {}^{229}Th$ in the vitrified waste (set 2: organic fraction not taken into account; set 2': organic fraction taken into account).

Spent fuel Most calculations of the migration of radionuclides released by the spent fuel have been made in the European Commission's SPA project (Spent Fuel Performance Assessment). A comparison of the fluxes of activation and fission products calculated with the two models of the source term (Table 4.4) indicates fluxes at the interface between the Boom Clay and the Neogene Aquifer occurring at about the same time; the fluxes calculated with the alpha auto-oxidation model are two to three times greater, so this is the model used for the calculations. The main *activation and fission products* are ^{79}Se, ^{99}Tc, ^{36}Cl, ^{129}I, ^{107}Pd, and ^{14}C. In the representative case of a calculation of the flux associated with the 1 980 tonnes of uranium oxide with a mean burn-up of 55 GWd·tHM^{-1} (1 980 tUOX-55), the maximum flux peak is that of ^{79}Se. It is about $2{\cdot}10^7$ Bq per year and occurs after 160 000 years (Fig. 4.11). The effect of the solubility limit is clearly visible for ^{99}Tc, ^{79}Se, and ^{107}Pd, as is the presence of ^{129}I in different components of the fuel. The main contribution made by the *actinides* to the activity flux is provided by ^{233}U, with a maximum flux of approximately $2{\cdot}10^4$ Bq per year if the mobile organic fraction is included and approximately $7{\cdot}10^3$ Bq per year otherwise (Fig. 4.12). The two peaks occur after some 10 million years, with the radionuclides only starting to reach the Neogene Aquifer after about 100 000 years in the former case and 1 million years in the latter. The scale and time of the maximum fluxes are more or less equivalent to those calculated for the vitrified waste (Fig. 4.8).

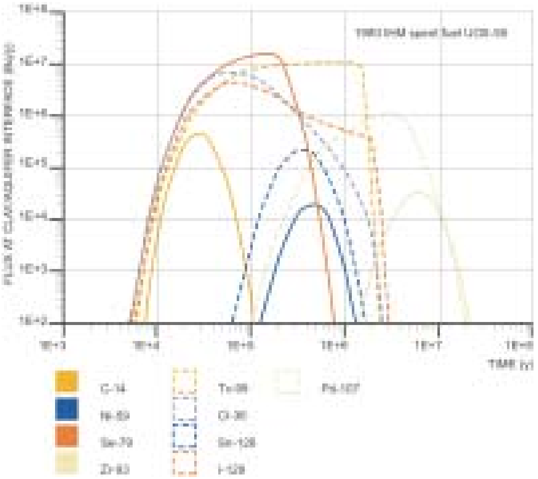


Figure 4.11 Activity flux at the interface between the Boom Clay and the Neogene Aquifer of the activation and fission products in the spent fuel (1 980 tUOX–55), calculated with the alpha auto-oxidation source term model.

Hulls and endpieces The main activation and fission products of the hulls and endpieces are ^{99}Tc, ^{129}I, ^{79}Se, ^{14}C, and ^{93}Zr. The effect of the solubility limit is only clear for ^{99}Tc. Its peak flux is about $9{\cdot}10^6$ Bq per year and occurs after 430 000 years (Fig. 4.13). The period of time after which all of the ^{99}Tc is dissolved is considerably shorter than for the vitrified waste: 550 000 years instead of 1.7 million years. If the calculations disregard the mobile organic fraction, the maximum activity flux of the *actinides* is due to ^{236}U (about 3 000 Bq per year after 12 million years), otherwise the maximum activity flux is due to ^{233}U (about 2000 Bq per year after 3 million years). The chain $^{237}Np \rightarrow ^{233}U \rightarrow ^{229}Th$ is the only one which shows a significant increase in flux peaks if the assessments include the mobile organic fraction. In this case, the radionuclides begin to reach the Neogene Aquifer after approximately 100000 years, instead of about 1 million years otherwise (Fig. 4.14). The overall aspect of the activity flux with the two peaks is therefore comparable to that obtained for the vitrified waste (Fig. 4.8).

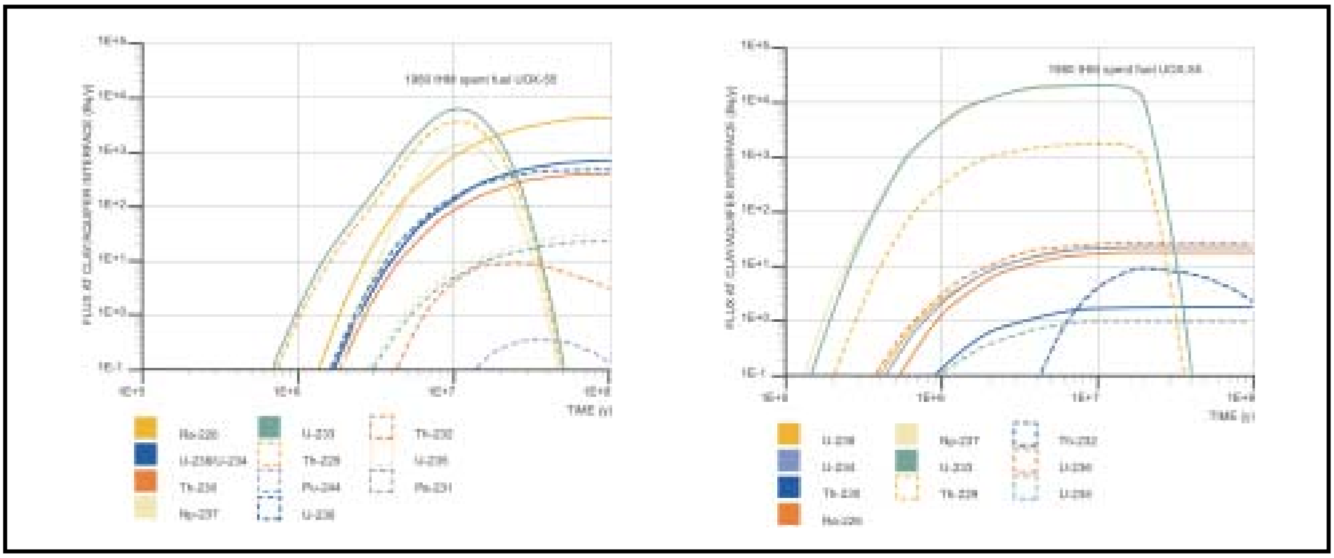


Figure 4.12 Activity flux at the interface between the Boom Clay and the Neogene Aquifer of the actinides in the chain $^{237}Np \rightarrow ^{233}U \rightarrow ^{229}Th$ in the spent fuel (1980 tUOX–55), calculated with the alpha auto-oxidation model, without (figure at left) and with (figure at right) the mobile organic fraction taken into account.

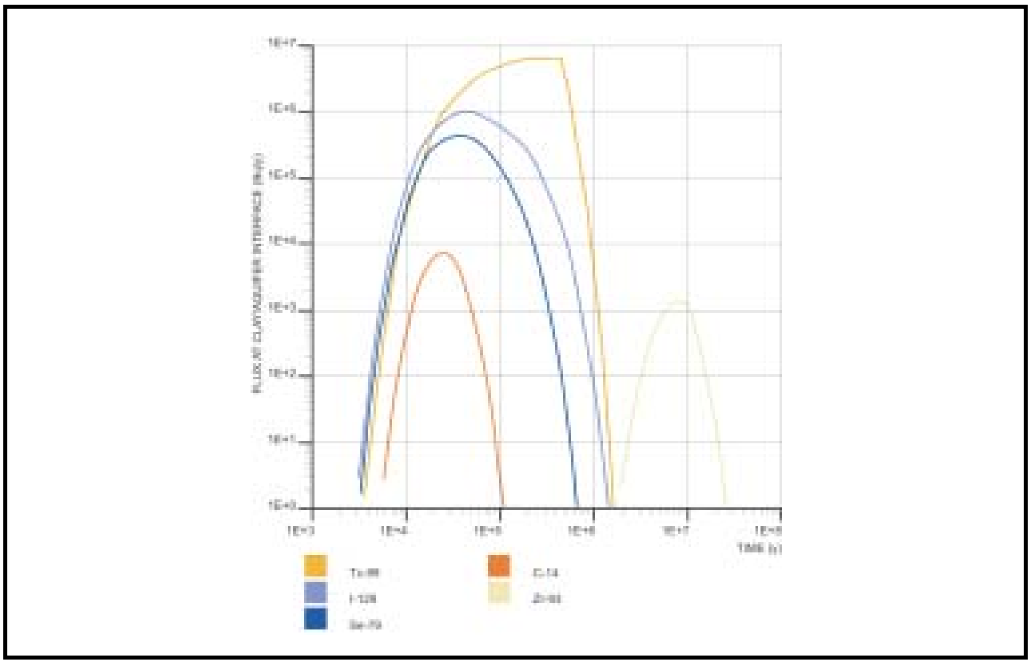


Figure 4.13 Activity flux at the interface between the Boom Clay and the Neogene Aquifer of the activation and fission products in the hulls and endpieces.

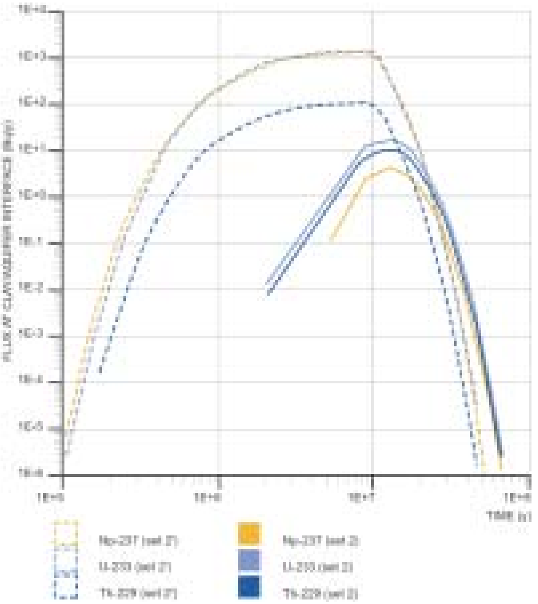


Figure 4.14 Activity flux at the interface between the Boom Clay and the Neogene Aquifer of the actinides in the chain ^{237}Np → ^{233}U → ^{229}Th in the hulls and endpieces (set 2: organic fraction not taken into account; set 2': organic fraction taken into account).

Activity flux in the Neogene Aquifer

The main contribution of the aquifers to the functioning of the disposal system is to allow the dilution and dispersion of the radionuclides before they reach the biosphere. The radiological impact is indeed inversely proportional to the dilution factor, defined as the ratio of the activity flux into the aquifer or river to the maximum concentration in the aquifer or river. Calculations of migration in the aquifer yield the concentrations of radionuclides in the water of a well and the activity fluxes towards rivers. The most important characteristics and parameters of the aquifer in the robust disposal system are the hydraulic conductivity of its various sub-layers, the Darcy velocity, the hydrodynamic dispersivities, and its thickness.

Up to now, most simulations of migration in the Neogene Aquifer have assumed that, as the Boom Clay, the local hydrogeology remains unchanged for 100 million years. In reality, however, the aquifer could undergo significant alterations within a few hundred years owing to climate change. Allowance can be made for these changes up to about 100 000 years by using predictions based on the orbital theory of Milankovitch. The longer-term alternation between glacial periods and interglacial periods will involve substantial and inevitable uncertainties in the behaviour of the Neogene Aquifer.

Calculations of radionuclide migration in the Neogene Aquifer are based on the local hydrogeological model, which is three-dimensional (see Section 3.2.4.4), whereas the simulations described in the SAFIR report used one- or two-dimensional simulations. These calculations therefore use parameter values that vary in space. The possible sorption of radionuclides by the minerals present in the aquifer has been disregarded, because the effect of this sorption is probably negligible compared to the retention which occurs during migration through the Boom Clay. Since, if sorption is neglected, all radionuclides migrate in an identical manner in the aquifer, the calculations have only been carried out for ^{129}I. These calculations assume a constant specific flux of 1 MBq per year from the Boom Clay into the Neogene Aquifer, uniformly distributed over the area of the disposal facility. The resulting maximum concentration calculated in the Diest Sands, which are the most suitable sands for water pumping because of their high hydraulic conductivity, is 1.5 Bq·m^{-3}. This corresponds to an apparent dilution factor in the aquifer of 670 000 m^3 per year.

Calculations of doses

The dose to which an individual of the reference group may be exposed via the different biosphere receptors considered is calculated by multiplying the concentration of radionuclides in the water collected from a well just above the disposal facility, or by multiplying the activity flux towards the rivers (mainly towards the Kleine Nete), by the corresponding biosphere conversion factors (see Section 3.7). Dose calculations assume a reference biosphere that remains stable for 100 million years. They indicate that all of the doses due to the Kleine Nete are about two orders of magnitude below those due to well water. Doses due to well water for the three classes of waste considered can be summarised as follows.

Vitrified waste The most important radionuclides in descending order of importance are ^{79}Se, ^{129}I, ^{126}Sn, and ^{99}Tc. The highest dose is the one from ^{79}Se—it occurs after 200 000 years and is approximately 10 µSv per year (Fig. 4.15). It is attributable partly to the uncertainties about its migration behaviour in the Boom Clay and partly to its conversion factor in the biosphere. The total dose exceeds 10^{-2} µSv per year between 7 000 years and 1 million years and exceeds 1 µSv per year between 20 000 and 350 000 years. The maximum dose due to the actinides is $3 \cdot 10^{-3}$ µSv per year (Fig. 4.16). It is due mainly to ^{229}Th and attains its maximum after 13 million years. Other relatively important actinides are ^{226}Ra and ^{231}Pa. The total dose due to the actinides is greater than 10^{-4} µSv per year between 2 and 100 million years.

Spent fuel (calculations for 1 980 tUOX–55) The most important radionuclides are ^{79}Se, ^{129}I, ^{36}Cl, ^{126}Sn, and ^{99}Tc. The maximum dose is due to ^{79}Se: it is 7 µSv per year and comes after 160 000 years (Fig. 4.17). The total dose exceeds 10^{-2} µSv per year for the period between 9 000 years and 2 million years. The maximum dose calculated for the actinides is essentially due to ^{229}Th (Fig. 4.18): it is $4 \cdot 10^{-3}$ µSv per year and appears after 10 million years. Another relatively important actinide is ^{226}Ra. The dose peak for the whole of the spent fuel (2 180 tUOX–45 and 1 980 tUOX–55), which is again due to ^{79}Se (Fig. 4.19), appears after 160 000 years and is approximately 20 µSv per year. In this case, the total dose exceeds 10^{-2} µSv per year during the period between 8 000 years and 3 million years.

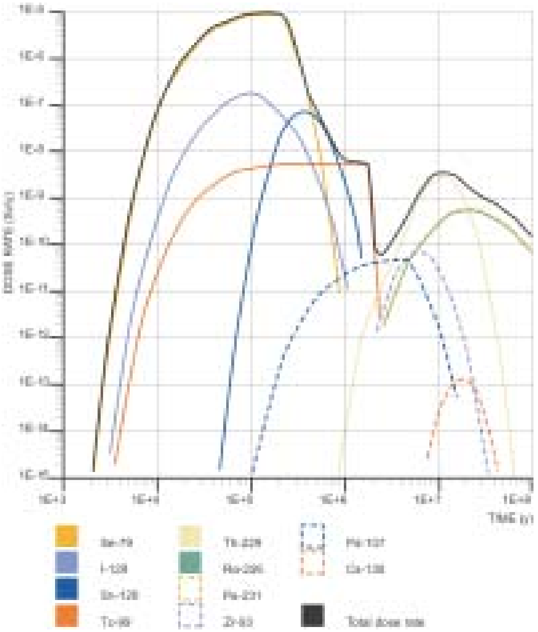


Figure 4.15 Total dose rate via a deep well for the activation and fission products in the vitrified waste.

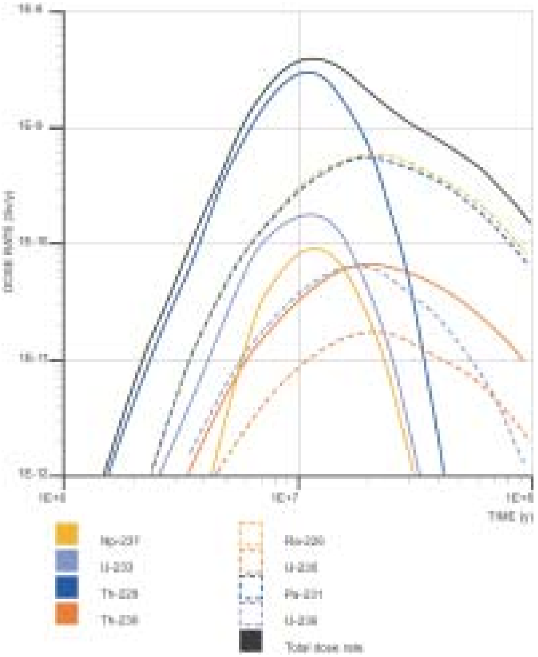


Figure 4.16 Total dose rate via a deep well for the actinides in the vitrified waste.

Hulls and endpieces The most important radionuclides are ^{79}Se, ^{129}I, and ^{99}Tc. The maximum dose, which is from ^{79}Se, is around 0.3 μSv per year and occurs after

36 000 years (Fig. 4.20). The total dose exceeds 10^{-2} µSv per year during the period between 7 000 and 300 000 years. The maximum dose calculated for the hulls and endpieces is therefore 30 times less than that calculated for the vitrified waste and is mainly the result of the smaller amount of ^{79}Se in the hulls and endpieces. The maximum dose due to the actinides is $2{\cdot}10^{-3}$ µSv per year and is due mainly to ^{231}Pa and ^{226}Ra. The maximum appears after 13 million years. The actinides give doses of over 10^{-4} µSv per year between 4 and 100 million years.

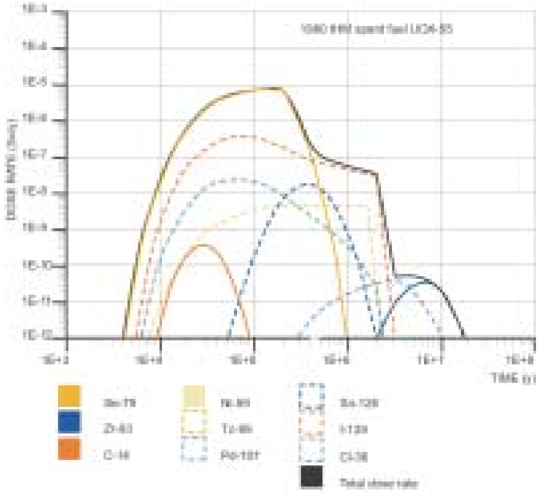


Figure 4.17 Total dose rate via a deep well for the activation and fission products in 1 980 tUOX–55.

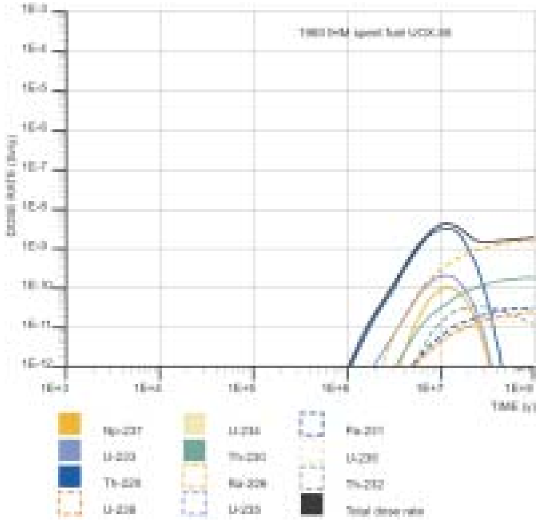


Figure 4.18 Total dose rate via a deep well for the actinides in 1 980 tUOX–55.

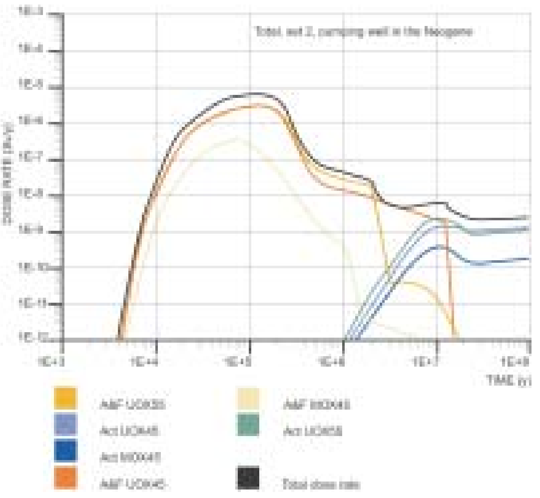


Figure 4.19 Total dose rate via a deep well for the activation and fission products and the actinides in the whole of the spent fuel.

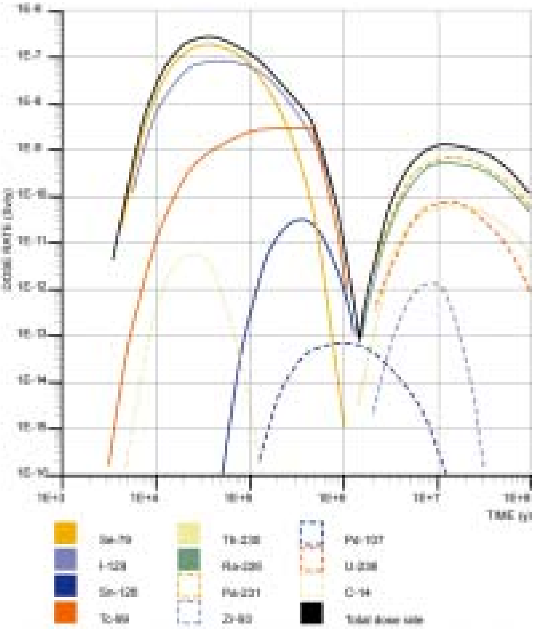


Figure 4.20 Total dose rate via a deep well for the activation and fission products in the hulls and endpieces.

4.3.2.2 Calculations of alternative safety and performance indicators

Three indicators whose calculation is virtually independent of the evolution of the environment of the disposal system have been used to complement the dose calculations.

Decayed fractions and containment factors By comparing the total cumulative activity that reaches the Neogene Aquifer in 100 million years with the initial total activity placed in the disposal system, it is possible to calculate the fraction that decays within the disposal system, i.e., the ratio between the quantity of radionuclides that disappear through radioactive decay inside the disposal system and the initial quantity of activity placed in the system. This can be used as a way to assess the overall performance of the system's barriers.

In the case of the vitrified waste, and except for a few very long-lived radionuclides such as ^{129}I and ^{107}Pd and some non-retarded radionuclides like ^{79}Se and ^{99}Tc, only a very small portion of the initial activity reaches the aquifer (Fig. 4.21):

- about $2{\cdot}10^{10}$ Bq of activation and fission products for a total initial activity of $7{\cdot}10^{19}$ Bq;
- about 10^{7} Bq of actinides (i.e., the mean concentration of actinides in 0.2 m^{3} of category A radioactive waste) for a total initial activity of around $5{\cdot}10^{17}$ Bq (mainly ^{241}Am and ^{244}Cm).

Thus the disposal system, with its functions of physical containment and of delaying and spreading the releases, acts as an extremely efficient containment system, with the major portion of the activity initially placed in the repository disappearing before it can reach the aquifer. The containment factor (the ratio of disposed activity to cumulative released activity in the aquifer) is $4{\cdot}10^{9}$ for the activation and fission products and $5{\cdot}10^{10}$ for the actinides.

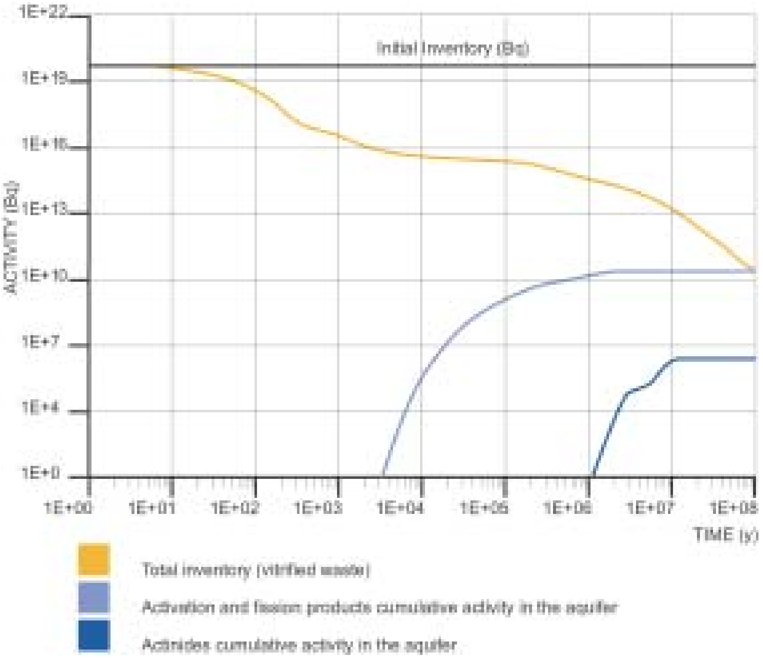


Figure 4.21 Cumulative activity reaching the Neogene Aquifer for the vitrified waste.

The total percentage of long-lived radionuclides reaching the biosphere is high, however: 99 % for ^{129}I, 94 % for ^{238}U, 92 % for ^{235}U, etc. Nevertheless, the function of delaying and spreading the releases ensures that this release is very much spread out over time, so a future individual would only ever be exposed to a very small fraction of the total activity placed in the disposal system. With the vitrified waste for example, the annual maximum flux of ^{129}I ($2 \cdot 10^{6}$ Bq per year) corresponds to $3 \cdot 10^{-6}$ of the total activity of ^{129}I disposed. For ^{79}Se, the annual maximum flux ($2 \cdot 10^{7}$ Bq per year) corresponds to $3 \cdot 10^{-7}$ of the initial activity of ^{79}Se.

Total activity flux at the interface between the Boom Clay and the Neogene Aquifer The maximum activity flux for the vitrified waste, spent fuel, and hulls and endpieces at the interface between the Boom Clay and the Neogene Aquifer is approximately $2 \cdot 10^{7}$ Bq per year. This is less than 100 $\text{Bq} \cdot \text{m}^{-2}$ per year, given that the area of the considered repository is 0.224 km^{2} to accommodate the vitrified waste and 1.17 km^{2} to accommodate the spent fuel.

This maximum annual flux is very small, since it is equivalent to the alpha activity of the uranium, thorium, and radium naturally occurring in a layer of Boom Clay of around 0.1 mm thick. (The mean activity of these isotopes in the clay is approximately 360 $\text{Bq} \cdot \text{kg}^{-1}$, or $7 \cdot 10^{5}$ $\text{Bq} \cdot \text{m}^{-3}$.) In addition, the flux of radionuclides that leaves the Boom Clay and reaches the Neogene Aquifer only adds 0.0008 % per year to the natural activity already present in the Berchem Sands, a sub-layer of the Neogene Aquifer approximately 20 metres thick and situated just above the Boom Clay. (The natural activity of uranium, thorium, and radium in this layer is approximately 400 $\text{Bq} \cdot \text{kg}^{-1}$, or $6 \cdot 10^{5}$ $\text{Bq} \cdot \text{m}^{-3}$.) Finally, the cumulative total activity due to the vitrified waste that reaches the Neogene Aquifer, integrated over a period of 100 million years (Fig. 4.21), can be compared to the alpha activity naturally present in the Berchem Sands. For the released activation and fission products, this corresponds to the alpha activity present in an approximately 10-cm-thick layer of the Berchem Sands and, for the actinides, it corresponds to the alpha activity in a layer approximately 0.1 mm thick.

Total uranium inventory In the very long term, the radiological impact of the repository will be due to the isotopes of uranium and their daughters, in particular, to isotopes of radium, thorium, and protactinium. A third alternative indication of the potential radiological impact in the very long term, therefore, is to compare the total initial inventory of uranium in the vitrified waste and in the spent fuel with the quantity of alpha activity naturally present in the Boom Clay around the disposal facility (approximately $7 \cdot 10^{5}$ $\text{Bq} \cdot \text{m}^{-3}$). For the total initial inventory of approximately $5 \cdot 10^{12}$ Bq U in the vitrified waste and approximately $2 \cdot 10^{14}$ Bq U in the spent fuel, the quantity of uranium isotopes that migrate through the Boom Clay from the disposal facility is actually close to the quantity of alpha activity already naturally present in the volume of clay that surrounds the disposal facility. Specifically, considering a clay layer that is 80 metres thick—the effective thickness of the Boom Clay layer—the equivalent volume of clay would have an area of 0.25 km^{2} for the vitrified waste and 4 km^{2} for the spent fuel.

4.3.3 Assessment of the altered-evolution scenarios

Whereas the SAFIR report presented results for one altered-evolution scenario only—the fault activation scenario—the SAFIR 2 report gives an initial and mainly qualitative analysis of the impact of the six altered-evolution scenarios identified in the scenario development (see Section 4.2.2.2).

- The probability of occurrence of the *exploitation drilling scenario* is low because of the low hydraulic conductivity of the Lower-Rupelian Aquifer and the fact that the chemical composition of the water in this layer makes it unfit for human consumption unless treated. If, hypothetically, this water was used untreated as drinking water and for agricultural purposes, as considered for the Neogene Aquifer in the normal-evolution scenario, it could lead to a dose of several mSv per year to an individual of the reference group. This is because the movement of water in this aquifer is slow and because this aquifer is not very thick (30 metres), so that only limited dilution and dispersion of radionuclides can occur. Thus, the radionuclide concentrations can be up to 1 000 times greater than those in the overlying Neogene Aquifer.

- For the *fault activation scenario*, the parameters used to describe the migration of water and radionuclides via the fault are set to arbitrary values. Calculations of the effects of the scenario indicate that its radiological impact is minimal and is of the same order of magnitude as that of the normal-evolution scenario because only a very small fraction of the disposed radionuclides can take part in the accelerated migration through the fault. Its probability of occurrence could be greatly reduced by choosing a disposal site that is free from any pre-existing geological structural weaknesses.

- The *severe glaciation scenario* has yet to be assessed quantitatively. According to the orbital theory of Milankovitch, however, the probability of it occurring during the next few tens of thousands of years is low—there should be no glacial periods more severe than the last three of the Quaternary, and in none of these did the ice cap cover the Mol–Dessel region. Nevertheless, there are still major uncertainties about the secondary mechanisms determining the climate on a scale of several hundred thousand years, such as the concentrations of CO_2 in the atmosphere, and ocean currents. A shift of the Gulf Stream during a glacial period, for example, could induce a far greater extension of the ice cap. Recent calculations show, however, that there should not be a glacial era severe enough to significantly extend the ice cap during the next 130 000 years. By this time, the activity of the disposed waste will have greatly diminished, and so the impact of a glaciation scenario would probably be limited.

- The impact analyses so far undertaken of the *poor-sealing scenario* of the main galleries and access shafts indicate that this scenario should have no major consequences. Migration by advection in the poorly-sealed main galleries remains extremely limited because the water flow into the repository is limited by the low hydraulic conductivity of the Boom Clay. Its probability of occurrence could be greatly diminished by ensuring a safety culture and a strict policy of quality assurance during closure of the repository.

- The scenario of *transport by gases* studies the coupling between gas flows and water flows in the event that a gas phase appears, and analyses its influence on the radiological impact. Assessments so far indicate that the vitrified waste, spent fuel, and probably the hulls and endpieces do not create any significant problem of gas production. This is due primarily to the use of stainless steels as packaging materials. For certain other waste classes containing a large quantity of carbon steel, pockets of gas may form in the near field, expelling the water through the clay, and even the formation of preferential migration pathways in the clay cannot be ruled out. The sub-scenario that studies the expulsion of water containing dissolved radionuclides from the near field has limited consequences, since in the worst case, the maximum radionuclide flux to the aquifer is only increased by a factor of 10. In the unrealistic sub-scenario that considers the creation in the clay of a migration pathway allowing the flow of water and gas, the migration through the argillaceous layer may—for a certain number of waste classes in category B—increase by a factor of about 100 compared with the normal-evolution scenario. Even in this case, the flux of radionuclides towards the aquifer is less than that for the vitrified waste and spent fuel. For the category B waste, therefore, the repository must be designed to allow for the possible formation of gas, so that the formed gases can escape without damaging the barriers of the disposal system and without significantly affecting its containment capacity. Every reasonable effort must also be made to reduce the sources of gas, for example by avoiding the use of carbon steel for waste packagings. Finally, assessments of the scenario of transport by gases require more knowledge of the various parameters and processes involved, especially the diffusion coefficients of the main gases that are formed and of the hydraulic characteristics of the fracture zones.

- The second variant of the *exploration drilling scenario*, the one that assumes that a borehole drilled through the disposal facility is not backfilled, and which therefore assesses the robustness of the disposal system if the barriers are disturbed by intrusion, will only have a very limited impact, as the borehole will close up gradually by convergence owing to the plasticity of the Boom Clay. One issue is whether the probability of occurrence could be significantly reduced by building the repository at greater depth.

Two altered-evolution scenarios have not yet been investigated.

- The *greenhouse effect scenario*. This scenario mainly affects the biosphere and to a lesser extent the hydrogeology, and could greatly reduce the temperature falls that are expected under the orbital theory of Milankovitch.
- The *scenario of the premature failure of an engineered barrier*. Its radiological impact will probably be less severe than might be expected because a large part of the clay layer will remain intact. It should be assessed in depth, however, since the mechanisms of migration under a temperature gradient are different from those considered in the normal-evolution scenario.

Finally, the first variant of the *exploration drilling scenario*, i.e., the human intrusion scenario, is not considered in the safety assessments, and this is moreover consistent with the international consensus with respect to its relevance. It is indeed very unlikely given current prospecting techniques, it is impossible to estimate its probability, and its consequences are independent of the repository design and of the chosen site. It will, of course, be essential to site the repository outside zones of natural resources.

4.3.4 Other results and considerations

All of the work done in assessing the normal-evolution scenario, and the initial and mainly qualitative assessments of altered-evolution scenarios, has yielded certain results and considerations which supplement the dose calculations and alternative indicators.

Building confidence in the migration models The excellent consistency between, on the one hand, the concentrations of non-retarded radionuclides calculated in advance based on the results of laboratory migration experiments and, on the other hand, the concentrations measured in situ on a large scale support the validity of the migration model in the Boom Clay used for these non-retarded radionuclides. The very slow migration of the retarded radionuclides—mainly the actinides—indicates periods for migration through the Boom Clay of 100 000 to 1 million years. This is confirmed by the finding that the natural isotopes of thorium and uranium that occur in the Boom Clay have been virtually immobile since it was deposited.

Comparison with the results of previous safety assessments

- *Activation and fission products* Hypotheses that are more conservative than adopted in the past have led the SAFIR 2 safety assessments to demonstrate the importance of two radionuclides—^{36}Cl and ^{79}Se—that were not considered in previous safety assessments or that did not give rise to significant doses. ^{36}Cl is an activation product formed by the irradiation of chlorine impurities in the fuel and the hulls. Its inventory is still not very well known and was underestimated in earlier assessments. ^{79}Se is a nuclide whose migration through the Boom Clay is not yet sufficiently understood. Recent safety assessments, therefore, have prudently assumed an absence of sorption and its transfer coefficients in the biosphere are often conservatively estimated. Its solubility and possibly its retention are thus parameters that greatly affect its flux towards the aquifer. If it is confirmed that selenium does not sorb on the Boom Clay, these parameters will, therefore, have to be known accurately.
- *Actinides* The highest doses are attributable to daughter radionuclides of uranium, especially ^{229}Th and ^{226}Ra.
- *^{129}I* As the considered ^{129}I activity for the vitrified waste has appeared greatly overestimated, the radiological impact of the ^{129}I in this waste is also greatly overestimated, and in the same proportions.

Influence of the value of the ^{79}Se half-life Whereas calculations for the Belgian safety assessments use a half-life of 65 000 years for ^{79}Se, a number of foreign sources have recently been quoting much higher values. An initial assessment has therefore been made of the impact on the calculated doses of a more probable half-life of 650 000 years. This assessment indicates a reduction by 5 of the maximum doses attributable to selenium, i.e., a maximum dose of approximately 2 µSv per year for the vitrified waste and approximately 1.5 µSv per year for the spent fuel. The period of exposure to selenium is longer, however.

Comparison of the radiological impact of the two reprocessing options The maximum doses obtained for the two reprocessing options are at least one order of magnitude below the dose constraints, which vary from 0.1 to 0.3 mSv per year. The maximum doses are 10 µSv per year for the reprocessing option and 20 µSv per year for the direct disposal option (Fig. 4.22). For the first 500 000 years, the differences between the total doses calculated for the two options are very low, a factor of 2 at the most. The maximum dose is due primarily to ^{79}Se in both cases. After 500 000 years, greater differences appear between the two options, but by this time, the doses are below the dose constraint value by 2 to 3 orders of magnitude. In the very long term, around 20 million years, the difference between the two options is approximately one order of magnitude owing to the greater quantity of actinides that is disposed in the direct disposal option.

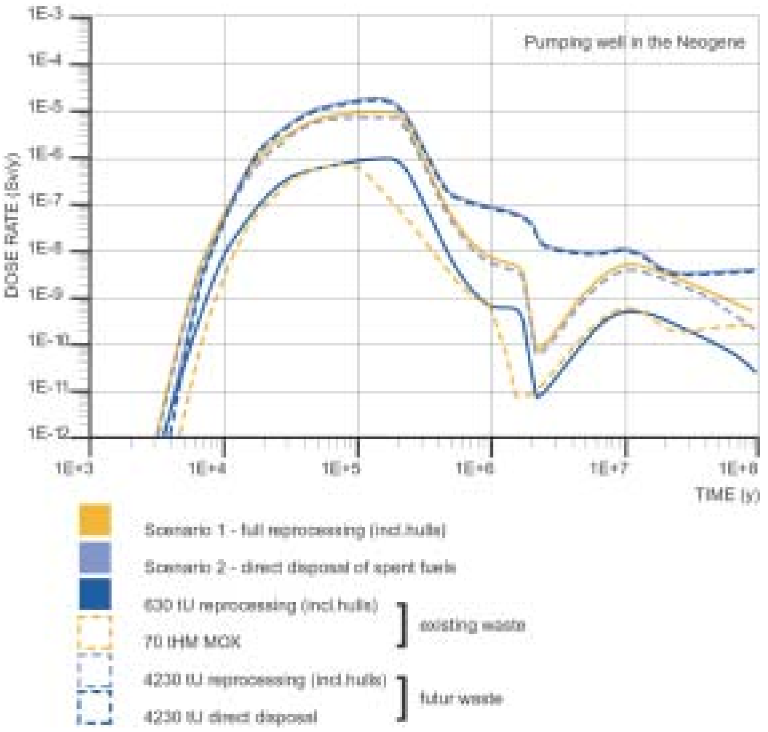


Figure 4.22 Evolution of total dose rates for the two reprocessing options in the case of the normal-evolution scenario.

Influence of complexation by the mobile organic matter Preliminary assessments indicate that the increase in the maximum flux of radionuclides which reach the Neogene Aquifer due to the complexation of actinides by the mobile organic matter is negligible for the three classes of waste considered. Some actinides may reach the aquifer in negligible quantities and more quickly—say after around 10 000 years—than estimated on the basis of the sorption behaviour observed for most of them. But after around 10 000 years, only non-retarded activation and fission products like ^{129}I and ^{79}Se reach the aquifer in much greater quantities.

Importance of uncertainties about fluxes and doses due to uncertainties about the values of the characteristic parameters of the disposal system

- *Uncertainties about the radionuclide inventories* Even using conservative assumptions, the radiological impact of the large majority of radionuclides is several orders of magnitude below the dose constraint, so the uncertainties surrounding the inventories are not a determining factor. It is only for the non-retarded radionuclides ^{129}I, ^{36}Cl, and ^{79}Se that the inventories must be accurate.
- *Uncertainties about the durability of the watertight packagings/overpacks* Assuming the Boom Clay performs its barrier function properly, these uncertainties are not a determining factor. This is because the packagings/overpacks can only significantly delay the fluxes of non-retarded radionuclides at the interface between the Boom Clay and the Neogene Aquifer if their durability exceeds 100 000 years, and because they are unable to significantly reduce these fluxes. The packagings/overpacks must, however, perform their function of physical containment during the thermal phase of the repository.
- *Uncertainties about the degradation rate of the glass, and the UO_2 and UO_2–PuO_2 matrices* These uncertainties have virtually no influence on the radionuclide fluxes because of the good performance of the argillaceous barrier, certainly in the case of the long-lived radionuclides, the retarded radionuclides, and radionuclides with a low solubility limit. Only if the waste matrices have a durability exceeding 500 000 years do they have a distinct effect on the flux of non-retarded radionuclides leaving the argillaceous layer. They may also make a more significant contribution for the relatively short-lived and non-retarded radionuclides such as ^{14}C. They do not assist in the containment of the actinides, as the low solubility of the latter is already sufficient to ensure their very slow release from the near field.
- *Uncertainties about migration parameters* The importance of these uncertainties is very limited for the non-retarded radionuclides because their determining parameters are the migration parameters, and these are adequately known for ^{36}Cl and ^{129}I or have been estimated very cautiously for ^{79}Se. (The values of the migration parameters for retarded radionuclides, and especially the values of retardation factors, are subject to major uncertainties however.)
- *Uncertainties about the effective thickness of the argillaceous barrier* Although the thickness of the argillaceous layer is one of the parameters that most affect containment, its impact on peak release is relatively unimportant and so, therefore, is the uncertainty about the exact value of the thickness. For an increase of 10 %, i.e., nearly 10 metres, in the thickness of the argillaceous barrier, the maximum radionuclides flux towards the Neogene Aquifer actually decreases by 18 % on average.

Role of the different barriers in the overall functioning of the disposal system The contribution made by the different barriers of the disposal system and by its environment to the overall safety of the system may be visualised by calculating the cumulative quantity of activity released by each barrier for representative radionuclides. Calculations for ^{126}Sn and ^{129}I—a retarded radionuclide with a half-life of 100 000 years and a non-retarded radionuclide with a half-life of 16 million years respectively—clearly demonstrate the dominant role of the geological barrier (Figs. 4.23 and 4.24).

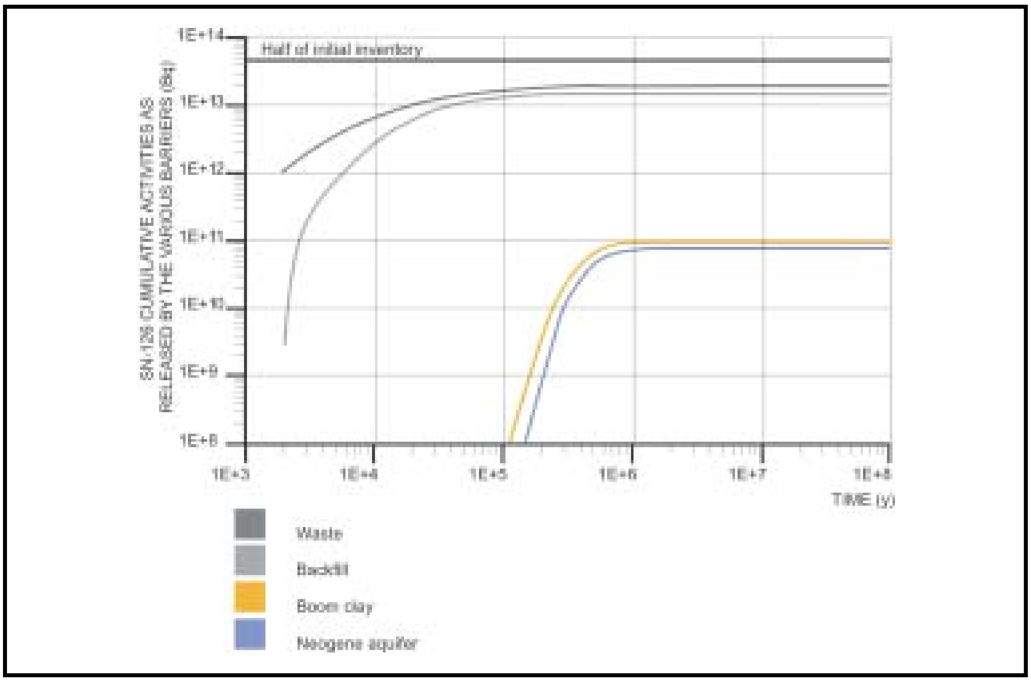


Figure 4.23 Cumulative quantities of ^{126}Sn released by the different barriers of the disposal system and by its environment for the disposal of 1 980 tUOX–55.

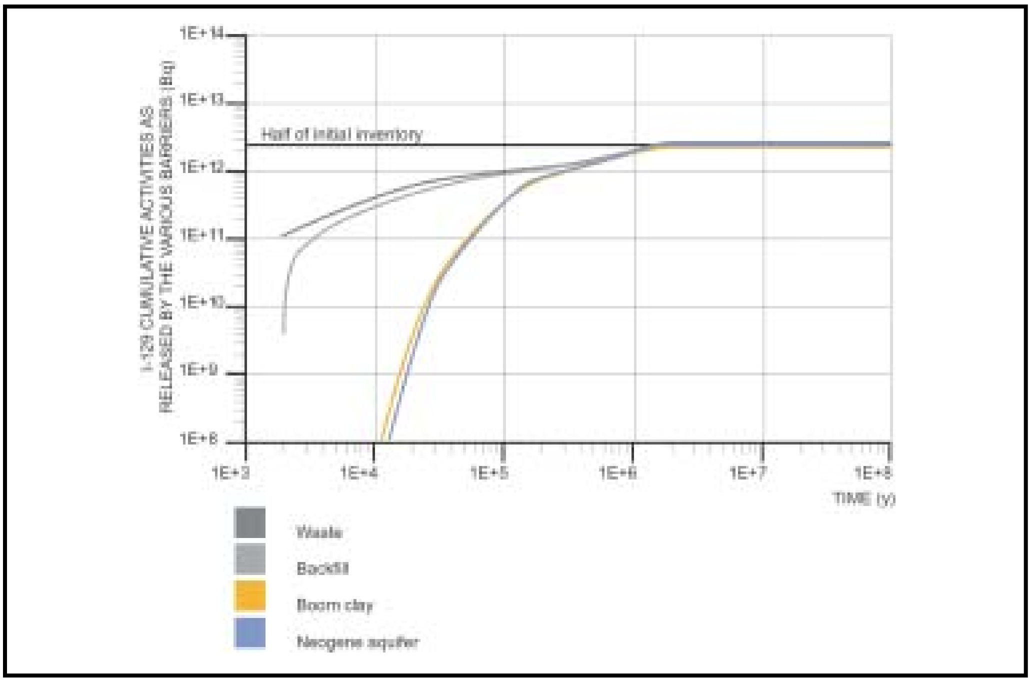


Figure 4.24 Cumulative quantities of ^{129}I released by the different barriers of the disposal system and by its environment for the disposal of 1 980 tUOX–55.

Assessment of the altered-evolution scenarios Initial, and mainly qualitative, assessments of certain altered-evolution scenarios provide a first indication that they do not significantly increase the radiological impact. However, these analyses need to be deepened and extended to the scenarios that have not yet been investigated, with a view to obtaining truly conclusive information about their impact.

4.4 Sub-criticality

The long-term radiological safety of a deep repository can be affected by the phenomenon of criticality, i.e., by a spontaneous and sustained nuclear chain reaction (see Section 2.2.4). This risk is therefore being studied, although these studies are still at an early stage. At present, they are confined to an examination of the risks induced by the disposal of spent fuel, because the quantities of fissile radionuclides that the spent fuel contains are far greater than found in the other waste classes.

The risks of criticality must be assessed both in the reference configuration, i.e., the configuration that corresponds to the initially proposed disposal geometry, with no alteration to the fuel or mechanical modification of its geometry, and in altered configurations. The calculations carried out for fuel assemblies in the reference configuration assume that the sole disturbance is the ingress of water into the packages. This saturates the filler sand, greatly increasing the moderation of neutrons, and, therefore in principle, the risk of a nuclear reaction. The calculations indicate, however, that the conditions remain broadly sub-critical in spite of the conservative hypotheses that are made. Except for an initial programme of research into the leaching of UO_2 through the interstitial water in the Boom Clay (see Section 3.4.1.2), there has as yet been no systematic study of the evolution—upwards or downwards—of the criticality risks associated with the inevitable gradual change in the reference configuration of the fuel assemblies.

4.5 Outlook

Over the coming years, the process of improving the quality of the long-term radiological safety assessments will focus on the following main areas:

- *In-depth discussions with the safety authorities on the general methodology of long-term safety assessments and the experience acquired with it*, the objective being to identify the areas that will need to be strengthened, adapted, or broadened in future phases of the programme.
- *Improving the methodology of long-term safety assessments*. This would include an improvement in the methodology of scenario development, a review of the FEPS that must be taken into consideration, and a better definition of the timescales over which the different components of the disposal system and its environment can be considered to be robust. The systematic use of safety functions and FEPS is aimed at achieving an advanced integration in the safety assessments of all the components of the repository design (including the waste that is to be disposed), the geological barrier, and the hydrogeological environment that are relevant for safety. The transparency of the safety assessment methodology will also be enhanced, especially for the waste inventories that are used, the conceptual models and calculation tools, and the disposal systems that are considered.

- *Refining the models used for assessing long-term safety*, especially as regards the aspects of abstraction and simplification of the disposal system and the modelling of the biosphere in the normal-evolution scenario. The relationship between the detailed research models, e.g., for the degradation of waste matrices or metal packagings, and the hypotheses or simplified models used in the safety assessments will be clarified.
- *Integrating the impact of the heterogeneities in the Boom Clay and the excavation disturbed zone on radionuclide migration*. Particular attention will have to be given to the potential impact of the presence of more permeable sub-layers in the Boom Clay on the radionuclide fluxes at the interface between the Boom Clay and the aquifers, and, hence, on radiological safety.
- *Systematising the definition, selection, and assessment of the altered-evolution scenarios* and, in particular, studying the effects of potential climate change (temperature increase, glaciations, etc.) on the clay and on the hydrogeological environment of the repository. The altered-evolution scenarios—some of which have been the subject of an initial description and a preliminary impact analysis—will be reassessed in an integrated and more transparent fashion in collaboration with the safety authorities. Through wide-ranging discussions with the scientific world in particular, this reassessment process will aim to strengthen the technical and scientific foundation on which the description and modelling of these scenarios is based.
- *Refining the definition and interpretation given to the various indicators of safety and environmental protection*, especially for the different timescales that are considered.
- *Defining methods to assess the robustness of the disposal system, and identifying and quantifying the elements that contribute to it*. This will include a clarification of the relationship between optimising radiological safety and enhancing the robustness of the system.
- *Identifying the different types of residual uncertainties and the means needed to reduce them, and refining the methods used to address them.* As the programme advances, an increasing attention will have to be given to showing that the remaining uncertainties can be adequately eliminated or that they have no significant impact either on technical feasibility or on the protection of humans and the environment.
- *Preliminary safety assessments for the waste classes that are conditioned in bitumen and cement*. These will relate mainly to aspects of compatibility with the Boom Clay.
- *Compiling all of the qualitative and quantitative arguments* that indirectly support the safety assessments. This is primarily information obtained from the characterisation of the geological barrier and the hydrogeological environment that forms the basis for the stability and containment capacity of the disposal system, and information obtained from studies of relevant natural analogues.

In addition to these points, the future work will also have to deal with the assessment of the nuclear and conventional operational safety and with the assessment of compliance with environmental protection regulations, using a methodology approved by the safety authorities. This is the framework within which the bases for radiological optimisation will be established (the ALARA principle), and this will be a major aspect of the future discussions with the safety authorities.

5 Assessing the costs: an analytical, parametric, and flexible methodology

Following recommendations by the SAFIR Evaluation Commission (1990), ONDRAF/NIRAS has developed a systematic methodology for assessing the costs of implementing the solutions it proposes for the long-term management of category B and C waste. The methodology involves an analytical and parametric appraisal of the basic costs of the different implementation stages of these solutions and then applying, to those costs, coefficients that reflect the level of uncertainty associated with each of them. ONDRAF/NIRAS has also established a mechanism designed to ensure the financing for this very long-term spending programme.

So far, ONDRAF/NIRAS has only carried out a detailed assessment of the cost of implementing an industrial deep disposal project for the vitrified waste and the spent fuel. These are indeed the only types of waste for which a reference design and safety assessments are at a sufficiently advanced stage, although these are still likely to evolve further. This cost assessment has however been undertaken on the assumption, thought probable, that a common repository will be developed for all types of waste in the geological group. This repository would be constructed and operated in two stages: first, the part intended for the category B waste and the moderately heat-emitting category C waste; second, the part intended for the vitrified waste and/or spent fuel. This staged approach would allow the construction of the part intended for the latter waste types to benefit from the experience already gathered. (The current cost assessment takes no account of the research and development costs, which for the period 1974–2000 were approximately 150 millions EUR or 6 billion BEF at year 2000 economic conditions, or of indirect costs and charges.)

An assessment of the basic costs, excluding uncertainty margins (Table 5.1), calls for an approach that is analytical, parametric, and flexible. This is so that it can be adapted quickly and easily to the changes that will inevitably occur in the input data (design, inventory, etc.) between now and the actual implementation of a repository, and so provide a clear picture of how these costs will be affected by such changes. The method involves producing—for each cost assessment—a costing sheet recording all the types and quantities of waste to be placed into the repository (see Section 3.1.2), the selected repository design and corresponding detailed capacity (see Section 3.3.1), the reference organisational chart of the company that will operate the repository, the durations of the various construction phases, an assessment of unit costs, a reference to sources of information, and the uncertainty margins. In this way, the approach also provides a vital basis for use in the technical and economic optimisation that will have to be conducted at a more advanced stage of the programme.

The reference timetable for the deep disposal of the vitrified waste and spent fuel has been developed from realistic operational scenarios based on the present level of knowledge about the repository design and about techniques of construction, operation, and closure. This reference timetable starts at the time when the competent authority issues the licences that authorise the investments to be made; this assumes that a site has been chosen. The estimated total minimum period of time required for the project, from granting of a licence to repository closure, would be approximately 40 years for the ‘complete reprocessing’ option and approximately 50 years for the option of ‘direct disposal’ of spent fuel. In both cases, this includes about 10 years for detailed design and safety studies. This reference timetable will be regularly updated, and is based on the assumption that the parties involved will not wait for the last of the waste to be emplaced before applying for permission to close the repository, or before actually closing some of its parts.

Table 5.1 Cost assessments of a repository for the vitrified waste and the spent fuel, based on complete reprocessing and direct disposal options [in 10^6 EUR at year 2000 economic conditions].

Implementation stages	**Complete reprocessing**			**Direct disposal**		
	basic cost	margin	estimated cost	basic cost	margin	estimated cost
Construction	190	1.95	371	430	2.40	1032
Operation	63	1.95	122	53	2.70	144
Closure	36	2.38	85	106	3.00	318
Total	**289**	**–**	**578**	**589**	**–**	**1494**

ONDRAF/NIRAS estimates the contingency margins using the methodology of the Electric Power Research Institute (EPRI). This was developed to analyse the costs of nuclear power facilities, and has since been adapted to analyse the costs of a radioactive waste repository. The methodology is used to compute the factors of uncertainty assigned to each of the three major stages in the implementation of a repository, which are dealt with as three separate projects. These are the detailed design and construction stage, the stage in which the waste packages are placed in the repository (operation), and the closure stage, which includes backfilling operations and dismantling of the surface facilities. (The current cost assessments do not include the costs of the institutional control phase, as its relative impact is regarded as negligible, nor are any costs of waste retrieval operations included.)

A feature of the EPRI methodology is that the cost analysis must include a judgement on the quality of the data on which it is based. The methodology therefore identifies two types of contingency margin.

- The *margins for project contingencies* reflect the risks involved in the implementation of the industrial project. These contingencies are smaller the more advanced the project and, hence, the more accurate its cost estimate. They are divided into four margins: 30 to 50 % for a so-called ‘simplified’ estimate, 15 to 30 % for a so-called ‘preliminary’ estimate, 10 to 20 % for a so-called ‘detailed’ estimate, and 5 to 10 % for the final estimate.
- The *margins for technological contingencies* reflect the level of knowledge of the technologies used, and are smaller where available references exist, e.g., comparable projects or pilot plants, or comparison data. These contingencies are also divided into four margins: at least 40 % for entirely new technologies, 30 to 70 % for technologies

for which some comparison data exist, 20 to 35 % if the technologies have been tested on a limited scale, and 5 to 20 % where they have already been applied at full-scale.

In practice, the current analyses assume that the level of progress reached by the disposal programme is a valid basis on which to make a preliminary estimate of the cost of the stages of construction and operation for the 'complete reprocessing' option, and a simplified estimate of the cost of its closure stage and the three stages of the 'direct disposal' option. They also assume that, for both options, the technologies are entirely new and have no comparison data.

Once the overall coefficients of the contingency margins have been calculated by combining the two margins, they can be applied to the basic costs to give the estimated costs (Table 5.1). Thus, the foreseeable costs assessed at the end of 1997 for the *complete reprocessing* option range from 290 to 580 million EUR at year 2000 economic conditions (12 to 23 billion BEF at year 2000 economic conditions). For the *direct disposal* option, they range from 590 to 1 500 million EUR at year 2000 economic conditions (24 to 60 billion BEF at year 2000 economic conditions). These assessments will be reviewed as knowledge evolves, especially at the end of the PRACLAY demonstration experiment. Results of this experiment should reduce the uncertainties surrounding a number of essential aspects of the repository design, such as the method and rate of construction and equipment of the galleries. However, ONDRAF/NIRAS is currently developing more sophisticated costing tools. These use in particular the amount of research and development budget still required to develop the design of the disposal facility as an indicator for assessing the technological maturity of a project.

The timetables for long-term management operations run over several decades and, therefore, ONDRAF/NIRAS has also developed a system of provisions on a tariff basis applicable to the waste that is transferred to it. These provisions are paid by the waste producers into a special fund called the *long-term fund.* In due course, this fund will guarantee the availability of the resources that are needed to implement the chosen long-term management solution(s). The provisions are calculated on objective allocation criteria and on the three following principles:

- the *reservation of capacity*: every major waste producer advises ONDRAF/NIRAS of his planned total waste production programme, thereby enabling ONDRAF/NIRAS to spread its fixed costs among the producers;
- the *tariff payment*: each producer pays into the long-term fund a contribution that corresponds to the total cost of the long-term management of the waste he transfers to ONDRAF/NIRAS;
- the *contractual guarantee*: each major producer commits to paying to the long-term fund the balance of fixed costs that are attributable to his waste and that are not already covered by the tariff payments.

Assessments of the cost of management solutions are, therefore, an important input to the calculation of the amounts that must be planned for in the long-term fund.

6 Conclusions and assessment of the confidence acquired

Conducted following the recommendations of the SAFIR Evaluation Commission (1990), the second phase of the ONDRAF/NIRAS methodological research and development programme (1990–2000) into the disposal of category B and C waste into a poorly-indurated clay has achieved significant advances in methodological, scientific, and technical terms. This programme aims to establish that a solution for disposal into a geological host formation is possible (i.e., safe and feasible) on Belgian territory. It has two main areas of activity:

- *to develop and improve all of the methods that are needed to define and implement a disposal solution*, such as the characterisation of the waste types, the characterisation and assessment of a host formation, the development of a repository design, the performance and safety assessments, and the identification of residual uncertainties;
- *to assess the feasibility of the solution and of the elements in support of safety* by basing itself, by hypothesis, on a reference case, the Boom Clay beneath the Mol–Dessel nuclear zone.

The programme has also considered the Ypresian Clays (beneath the Doel nuclear zone) as an alternative host formation, although to a lesser extent. The research work carried out at Mol–Dessel and Doel does not imply any decision as to the choice of the site where the studied solution might be implemented. The work is also provisionally limited to a study of the waste classes regarded as being the most demanding radiologically and in terms of heat emission. From an early stage in its development, the Belgian programme has benefited from the information obtained from the construction and operation of the HADES underground research facility, which is located at a depth of 223 metres within the Boom Clay beneath the SCK•CEN site at Mol.

None of the information obtained from the research has so far indicated any flaw that might prohibit the disposal of the vitrified waste from the reprocessing of spent nuclear fuel into the Boom Clay. This increases confidence in the studied solution and confirms that disposal in a poorly-indurated clay remains a viable option for the types of waste considered in the SAFIR 2 report.

Today, the knowledge that has been accumulated makes it possible to confirm the qualities of the Boom Clay as a natural barrier. The work carried out has demonstrated the feasibility of constructing the underground facilities needed for disposal at depths of 200 to 250 metres. ONDRAF/NIRAS has also expanded its confidence in its methodology of long-term safety assessments and in its ability to design a disposal facility capable of protecting humans and the environment from the potentially harmful effects of radioactive waste for as long as is necessary.

Though the basic choice of the Boom Clay is not in question, the confidence that can now be placed in the proposed disposal system, which is based primarily on the qualities of the host formation as a barrier, is still not sufficient to give a final answer on the technical feasibility and long-term safety of a repository in this formation. The retention of the radionuclides by the natural barrier, the performance of the engineered barriers, and certain aspects of design and of compatibility of the waste are all factors that are still surrounded by uncertainties. These uncertainties must be eliminated or reduced to an acceptable level before practical implementation can be undertaken. Moreover, the operational safety of such a facility, and its compliance with environmental standards (chemotoxicity, etc.), have so far only been studied on a preliminary basis. These reservations apply even more so to the alternative option of disposal in the Ypresian Clays.

This final chapter synthesises the most significant achievements in the period 1990–2000, and then outlines the technical and scientific aspects that must be considered in order to define the third phase of methodological research and development, as presently envisaged by ONDRAF/NIRAS. It concludes with an assessment of the present level of confidence in the studied reference option.

6.1 Main achievements

The main achievements of the work carried out between 1990 and 2000 relate to the scientific and technical knowledge obtained, and also to the identification of unresolved issues and the assessment of the relative importance of the remaining uncertainties.

6.1.1 The knowledge acquired and the unresolved issues

Inventory and knowledge of the conditioned waste to be disposed of

- *Establishment of a coherent overall approach to waste classification.*
- *Establishment of a general classification for conditioned radioactive waste*, which facilitates the definition of the inventory and transparent management.
- *Improvement of the inventories* (volumes, concentrations in critical radionuclides) *to be considered for the complete reprocessing option and the direct disposal option of the spent UO_2 fuel* produced by the current Belgian nuclear programme. The physical characteristics (heat emission in particular) and chemical characteristics (especially the presence of heavy metals) have still to be confirmed for all the waste classes and for the category B waste in particular.
- *Establishment*, on the basis of the general rules approved by the authorities, *of acceptance criteria for the vitrified waste*, which take account mainly of the requirements associated with the short- and medium-term management of this waste (transport, interim storage).

Assessment of the Boom Clay beneath the Mol–Dessel nuclear zone as a natural barrier, and knowledge of the environment of the disposal system
(see also the summary box at the end of Section 6.3)

- *Improvement of the capability for characterising clays*, most notably using high-resolution reconnaissance methods. An integrated interpretation (which is still ongoing) of all of the gathered data suggests the absence of structural discontinuities (faults) affecting the Boom Clay beneath the Mol–Dessel nuclear zone. It also allows to trace in the underground the fine lithological variations, which are characteristic of this formation and which are observed at the surface (clay pits).
- *Confirmation of the value of the hydraulic conductivity* (10^{-12} $m \cdot s^{-1}$) obtained on core samples (centimetre scale), with in situ tests in boreholes (metre scale), or around the underground research facility (decametre scale).
- *Review of the hydrogeological model* indicating the role of the local discharges of groundwater flows. There is, however, an inconsistency between the value of hydraulic conductivity measured locally in the Boom Clay and the value indicated by regional modelling (hundred-kilometre scale). The complexity of the aquifer beneath the clay and the possibility of a hydraulic short-circuit via regional-scale faults should be considered with a view to resolving this inconsistency. The analysis of the origin and evolution of the chemistry of the aquifers and aquitards is still at an early stage, but it could help corroborate the results of groundwater flow modelling.

- *Confirmation of the properties of the Boom Clay as a natural barrier to radionuclide migration.* The experimental study of the properties controlling migration in the clay has been much improved. The migration of critical radionuclides has been studied experimentally in the surface laboratory. The diffusion-controlled nature of the migration of solutes in the Boom Clay has been confirmed by tests with retarded and non-retarded tracers in a representative volume of the clay and over periods of about a decade. Confidence in the quality of the natural barrier is further enhanced by the observation of the quasi-immobility over geological timescales of the uranium and thorium naturally occurring in the host formation. A systematic analysis of the migration parameters of the radionuclides that are not retarded, or only slightly retarded, over the total thickness of the formation shows that these parameters are within the ranges considered in the safety assessments. Uncertainties remain as to the exact mechanisms of sorption for certain retarded radionuclides and the long-lasting character of geochemical conditions that are favourable to radionuclide retention.

- *Schematic subdivision of the Boom Clay beneath the Mol–Dessel nuclear zone into different thicknesses depending on the considered viewpoint*. The thickness for which the Boom Clay presents virtually constant *migration parameters for the non-retarded radionuclides* is approximately 90 metres, and so includes the transition zone at the top of the formation. For calculations of radionuclide migration through the clay, however, the thickness considered for the natural barrier is only 80 metres. The difference is accounted for by the thickness excavated for the construction of the repository, estimated to be 5 metres maximum, and the thickness of the zone where migration parameters could have been disturbed in the long term by the construction and presence of the repository. The latter is estimated to be 5 metres, considering the self-healing phenomena of the excavation-induced fractures. Depending on the context, therefore, the different thicknesses attributable to the Boom Clay are as follows (Fig. 6.1): a *stratigraphical thickness* (between the base and top of the formation), a *lithological thickness* (the most argillaceous part of the formation), a *thickness of the aquitard* (for which $K_v < 10^{-11}$ m·s^{-1}), a *thickness in which the migration parameters are constant*, and a *thickness of the natural barrier used in safety assessments*.

Design and construction of the disposal facility

- *Establishment of design bases for the repository that ensure the long-term safety functions*, taking into account the requirements inherent to the host formation and to the depth of the existing underground facilities. In particular, these should consider the need *(i) to ensure the function of physical containment* of the waste during the thermal phase so as to prevent leaching of matrices and radionuclide migration under significant thermal gradients, *(ii) to separate the different waste classes* so as to minimise the risks of interactions between different types of waste and materials, and so to reinforce the robustness of the system, and *(iii) to minimise the geomechanical, thermal, geochemical, and hydrogeological disturbances* induced in the host formation.

- *Definition of a reference design* (geometry and materials that make up the disposal facility) *for the vitrified waste and for the spent fuel*. The design defined for the vitrified waste is the reference used for the PRACLAY full-scale in situ demonstration experiment, which is one of the key aspects of the present and future programme. The repository design is only at the preliminary stage for the other waste classes, however.

- *Highlighting*, during the preparation of the PRACLAY experiment, and especially during the construction of the OPHELIE surface mock-up, as well as during the drafting of the SAFIR 2 report, *of several unresolved issues related to the industrial implementation of the facility and the control of interactions between its different components.*
- *Improvements of excavation techniques for underground facilities*: confirmation that it is possible to sink a shaft in the Boom Clay without first having to freeze the rock, and definition of an industrial excavation method for the galleries aimed at reducing the convergence of the clay, and which will be tested when the connecting gallery is constructed (PRACLAY project). The appearance of fissures and fractures at the base of the second shaft raises major issues about the disturbances induced by excavations of large diameter and about their impact on safety.
- *Demonstration that it is possible to design seals with a low permeability to gas*, even under high overpressure, and to water.
- *Accumulation of significant practical experience of operational safety over more than 20 years with the construction and operation of the HADES underground research facility* (thanks in particular to in situ experiments involving radioactive sources). While over the last 10 years priority has been given to long-term safety, the analysis and optimisation of operational safety (mining and radiological) is still at an early stage.

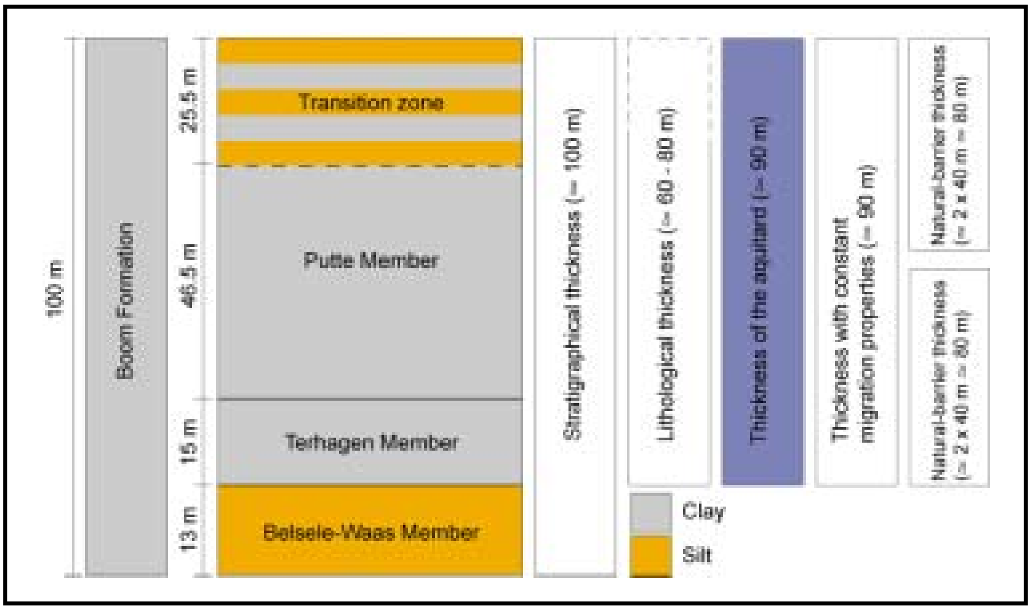


Figure 6.1 The different thicknesses of the Boom Clay layer beneath the Mol–Dessel nuclear zone.

Understanding the post-closure functioning of the deep disposal facility, and the disturbances induced by the presence of the repository in the Boom Clay

- *Improvement of the understanding of the behaviour of the waste matrices*. A minimum durability of 10 000 years has been assumed for the glass, based on the initial corrosion rates, which is a conservative assumption. The devitrification of glass is indeed a very slow process and has no significant impact on the dissolution of the matrix. Not enough is yet known, however, about the durability of the UO_2 matrices and the other components of the spent fuel, or about the compatibility of the cement and bitumen with the Boom Clay. The knowledge that has been acquired about the bituminised waste indicates that the matrix will contribute little to containing the radionuclides, and so the bitumen is disregarded as a barrier in the safety assessments. Moreover, the study of their compatibility with the surrounding medium will have to consider phenomena such as the ageing, swelling, and radiolysis of the bitumen matrix and the release of sodium nitrates (Eurobitum waste). The compatibility of waste classes other than the vitrified waste, which is considered to be the most demanding waste in thermal, radiological, and chemical terms, thus remains an unresolved issue.

- *Improvement of the understanding of the behaviour of the packagings/overpacks*. Data gathered in situ tend to confirm the existence of metals that are sufficiently resistant to generalised corrosion and pitting corrosion to be suitable for use as materials for packagings/overpacks, which must be able to perform the physical containment function throughout the thermal phase of the repository. The potential presence of other types of corrosion could, however, cast doubt on the choice of the reference material for the packaging/overpack, i.e., an austenitic stainless steel. The origin of chlorides sampled from the interstitial water of the OPHELIE mock-up, and their impact on the durability of the packagings/overpacks, remain to be investigated.

- *Improvement of the understanding of the behaviour of the backfill material*. The backfill material proposed for the reference design is a mixture of swelling clay (to provide mechanical stability and homogeneous properties), sand (to limit the swelling pressure), and graphite (to improve the dissipation of the heat emitted by the waste). The backfill has the thermal conductivity needed to dissipate the emitted heat, but its hydration requires further investigation. The evolution of its chemistry during the thermal phase and the impact of the graphite on the corrosion of the steels are unresolved issues.

- *Studies of the thermal effects of the highly heat-emitting waste* (glass and spent fuel). With the current knowledge, these effects, whether in the near field or in the far field, cast no doubt on the proposed design of the repository or the selected materials. The PRACLAY demonstration experiment will be used to refine the knowledge of the near field, especially as regards resaturation of the backfill material. The CERBERUS experiment has also shown that the mineralogy and geochemistry of the Boom Clay are not significantly modified by radiation or by a temperature increase. To minimise thermal effects, a first series of criteria defining the maximum temperatures allowable at specific places in the disposal system and its environment has been established, but remains to be confirmed (especially for the aquifers, in the absence of regulatory standards).

- *Study of gas generation and migration.* This study has revealed a limited capacity for gas diffusion in the Boom Clay and a limited gas generation by the vitrified waste or spent fuel and their respective packagings/ overpacks. This indicates there will be no real difficulties associated with these phenomena for these two waste classes. Nevertheless, the gas generation will have to be considered in the radiological and conventional safety assessment and in the design of that part of the disposal facility intended to receive the other waste classes.

- *Studies of disturbances induced by radiolysis*. The absorption of the gamma radiation by the engineered barriers and the strong sorption of the main alpha emitters by the backfill material guarantee a low level of irradiation of the clay. Experiments have shown the absence of any significant chemical or mineralogical modifications due to the exposure of the clay even to high irradiation level.

- *Studies of disturbances induced by the presence of concrete.* The concrete lining of the disposal galleries will not by itself induce any significant alkaline disturbance and will thus have no significant impact on the geochemistry of the near or far fields.
- *Study in progress of the impact of nitrates present in the bituminised waste and of other chemical species present in the waste* on the geochemistry of the Boom Clay and on radionuclide migration.

Long-term safety assessments

- *Improvement of the methodology of long-term safety assessment*, thanks mainly to an improvement in the methodology for developing scenarios and the definition of safety indicators additional to the individual dose.
- *Confirmation of the favourable results regarding compliance with radiological standards* for the three waste classes considered to be the most demanding from this standpoint, i.e., the vitrified waste, the spent fuel (UO_2 and MOX), and the hulls and endpieces. The key importance of the host formation for long-term safety has also been confirmed.
- *Confirmation of the dominant role of the non-retarded or poorly-retarded radionuclides* (^{129}I, ^{36}Cl, ^{79}Se, ^{126}Sn, ^{14}C) *in the radiological impact*. Their migration by diffusion through the clay can be regarded as being sufficiently well understood, but uncertainties remain as to the geochemistry of tin and selenium. In the normal-evolution scenario, these radionuclides create the most significant radiological impact for the direct disposal of spent fuel. This impact occurs after about 20 000 to 40 000 years, but is still one order of magnitude below the dose constraint (and hence two orders of magnitude below the dose due to natural background radiation in Belgium). The radiological impact of all the other radionuclides is several orders of magnitude below the dose constraint. The quantity of radionuclides in the waste (uranium progeny) responsible for the second radiological peak after several million years is comparable with the amount of uranium naturally occurring in the host formation around the disposal facility.
- *Preliminary assessment of the radiological consequences of several altered-evolution scenarios of the disposal system and of its environment.* The assessed scenarios include the generation of gas in the repository, a pumping well in the aquifer under the Boom Clay, and the poor sealing of the access routes to the repository. Their radiological consequences are low and similar to those of the normal-evolution scenario.
- *Preliminary assessment of the risks of criticality*. This indicates that this phenomenon should not pose any major problem for safety.
- *Preliminary assessment of the environmental impact of toxic chemicals in the waste*. This indicates that the waste chemotoxicity does not have adverse consequences for the environment.
- *Systematic use of data collection forms for safety assessments.* For each parameter, these forms give the best quantitative estimate of its value, the extreme values and the associated uncertainties, as well as arguments supporting the choice of those values.

Overall assessment of the disposal system and its environment

- The *long-term safety functions* approach makes it possible to undertake a systematic assessment of the functions performed by the disposal system and its environment as a whole, as well as by each of their components individually. It can also be used to establish a strong link between repository design, understanding of the phenomena taking place in the repository over time, and safety. Table 6.1 lists the specific functions performed by the main components of the disposal system and its environment for the three main phases following repository closure. They are defined as follows:

  Thermal phase: the period following the closure of the repository and during which physical containment by the packaging/overpack must be assured. It corresponds to the period in which a significant thermal gradient is present between the waste and the undisturbed Boom Clay, and lasts several centuries for the vitrified waste and several thousand years for the spent fuel.

  Isolation phase: the period following the thermal phase and during which the containment of the waste by the engineered barriers is still significant. In this period, the function of delaying and spreading the releases is important for those radionuclides that reach the host formation. This phase lasts for about 10 000 years, during which the radiological impact on the environment is virtually zero.

  Geological phase: the period beyond 10 000 years and during which the functions of delaying and spreading the releases and of dilution and dispersion play a predominant role. During this time, there will be a very low radiological impact on the environment.

- The differences between the functions actually performed by the various components of the disposal system and the functions taken into account in long-term safety assessments can be interpreted as *long-term safety reserves* of the system and of its environment. These reserves help reinforce the robustness of the proposed solution.

Assessment of the Ypresian Clays as an alternative host formation

- *Preliminary geological and hydrogeological survey of the Ypresian Clays beneath the Doel nuclear zone*. The results are still being analysed, and it is too early to give a detailed assessment of the potential of the Ypresian Clays as a host formation.
- *Indication of a thickness of about 114 metres with a high argillaceous fraction and low hydraulic conductivities* (10^{-10} m·s^{-1} in situ and 10^{-11} to 10^{-12} m·s^{-1} in the laboratory).
- *Indication of the presence of saline interstitial waters, the presence of intra-formational faults on the regional scale, and of geomechanical characteristics indicating potential excavation difficulties.*

Cost assessment and financing

- *Development of a methodology for assessing the costs of deep disposal that is analytical, parametric, and flexible*. The methodology can be used to resolve the problem of the uncertainty margins inherent to very long-term projects, and can be easily adapted to any changes in the repository design.

- *Development of a system of cost provisions* on a tariff basis for the conditioned and non-conditioned waste that is taken over by ONDRAF/NIRAS. These provisions will feed into a long-term fund which, when the time comes, must guarantee the financial means needed to implement the chosen long-term management solution(s).

Table 6.1 The long-term safety functions performed by the main components of the disposal system and its environment for the different phases following repository closure. (The functions taken into consideration in long-term radiological safety assessments of the normal-evolution scenario of the disposal system are shown in bold type: C1 = watertightness (physical containment); R1 = resistance to leaching (delaying and spreading the releases); R2 = diffusion and retention (delaying and spreading the releases); D = dilution and dispersion. In light type, the safety reserves.)

Component	Thermal phase (several centuries to several thousands of years)	Isolation phase (< 10000 years)	Geological phase (> 10000 years)
Glass matrix	–	R1	R1
UO_2 matrix	–	R1	R1
Cement matrix	–	–	–
Bitumen matrix	–	–	–
Primary packaging	C1	R2	–
Packaging/overpack	C1	R2	–
Disposal tube	C1	R2	–
Backfill	C2	R2	R2
Sealing	C2	R2	R2
Lining of galleries	–	–	–
Lining of shafts	–	–	–
Host formation	C2	R2	R2
Aquifers	–	D, R2	D, R2
Biosphere	–	D	D

6.1.2 Relative importance of the remaining uncertainties

The assessment of the relative importance of remaining uncertainties is another significant achievement of the 1990–2000 programme. This assessment is based primarily on

- a knowledge of the processes and characteristics that control the functioning and evolution of the deep disposal system;
- an analysis of the way in which the disposal system and its environment perform the long-term safety functions;
- the results of the safety assessments.

The residual uncertainties that most affect long-term radiological safety are discussed below in descending order of importance of the components of the disposal system and of its environment:

- the natural host formation (function R2);

- the packaging/overpack (function C1);
- the waste matrices (function R1);
- the aquifers (function D);
- the biosphere (function D).

This list does not include the uncertainties directly related to the implementation of the reference design, except for those relevant to the containment function during the thermal phase. While these uncertainties are no less important, they are seen as technological, and it should be possible to reduce them sufficiently by adopting proven engineering approaches and by performing a demonstration experiment of the PRACLAY type.

The discussion of uncertainties differentiates between uncertainties about scenarios, uncertainties about models (processes, conceptual models, and numerical codes), and uncertainties about the parameters used for safety assessments. The overall assessment of these residual uncertainties is put into perspective as part of the assessment of current confidence in the studied solution (see Section 6.3).

The natural host formation – Boom Clay

The uncertainties associated with performance of the Boom Clay are highly important, because it is the clay that becomes the principal barrier once physical containment can no longer be assured.

The scenario uncertainties relate to the evolution or potential disturbance of the argillaceous barrier due to external events (seismic activity, climate change, geochemical change, etc.) or to processes inherent to the disposal system (production of gas, temperature increase, creation of an alkaline front, excavation, etc.).

The importance of the uncertainties *inherent to external events* varies according to whether the radionuclides are retarded or not. They have little importance for the non-retarded radionuclides because these radionuclides migrate during the isolation phase (approximately 10 000 years), during which the host formation will undergo hardly any changes likely to significantly affect their movement. They are more important for the retarded radionuclides as they migrate over a much longer period of time (approximately 100 000 years to one million years). The potential disturbances to the Boom Clay will be largely dictated by the environmental changes during the geological phase, especially as a result of climate change. These disturbances and the related uncertainties have not yet been adequately quantified. The Boom Clay's ability to withstand chemical, mineralogical, hydraulic, and even mechanical changes, for example, is undoubtedly considerable, but remains to be confirmed. The potential impact of external disturbances on radiological safety will, nevertheless, diminish over time because of the considerable decrease in the radiotoxicity of the waste during the thermal and isolation phases due to radioactive decay.

Considering the disturbing processes *inherent to the disposal system*, the temperature increase in the Boom Clay could always be limited to a value that would not induce any appreciable changes by making appropriate modifications to the repository design.

However, the uncertainties linked to the following disturbances deserve more sustained attention:

- the production of gas by corrosion, mainly involving the category B waste;
- the migration of an alkaline front following the degradation of the concrete;
- the possible swelling of the bituminised waste (mainly the Eurobitum waste) or release of large quantities of sodium nitrates by the same waste;
- the appearance of fractures during excavation.

The model uncertainties are minimal for the *non-retarded* radionuclides, as the physicochemical processes determining their migration have been clearly established and the calculation models broadly tested (migration experiments on different scales, benchmark exercises, numerical codes used at international level, etc.). For the *retarded* radionuclides, however, a distinction between retention by sorption and retention by precipitation is essential for understanding the geochemistry and migration of the elements and the modelling of experimental results. The study of the behaviour of the radionuclides that occur naturally in the Boom Clay will, however, still generate a large amount of information. Complexation with mobile organic molecules does not seem to be a major source of uncertainties, but this remains to be confirmed for certain radionuclides. Finally, the possibility of advection within the host formation (more permeable bands) will have to be investigated, but probably does not represent a major source of uncertainties either.

The parameter uncertainties are, for the *retarded* radionuclides, directly associated with the retardation mechanisms (sorption, precipitation, etc.) and, therefore, with the above model uncertainties. The vertical homogeneity of the host formation in terms of the migration properties of these radionuclides remains to be verified. Information about the migration parameters of *non-retarded* critical radionuclides is adequate.

The packaging/overpack

The uncertainties surrounding the watertight metal overpack for the vitrified waste and the watertight metal packaging for the spent fuel seem less significant for safety than the uncertainties about the argillaceous barrier, for the following reasons.

The scenario uncertainties that must be dealt with first concern the scenario of premature failure of physical containment during the thermal phase. They will have to be taken into account in the future safety assessments. They may be reduced by appropriate choices of materials and construction techniques (e.g., welding methods), by a quality assurance programme, and by a repository design favouring corrosion prevention.

There are also significant uncertainties surrounding the evolution of the geochemistry of the near field (and in particular the evolution of the backfill material during the thermal phase and its resaturation) and its influence on the rates and types of corrosion.

The model uncertainties are related to the modelling of the process or processes of corrosion that will determine the durability of the packagings/overpacks. The present programme has not yet been able to screen out certain potentially severe types of corrosion, such as stress corrosion, intergranular corrosion, and microbial corrosion, so that these uncertainties remain high, and could involve a review of the choice of the packaging/overpack material. Reducing these uncertainties is one of the key aspects for the next phase of the programme, in order to provide a set of arguments that support the physical containment function (choice of material, geochemical conditions in the near field, corrosion prevention, technical and industrial feasibility).

The parameter uncertainties are—according to the safety assessments—relatively unimportant, because the radiological impact is not sensitive to the durability of the packaging/overpack beyond the thermal phase. They are completely overshadowed by the performance of the argillaceous barrier and the uncertainties about the scenario of premature failure of the packaging/overpack.

The waste matrices

There are a number of reasons why the uncertainties surrounding the waste matrices have to be considered. With the vitrified waste and spent fuel, the matrix can, by its durability, make an effective contribution to the safety function of delaying and spreading the releases; this contribution is in addition to that of the Boom Clay. The waste matrices can disturb the behaviour of the other barriers, however, and of the Boom Clay in particular. Although a significant disturbance of the Boom Clay by the vitrified waste and spent fuel is virtually precluded (few chemical effects, possibility of reducing the thermal impact, protection from the effect of direct radiation in the clay by the presence of the backfill, minimal gas generation, no swelling), the chemical and physical compatibility of the bitumen and cement matrices with the disposal system still constitutes an uncertainty that must be reduced. Hence, the remainder of the text discussing matrices deals exclusively with the glass and spent fuel as barriers. Finally, knowledge about the inventory of critical radionuclides in the waste matrices must be adequate.

The scenario uncertainties are insignificant because they are covered by the two other forms of uncertainty.

The model uncertainties are associated with the degradation mechanisms that determine the durability of the matrix and the release of radionuclides. Knowledge about the degradation mechanisms has reached an advanced stage for the vitrified waste but is still inadequate for the spent fuel. Safety assessments deal with these uncertainties by applying two degradation models that yield different durabilities. Uncertainties about the durability of these matrices are of minor importance, however, since the long-term radiological safety is insensitive to them. This is because the contribution made by the matrices to the safety function of delaying and spreading the releases is largely overshadowed by the contribution of the Boom Clay.

An additional uncertainty about the spent fuel is how to achieve a well-argued simplification of the source term (representation of the heterogeneity of the fuel assemblies) that will have to be used in safety assessments.

As regards **parameter uncertainties**, the radionuclide release rate from the waste matrices has only a limited effect on the radiological impact. This echoes the conclusion reached about the above model uncertainties. The uncertainties about the critical radionuclides inventories have no real effect on long-term radiological safety, given the margins between the results of these assessments and the applicable protection standards. Nevertheless, it will be essential to confirm these inventories (and those of potentially chemotoxic elements) for the waste that will actually be disposed of.

The aquifers

The aquifers do not constitute a barrier as such, but they help dilute and disperse the fluxes of radionuclides leaving the Boom Clay. The uncertainties surrounding the aquifers thus have an indirect bearing on the assessment of the performance of the system if this assessment uses the dose as a safety indicator. Changes in the aquifers (hydrodynamic and/or hydrogeochemical) could also disturb the host formation.

Two of the uncertainties about the aquifers concern the *local scale* and deserve further attention, namely the localised nature of the groundwater discharge zones and the thermal impact on the flows and on the chemistry and biology of the groundwater. The other uncertainties concern the *regional scale.* They are

- **scenario uncertainties** — these uncertainties concern future evolutions due to natural and artificial causes (climate changes, water pumping, etc.);
- **model uncertainties** — these uncertainties concern the geometry to be considered and the boundary conditions of the hydrogeological system;
- **parameter uncertainties** — these uncertainties affect, first, the extent and hydraulic conductivities of the various aquifers (the deep aquifers in particular) and, second, the uncertainty that remains over the large-scale hydraulic conductivity of the Boom Clay (the presence of hydraulically active faults), which affects the results of regional hydrogeological modelling.

The scenario uncertainties are dealt with by reference to the natural barrier, since its resistance to environmental change is an important factor (e.g., in the event of a reversal of the hydraulic gradient). In safety assessments, the other uncertainties may be expressed by uncertainties about the parameters, especially about the dilution capacity. The maximum radionuclide fluxes likely to leave the disposal system and reach the aquifers must, therefore, be low enough for the uncertainty about this dilution factor to become negligible.

The biosphere

Like the aquifers, the biosphere is not a barrier. The uncertainties about the biosphere therefore only affect the assessed performance of the disposal system indirectly, and only if dose is used as a safety indicator.

As well as uncertainties about the biosphere, there are uncertainties about the activities taking place in the biosphere, especially those associated with human intrusion. The disturbance of the disposal system by human intrusion is addressed mainly as an uncertainty about the natural barrier and the disposal facility, i.e., what is the residual performance of the system in the event of a borehole being drilled down to the waste, for example? This aspect will be dealt with in specific human intrusion scenarios in the future.

6.2 Orientations of the future methodological research and development programme

At the present time, ONDRAF/NIRAS does not have all of the information needed for an exact and specific definition of the next phase of its programme of methodological research and development. At the request of the Belgian Government, the SAFIR 2 report will indeed be submitted to the OECD Nuclear Energy Agency (NEA) for international peer review. The conclusions of this review and the decisions that will be taken by the supervisory authority of ONDRAF/NIRAS about what action should follow the SAFIR 2 report should be available by the end of 2002 or during 2003. Nevertheless, it is already possible to identify a number of scientific and technical issues to take into account for future methodological research work, on the basis of the achievements so far, the perspectives that have already been identified, and the assessment of residual uncertainties. These proposed issues do not prejudge the decisions that will be taken elsewhere as part of the expected public dialogue on the long-term management of radioactive waste (see the ONDRAF/NIRAS document entitled '*Towards a Sustainable Management of Radioactive Waste*' that accompanies the SAFIR 2 report), nor do they pre-empt any additional requirements that may be imposed, especially in terms of waste retrievability.

Importantly, while it is not necessary for the future programme to remove all residual uncertainties, they must be reduced sufficiently and adequately, given the different decisions that must be taken.

The scientific and technical issues to be examined in future methodological research and development work are related to six main themes. These are themes on which ONDRAF/NIRAS will provide early and satisfactory answers to essential issues that are still unresolved, while harmonising the different aspects of the disposal system. The results of the PRACLAY experiment, in particular, will be used to prepare the transition from the third phase of methodological research and development to the pre-project phase.

6.2.1 Main themes of research

Integration The programme will use a structured approach (systematic and system-oriented) to integrate and harmonise all aspects of the disposal system. This will require improvements in the management of the interfaces between research and development work (understanding) on the one hand, and repository design work and safety assessments on the other. The systematic analysis of FEPS (features, events, and processes) to underpin the development of more credible evolution scenarios, and the generalisation of the safety functions approach, which will be extended to cover the aspects of operational safety, will serve to integrate the various disciplines.

Robustness The programme will systematically study the potential impact of all of the proposed choices, especially those about repository design, on the robustness of the disposal system, i.e., that its functions are not diminished by remaining uncertainties. The programme will consider (i) the implementation of the proposed solutions, (ii) the confidence that can be placed in the demonstration of the performance expected of the various components of the disposal system, (iii) the importance of the role and performance of each component of the repository in the overall performance of the system (analysis of the redundancy and functional independence of the barriers), and (iv) the identification of possible future weaknesses. Robustness indicators will be developed and used to this end.

Safety The programme will refine the safety assessments to test the integration of the different components of the system and its robustness, in particular by identifying and controlling uncertainties and using different safety indicators. This will be done in consultation with the safety authorities.

Demonstration The programme will focus on aspects directly linked to the implementation of the repository design and will thus emphasise feasibility and demonstration within the framework of a balanced scientific verification of the models used. The PRACLAY full-scale demonstration experiment, for instance, will be continued, as this is fundamental, not just as a feasibility test, but also as a way of verifying models and for reasons of visibility.

Transferability The programme will systematically assess to what extent and how effectively the methodological, technical, and scientific knowledge acquired about the Boom Clay at Mol–Dessel can be transferred to other host formations (the Ypresian Clays especially) or to other sites. The rationale for this exercise is not just a concern to optimise the results and the course of the research work, but also to analyse the flexibility of the solution under study.

Traceability Given the time needed to develop and implement a deep disposal system, the highly multi-disciplinary nature of the studies undertaken, and the mass of results that have already been acquired, the programme will aim to establish a management system for tracing information. This system is required to guarantee the durability, accessibility, transparency, and distribution of this information. It will also be required to ensure the exhaustive and systematic collation of all of the results, data, models, hypotheses, decisions, interpretations, etc., and to rationalise this information, so as to facilitate an assessment of its quality and relevance, as well as its efficient dissemination both within the programme and to other parties involved. Finally, it must be able to perform these functions over several generations.

6.2.2 The elements to be considered

The elements to be considered when defining the third phase of the methodological research and development programme affect all aspects of deep disposal and concern essentially—for reasons to do with budget and with the setting of priorities—the reference option, i.e., the Boom Clay at Mol–Dessel. These elements can be expressed schematically according to the framework used in Section 6.1.1.

Inventory and knowledge of the waste to be placed into the repository

- *Introduction of an overall quality system* that must guarantee the quality of information about the inventory and characterisation of the waste with a view to its deep disposal, and improve the traceability and transparency of this information (production scenarios, calculation codes, controls, etc.).
- *Confirmation and maintenance of the inventory* (volumes, concentrations of radionuclides that are critical for short-term and long-term safety) for all of the waste classes, except the vitrified waste and UO_2 spent fuel. Confirmation of physical and chemical properties of all the waste classes.
- *Development of waste production forecasting scenarios that take greater account of possible future changes* in energy production and in the overall management of the nuclear fuel cycle.
- *Establishment of the necessary waste acceptance criteria*.

**Assessment of the host formation as a natural barrier
and knowledge of the environment of the disposal system**

- *Integration, harmonisation, and systematic processing* (origin, location, and quality) *of all geoscientific data* in order to increase confidence in the barrier properties of the host formation and in the ability to characterise it and understand its behaviour.
- *Refinement of knowledge about the lithological heterogeneities and structural discontinuities of the Boom Clay and their effects* on groundwater flows (spatial variations in hydraulic conductivity and extrapolation on different scales) and on radionuclide migration.
- *Continuation of radiochemical characterisation*, so as to help assess the homogeneity of the formation, study the long-term behaviour of the uranium and thorium and the interactions between the clay and the overlying aquifer, and establish a point of comparison for safety indicators, such as radionuclide fluxes and concentrations.
- *Refinement of the regional hydrogeological model*, so as to take explicit account of the aquitards and consider the vertical and horizontal variations in the hydraulic conductivity of the Boom Clay and the Lower-Rupelian Aquifer. This may eliminate or explain the inconsistency found between the values of the hydraulic conductivity of the Boom Clay measured locally and those calculated on a regional scale.
- *Development of an integrated approach for the hydrogeological models used at the different scales* (harmonisation of calculation codes and boundary conditions).
- *Confirmation of the local character of the discharge zones of groundwater flows*.
- *Assessment of the sensitivity of the geological, hydrogeological, and hydrogeochemical system* (including the radionuclide migration properties) *to natural or artificial disturbances* (pumping, seismic movements, climate and environmental changes, etc.)

as one of the bases of scenario analysis that are necessary for long-term safety assessments.

- *Use of hydrogeochemistry to test the results of the hydrogeological models.*
- *Deepening of the understanding of the retention processes at work in the Boom Clay*, so as to justify confidence in the values of the migration parameters selected for the critical retarded radionuclides.
- *Finalisation of the study of the impact of organic matter on radionuclide migration* in the Boom Clay.
- *Analysis of the specifics of the Ypresian Clays towards deep disposal and the knowledge acquired about the Boom Clay*: presence of saline interstitial water, low mechanical strength, low thermal conductivity, presence and role of preferential pathways for the migration of fluids.

Design and construction of the disposal facility

- *Definition of the technical criteria for the general design of the repository and of its components, and analysis of possible choices.* Clear requirements must be laid down for maximum permissible increases in temperature for the different components of the repository and its environment as well as for waste retrievability during a defined period of time, if required.
- *Given the requirements associated with radiological and operational safety and with technical and economic feasibility, review of the design bases of the repository using a systematic approach that considers the disposal facility and the host formation as a whole and places sufficient emphasis on the potential interactions between its various components and their complementarity.* The future programme will then undertake to redefine the repository design and, more specifically, to review the reference design for the vitrified waste and spent fuel and to define the design for a representative class of category B waste. It will subsequently seek to incorporate the different designs into a single and coherent disposal system that is technically satisfactory, clearly specified, and properly justified, and which can be shown to meet all of the initial requirements including those associated with in situ implementation.
- *Use of the PRACLAY experiment for a full-scale demonstration of the feasibility of the revised reference repository design.*
- *More detailed study and optimisation of the choice of materials for the different components of the disposal system.* For the packagings and overpacks, the future programme will adopt an integrated approach that takes account of all of the parameters likely to affect corrosion. It will focus on a better understanding of the evolution of the geochemistry of the environment over time and on a strategy of corrosion prevention. It will examine the problems of welding in terms of feasibility and corrosion behaviour. It will also study the composition of the backfill and sealing materials according to their function, expected performance, and emplacement.
- *Assessment of the possibilities for the removal of gases* generated by the corrosion of the category B waste without compromising the performance of the natural barrier.

- *Reassessment of the thermal impact* on all components of the disposal system and its environment and, if required, modification of the geometry of the facilities.

- *Identification and assessment of the aspects of technical flexibility of the repository design, especially those aspects of importance for the retrievability* of the waste (on a period of time that is still to be defined).

- *Elaboration of methods for operating the repository*. The operating system will be conditioned by whether or not the facility will have to be considered as a potentially contaminated zone.

- *Assessment of the methods for closing the repository and associated monitoring.* This assessment will also have to consider aspects related to safeguards and the still-to-be-defined requirements relating to waste retrievability as well as the impact on short-term and long-term safety.

Understanding of the functioning of the disposal facility after closure and of the disturbances induced by the repository in the Boom Clay

- *Confirmation of the barrier properties of the glass matrix under representative disposal conditions.* As the durability of the vitrified waste matrix produced by reprocessing has no significant impact on the radionuclide flux at the interface between the Boom Clay and the aquifers, the future programme will have to assess acceptable uncertainties about this parameter. In particular, the ultra-conservative nature of the value currently used will be demonstrated and the associated safety reserve estimated. This programme will also extend the study of the leaching behaviour to other radionuclides considered to be critical or potentially critical.

- *Assessment of the disturbances induced by the different engineered components of the disposal system in the host formation*. The future programme will be required to show that the favourable geochemistry of the host formation, whose long-term maintenance is vital for the safety of the disposal system, will not be unacceptably disturbed by the presence of the repository. In particular, it will study the impact of the disturbances induced by chemical fronts (including an oxidation front induced by the excavation and operation of the repository) on the retention properties of the clay.

- *Assessment of the methods of construction of the repository.* The future programme will give priority to improving the understanding and modelling of the instantaneous hydromechanical behaviour of the Boom Clay during excavation by estimating the dimensions of the excavation-disturbed zone and its impact on radionuclide migration. It will expand the study of the delayed geomechanical behaviour of the clay, and especially the evolution over time of excavation-induced fractures (confirmation of the self-healing properties of the clay), and the stresses exerted by the formation on the linings as well as deformation of those linings.

- *Study of the generation of gases* by anaerobic corrosion—and corrosion of the packaging of the category B waste in particular—and by microbial activity as a function of time, and a study of its links with the geochemistry. This study will have to be supplemented by an analysis of the migration of these gases within the clay (fracturing, improving the accuracy of the diffusion coefficients of hydrogen and methane), and by an analysis of the technical options for the controlled removal of the gases without compromising waste containment.

- *Study of the behaviour of spent fuel under representative repository conditions*.
- *Deepening of the study of the behaviour of waste classes whose compatibility with the clay is uncertain, especially the behaviour of the bituminised waste.*

Assessment of operational safety and long-term safety

- *In-depth discussion with the safety authorities about the general methodology of long-term safety assessments.*
- *Improvement of this methodology* with, in particular, an improvement in the methodology used to develop scenarios, a review of the FEPS that must be taken into consideration, and a better definition of the timescales during which the different components of the disposal system and its environment may be regarded as robust.
- *Improvement of the models used for long-term safety assessments*, in particular, related to the abstraction and simplification of the disposal system and the modelling of the biosphere in the normal-evolution scenario.
- *Consideration of the impact on radionuclide migration of the heterogeneities in the Boom Clay and of the excavation-disturbed zone.*
- *Systematisation of the definition, selection, and assessment of the altered-evolution scenarios*, particularly of the effects of potential climate changes on the clay and on the hydrogeological environment of the repository (temperature increase, glaciation, etc.).
- *Improvement of the definition and interpretation to be given to the various indicators of safety and environmental protection*, especially for the different timescales involved.
- *Identification of the different types of remaining uncertainties and of the means necessary to reduce them, if required, and improvements of the methods needed to address them.*
- *Safety assessments for the waste classes that are conditioned in bitumen and cement.*
- *Compilation of all of the qualitative and quantitative arguments* indirectly supporting safety assessments.
- *Reassessment of the chemotoxicity* of the disposal system based on an updated waste inventory and set of migration parameters.
- *Definition of the bases for assessing operational safety*, both nuclear and conventional, *and assessment of this safety and of compliance with environmental protection regulations*, using a methodology agreed upon by the safety authorities.
- *Establishment of the bases of radiological optimisation (the ALARA principle).*

Overall assessment of the disposal system and its environment

- *Definition of the methods for assessing the robustness of the disposal system, and identification and quantification of the contributing factors.*

- *Extension of the safety functions approach to operational safety.*

Assessment of the Ypresian Clays

- *Continuation of the preliminary studies* of the Ypresian Clays beneath the Doel nuclear zone, focusing on their specifics such as the presence of saline water (effect on metal corrosion and containment, speciation, and radionuclide migration), its low mechanical strength (impact on construction options), its low thermal conductivity, and the presence of preferential migration pathways. (The degree of knowledge to be acquired is of course far less than for the Boom Clay, since this is a preliminary assessment of the potential of these clays as a host formation.)

Assessment of costs and financing

- *Improvement of the procedure used to estimate margins of technological and project uncertainties, and its application to the different waste classes* in the geological group as the repository designs for each of these classes become sufficiently reliable, followed by a review of the assessments at regular intervals or as necessary.

Quality assurance

- *Certification to ISO 9001–2000 of the research and development management operations once the IAEA recommendations have been incorporated.*

6.2.3 The next steps

The deep disposal of category B and C radioactive waste into poorly-indurated clays is, in many ways, an innovative project and must go through all of the characteristic steps of a project of this type: basic research, methodological research, applied research, demonstration experiment, preliminary design work, licence applications, pilot phase, construction, etc. The present programme must be continued in order to harmonise its various aspects—understanding, design, and assessment—and take them to the degree of maturity required to move on progressively from the phase of methodological research and development to the pre-project phase. The PRACLAY demonstration experiment acts as a pivot between these two phases (Fig. 6.2). PRACLAY (1995–2015), which is centred on a direct demonstration of feasibility, rather than on a long-term safety assessment by indirect means, has two fundamental objectives:

- it must make it possible to assert with confidence the technical feasibility of the options selected for the design, given the state of current technologies (the role of *confidence* in feasibility). The installation of the in situ experiment itself should already confirm a significant proportion of the feasibility of the proposed design.
- it must corroborate the results obtained by the research and development work (the role of *bolstering* confidence in the models, their underlying hypotheses, and their predictions). The final results of this experiment will therefore be used to refine the operating ranges of the different components of the disposal system and will provide valuable information for the exercise of improving and optimising the designs, which will be the subject of the pre-project phase.

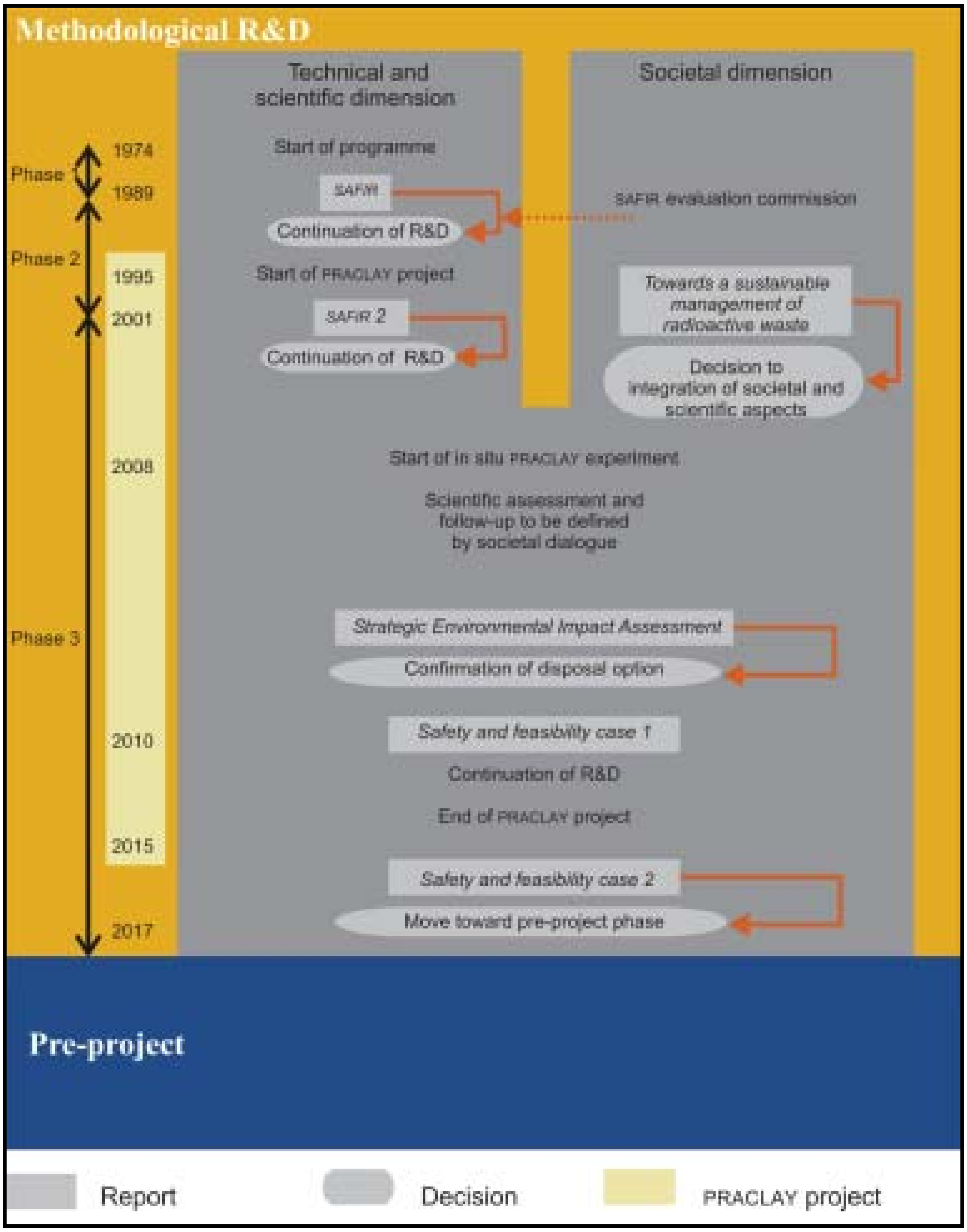


Figure 6.2 Schematic of the various phases of the programme of deep disposal into the Boom Clay as proposed by ONDRAF/NIRAS (without prejudging the decisions that will be taken on this matter).

Once the PRACLAY experiment has been installed in situ and the first few years of its functioning have been monitored, the level of confidence in the feasibility of the studied solution should be high enough for a first *Safety and Feasibility Report* for the disposal of the category B and C waste into poorly-indurated clays to be produced around 2010. Unlike reports of the SAFIR type, which cover an arbitrarily defined period and which are part of a process of methodological research and development, this report will be wholly autonomous. It will be a basis for successive iterations in aspects of feasibility and safety, and will be the product of a scientific and technical consultation with the Belgian nuclear safety authorities, a consultation that will start on the basis of the SAFIR 2 report. Besides making recommendations on the methodological research and development work still to be finalised, and on the preparation of the pre-project phase, this first report will contain statements on the following aspects:

for the Boom Clay at Mol–Dessel:

- the arguments supporting, first, an appropriate understanding of the site and of the disposal system, and, second, the safety assessments;
- the feasibility of the design, including possibilities of retrieval and control;
- conventional and radiological safety, and environmental protection during the different phases of the repository;

for the Ypresian Clays at Doel:

- the potential of the Ypresian Clays in terms of feasibility and safety;
- the transferability of the knowledge acquired about the Boom Clay;
- the benefits and objectives of a deep characterisation facility that may be constructed and operated after the phase of methodological research and development.

On completion of the PRACLAY demonstration experiment, a second *Safety and Feasibility Report* would be drafted in about 2017. This would review and sum up all of the results obtained, in particular those aspects supporting confidence in the models and in their predictions. It is this second report that could be the basis of a decision to end the methodological research and development phase and embark on the pre-project phase. This phase would aim specifically to qualify the disposal system proposed for all of the waste concerned, and would do this for a specific host formation and a specific site to be defined. It would include a general description and justification of the various components of the repository design (characteristics, geometry, construction methods, operating techniques, qualification methods, etc.), a description and justification that would necessarily be based on the results of a prior technical, economical, and radiological optimisation (ALARA) exercise. Like all the implementation phases of deep disposal, this pre-project phase would need to be supported by a series of additional research and development studies. These would be intended primarily to confirm the predictions made and to adapt to the actual conditions prevailing underground and the actual waste to be disposed of in the repository, i.e., to ensure the flexibility needed for implementing a project of this kind.

Evidently, the issues linked to the long-term management of radioactive waste must be considered in a framework broader than a strictly technical/scientific context, and so the ONDRAF/NIRAS future programme will need to integrate socio-economic dimensions more closely with the technical and scientific aspects. Such interdisciplinary programme, involving pure, applied, and human sciences, will have to be structured in a way that supports the decision-making process about the long-term management of radioactive waste on as broad a base as possible. This is the subject of the ONDRAF/NIRAS document entitled '*Towards a Sustainable Management of Radioactive Waste*' that accompanies the SAFIR 2 report. To ensure the success of this essential integration exercise, ONDRAF/NIRAS proposes to establish a *Strategic Environmental Impact Assessment* document to help assess long-term management options, bearing in mind their respective environmental effects.

6.3 Assessment of confidence

Confidence is the result of a positive judgement based primarily on qualitative arguments relating to the understanding and knowledge acquired about the FEPS that govern the functioning and evolution of a given system. Confidence is a relative concept because the level of confidence that is needed depends on the decisions that have to be taken. In the present case, the level of confidence needed for a decision to continue the methodological research and development work is below the level that will be required to apply for a licence to operate a disposal facility.

So far as disposal is concerned, confidence in safety and feasibility is based on three types of consideration:

- identification of the acquired knowledge and unresolved issues;
- assessment of the relative importance of the remaining uncertainties;
- definition and description of the work needed to sufficiently reduce those uncertainties that influence safety most.

The ability of ONDRAF/NIRAS to assert that the option of deep disposal into a poorly-indurated clay continues to be a viable option for the waste considered in the SAFIR 2 report is based, therefore, on a number of supports. These are a detailed analysis of all of the technical and scientific knowledge that has been acquired so far, an analysis of the uncertainties that remain and their effect on the confidence which can be placed in the proper functioning of the studied disposal system, and an analysis of what is needed to solve the remaining issues. The next (third) phase of the programme of methodological research and development, broadened by the incorporation of the societal and economic dimensions, must make it possible to further reinforce the acquired confidence by focusing on the unresolved issues and uncertainties. The overall appraisal of the confidence level is determined by the answers that can be given to the following six questions.

Is it possible to design and build a deep disposal system for the category B and C waste?

There have been major advances in the design of a deep disposal system, and much information has been gathered about the excavation, construction, and operation of underground facilities in a poorly-indurated clay at depths of about 220 metres. In addition, the preparation of the SAFIR 2 report and the PRACLAY demonstration experiment (especially the realisation of the OPHELIE mock-up) has led to highlighting several residual uncertainties and potential issues in the actual implementation of the reference repository design.

Confidence in the ability to resolve the identified uncertainties and problems in the next phase of the programme is based on the following factors:

- the existence of a systematic and system-oriented design methodology developed by ONDRAF/NIRAS in collaboration with waste management agencies abroad, and which is based on the safety functions that the disposal system must perform;
- intensifying studies of the interfaces and interactions between the different components of the disposal system as part of the future programme;

- the knowledge acquired about the behaviour of the materials of the disposal facility and the industrial availability of a wide range of materials allowing a high degree of flexibility in the choices (mainly as regards packaging/overpack and backfill materials);
- the essential role that will be played by the PRACLAY demonstration experiment, as much in terms of confirming feasibility as in supporting both models and the transition to a pre-project phase;
- the technical and industrial knowledge already acquired from deep disposal programmes in other countries;
- the technological developments and knowledge acquired over the past 20 years from the construction of underground facilities in poorly-indurated clays, suggesting the possibility of future improvements.

Is it possible to characterise the proposed disposal system and understand its functioning?

Satisfactory progress has been made in the overall understanding of the functioning of the disposal system as defined on the basis of the acquired knowledge, the definition and application of safety functions, and the results of long-term safety assessments. The major importance of the safety function of delaying and spreading the releases, a function that is performed mainly by the natural barrier (the Boom Clay), has clearly been confirmed. The characterisation of the host formation and the assessment of all of its modifications and disturbances thus play a central role (see also the box at the end of this section).

In this context, the characterisation of the natural barrier has progressed well following the adaptation of proven methods of geological, hydrogeological, geomechanical, and geochemical characterisation to the specific needs of investigating a poorly-indurated argillaceous formation.

Good progress has been made in understanding the phenomena and processes controlling the migration of critical radionuclides in the host formation. This results from the multi-faceted research programme: a range of experimental approaches in the laboratory and in situ, a study of radionuclides naturally occurring in the Boom Clay, the use of different conceptual migration models, broad international cooperation on experimental and conceptual aspects and on the creation of reliable databases. It seems possible that the remaining uncertainties, i.e., those surrounding the retention processes of certain critical radionuclides, can be resolved with the available research methods.

The impact of mechanical and chemical disturbances to the Boom Clay induced by the excavation and construction of underground facilities remains one of the crucial aspects of the future programme. Key issues in this respect are a direct demonstration of the possibility of using industrial construction techniques that minimise disturbances and the characterisation and understanding of how these disturbances evolve over time.

Elsewhere, confidence in the ability to characterise phenomena associated with the production, accumulation, and migration of gas in a disposal system located in a low-permeability clay is high, as it has been developed within an international framework. The repository design can also be modified to prevent localised increases in gas pressure.

Guaranteeing the safety function of physical containment using a metal packaging/overpack that is corrosion resistant seems an attainable goal, particularly since there is a significant margin as regards corrosion prevention. This prevention could be achieved by opting for alloys that are of a better quality than the current reference material and/or by ensuring favourable geochemical conditions in the surrounding medium. The future programme will have to be reinforced by a systematic study of all types of corrosion for the proposed metal materials. Furthermore, the retention of radionuclides on metal corrosion products (iron oxides and hydroxides), which are known for their strong sorption capacity, has not yet been considered, and is likely to reduce releases from the near field, including in the event of the premature failure of the containment ability of the packaging/overpack.

Can values of parameters that relate to the disposal system be extrapolated in time and space?

The spatial and temporal extrapolation of the parameters of both the natural and engineered barriers is, and will remain, crucial to the long-term safety assessment of a repository. This extrapolation can only be analysed if the nature of the processes and phenomena governing the behaviour and evolution of the barriers and the disturbing factors is sufficiently known.

Radionuclide migration through the natural barrier Because this migration is diffusion-controlled, only extrapolation over time is an issue, since spatial extrapolation can be dealt with by a representative sampling of the Boom Clay. It will therefore be necessary to demonstrate the geochemical and physical stability of the host formation over long periods. Several arguments endorse such stability: the self-healing capacity and chemical buffering, the rapid establishment following sedimentation of the current geochemical conditions, etc. The confirmation of these and, if necessary, other arguments seems to be within reach, mainly by means of geoprospective analyses and by further characterisation of the behaviour of the radionuclides naturally occurring in the Boom Clay. Moreover, the assumption of the lack of any significant advective movement in the Boom Clay should be corroborated by studies of its large-scale hydraulic conductivity (via faults on the regional scale) and of the potential groundwater flows in sublayers having a coarser granulometry. This should also make it possible to extrapolate the gathered data onto centimetre, metre, and decametre scales, which show coherent values of hydraulic conductivity.

Durability of the packaging/overpack Extrapolation over time is also crucial because the watertightness of this barrier has to be assured over periods ranging from several centuries to several millennia. To do this, it will be necessary to apply safety margins that are adequate in terms of the possible corrosion processes, for example by over-engineering (thickness, quality) the packaging/overpack as a function of the corrosive environments and the anticipated corrosion phenomena.

Durability of waste matrices Here again, extrapolation over time is paramount, and has been possible because the mechanisms of glass matrix degradation in an argillaceous medium are well known. The low hydraulic conductivity of the clay means that the system can be regarded as static, and one in which the diffusion processes control the leaching rates. Long-term safety assessments also show that the influence of the durability of the matrices is largely overshadowed by the performance of the Boom Clay. Therefore a stable matrix provides a safety reserve. An improvement in the knowledge of the degradation mechanisms of the spent fuel is still necessary, but could be based on the considerable amount of experience that has been acquired abroad in this field.

Feasibility As regards the spatial extrapolation of technical feasibility, the PRACLAY demonstration experiment will largely contribute to confirming the knowledge and current confidence in the characteristics of the different components of the disposal system.

Natural analogues have not been used very much until now, even though a synthesis of their applications to the case of a repository in poorly-indurated clays has been established. Generally speaking, they can be used to enhance confidence in the intrinsic qualities of the clays as natural barriers, and this has been illustrated in particular by the results of the studies of the following natural analogues:

- *physical containment* Clay has been shown to protect biodegradable material from degradation, such as in the case of the Quaternary fossil woods of Dunarobba or the Miocene fossil woods of the Entre-Sambre-et-Meuse region. Fragments of Oligocene volcanic glass have also been found in the Boom Clay. They show no signs of dissolution, despite being buried for almost 30 million years. The persistence of this volcanic glass in the Boom Clay is another indication of the stability of vitreous materials in this environment.
- *retention* Clay in general has a good capacity for chemically trapping the radionuclides, as demonstrated by natural analogues such as the ones of the Alligator Rivers or by karsts in the Entre-Sambre-et-Meuse region. These particularly highlight its ability to trap secondary minerals that are rich in pollutants and neoformed at the interface between fluids and solids. This trapping capacity is common to a number of natural materials characterised by a high specific surface area.
- *resistance to geochemical alteration* The Boom Clay contains carbonates and a pyrite/siderite combination that would buffer the acidity and the oxidising potential of any percolating fluids. The study of different occurrences in Belgium of clays that have undergone acid alterations or significant oxidation shows that the resulting minerals have high specific surface areas and, hence, high trapping capacities.

Can the safety of a deep repository be assessed?

The methodology of long-term safety assessment is based on a broad international consensus. The successive assessments conducted in the Belgian programme during the period 1985–2000 provide a coherent picture of the characteristics or processes that determine the safety of the studied disposal system, of the relative importance of the various uncertainties, and of the contribution made by the critical radionuclides to the overall radiological impact. This has been achieved despite the fact that the conceptual and numerical models used have changed considerably in the course of time.

Confidence in the methodology could be enhanced in the future by enriching its scientific bases (e.g., through international reviews and more intense interactions with the academic world), and by improving its transparency and traceability. This could be achieved by reinforcing the coherence of the models, hypotheses, data, and boundary conditions, and by implementing the necessary elements of quality assurance and knowledge management.

The use of safety indicators other than dose and risk seems promising, but the bases for comparison and judgement will need to be developed further.

Is the studied disposal system safe?

All of the calculations carried out for the normal-evolution scenario indicate that the studied disposal system is safe in radiological terms—the radiological impact calculated for an individual of the reference group is systematically and clearly below the dose constraint. The initial results of the quantitative or qualitative safety assessments of the altered-evolution scenarios indicate the robustness of the considered disposal system: despite the major disturbances to the system that are assumed in each of the altered-evolution scenarios, its overall performance remains broadly intact. Confidence in the results of the safety assessments is relatively high for several kinds of reasons:

- *the systematic use of conservative assumptions*, hence the existence of safety reserves (Fig. 2.6 and Table 6.1). This is because safety assessments
  - probably greatly underestimate the durability of the engineered barriers, especially of the glass matrix;
  - largely ignore the role of engineered barriers other than the packaging/overpack;
  - disregard the fact that radionuclide sorption on the corrosion products of the packaging/overpack and other metal materials can greatly retard their migration;
  - use a reference group whose assumed way of life is very conservative, in terms of the assumptions that govern radiological exposure.
- *the presence of numerous elements of robustness* in the disposal system:
  - high degree of redundancy in the safety functions and in the roles assigned to the various barriers;
  - factors linked to the clay: self-healing properties, relative simplicity of radionuclide migration processes, especially those for the migration of the non-retarded radionuclides;
  - factors linked to the engineered barriers: design of disposal facilities aimed at simplicity, facilitating the near-field modelling; use of a packaging/overpack that avoids the need to allow for thermal couplings during leaching and radionuclide migration; engineered barriers protecting the clay from radiolysis;
  - high insensitivity of the system’s performance to the models used for waste matrix degradation;
  - the flux of actinides at the near field / far field interface is restricted due to their low solubility: this makes the radiological impact independent of their inventory and of the uncertainties surrounding it.
- *the use of different types of safety indicators* — the radiological impact can be assessed using different and complementary approaches. The fluxes and

concentrations of radionuclides at the interface between the Boom Clay and the aquifers are comparable with the alpha activity that is naturally present (U, Ra, and Th) both in the Boom Clay and in the overlying aquifers.

- *the coherence of the results obtained since the beginning of the programme*, despite major changes as regards the data, concepts, models, and codes used.

How well is the relative importance of the different types of uncertainty in safety assessments understood?

The scientific programme and the safety assessments, and especially a consideration of the disposal system in its entirety, have led to a much better understanding of the relative importance of the different types of uncertainty in the assessments of long-term safety. Greater interaction with the broad academic and scientific world is envisaged, with a view to improving confidence in this aspect.

Major characteristics and principal unresolved issues relating to the Boom Clay beneath the Mol–Dessel nuclear zone as a host formation

Simplicity, homogeneity, uniformity

- Recent sedimentary basin, slightly disturbed by tectonics, with quasi-horizontal layers.
- Very good lateral continuity.
- Good relative vertical homogeneity with regard to migration parameters (poorly-retarded or non-retarded radionuclides).
- Absence of preferential migration pathways.

Geometry

- Large enough to accommodate a repository away from zones affected by faults.
- Depth not ruling out risks of human intrusion in the disposal facility, but its design is resilient to intrusion events.
- Limited thickness requiring the vertical extent of the repository and associated disturbances to be minimised so as to maximise the thickness of the natural barrier.

Mechanical stability

- Region considered to have low seismic activity. *A reassessment of the seismic risk is in progress owing to the presence of a major active tectonic structure, the Roermond Graben, on the western boundary.*
- Mechanical buffer capacity (plasticity) in the event of an earthquake.
- Geothermal activity at great depth, but not representative of volcanic or magmatic activity.
- Sufficient depth to escape erosion phenomena.
- Capacity for long-term self-healing (*to be confirmed*) of fractures induced by excavation or gas pressure.
- *The detailed understanding of the thermo-hydro-mechanical behaviour must be improved.*

Hydrogeology

- Very low hydraulic conductivity.
- Hydraulic gradient through the Boom Clay downwards and minimal.
- Negligible advection. *The possibility of an advective flow in the silty double band or in faults on the regional scale remains to be assessed.*
- Low capacity of dissipation of the gases potentially generated in the disposal facility.

Possibility of construction

- Possibility of constructing shafts and galleries demonstrated by the construction of the HADES underground research facility. *A demonstration of an industrial method for excavating galleries is planned (PRACLAY).*
- Excavation lining must be placed rapidly to limit the induced disturbances and galleries must be circular.
- Excavation-induced fractures (second shaft). *Their origin and behaviour are the subject of an in-depth study.*
- Behaviour of galleries is unknown over long operational periods (retrievability).
- Fairly low thermal conductivity, leading to a risk of major temperature increase in the disposal system and its environment.

Geochemistry and hydrogeochemistry

- Migration of species in solution controlled by diffusion.
- Slightly alkaline and very reducing conditions that limit the solubility and mobility of many radionuclides.
- High retention capacity for radionuclides. *The retention mechanisms of certain radionuclides are not yet fully understood however.*
- Quasi-immobility over geological timescales of the uranium and thorium that occur naturally in the clay.
- High content of organic matter, which is mainly immobile as it is associated with the clay minerals, inducing strong retention of the actinides and trivalent lanthanides by sorption.
- *The potential impact of the organic matter that is in solution and mobile on the migration of radionuclides is being investigated. The effect of this potential increase in mobility on the radiological impact is probably limited.*
- No migration of radionuclides associated with colloids (ultra-filtration).
- Good homogeneity of a large part of the Boom Formation as regards the migration properties of the non-retarded or poorly-retarded radionuclides.
- System geochemically in equilibrium, displaying significant pH buffer capacity and redox potential, with the result that the presence of a repository should induce little geochemical change. *The natural and repository-induced geochemical evolution of the clay over the long term remains to be investigated however.*
- Conditions favourable to very low generalised anaerobic corrosion for the conventional stainless steels.
- Possibility of thiosulphates and sulphates being generated by radiolysis or oxidation (aggravated risk of pitting corrosion on steels), few geochemical (or mineralogical) changes following significant radiation and prolonged heating.
- Presence of pyrite likely to locally create severe geochemical conditions for metal corrosion following its oxidation.
- Presence of methanogenic bacteria, but current microbial activity is limited in the clay under natural in situ conditions. *The impact of microbial activity due to contamination on the engineered barriers remains to be investigated.*

Environment and the risk of human intrusion

- Presence of aquifers (especially the Neogene Aquifer, which is a very important reservoir of drinking water), constituting a significant constraint. *The consequences of the thermal impact on the aquifers must be assessed in greater detail.*
- High dilution capacity of the Neogene Aquifer.
- Presence of glauconite in the overlying sands (a potential sorbent).
- *The sensitivity of hydrogeological and hydrogeochemical conditions to climate changes must be analysed.*
- No risk of clay being mined as it is available in large quantities at the surface.
- Minimal risk of intrusion to exploit the lower aquifer as it is not very productive and saline.
- Underground resources on the scale of the Campine Region (geothermics and recovery of mine gases).

Modelling

- Modelling facilitated by the relative simplicity of the geometry and the homogeneity of the geological strata.
- Migration that can be modelled with a small number of parameters.
- Geochemically homogeneous medium.

Postscript

In publishing the SAFIR 2 report, ONDRAF/NIRAS has provided its supervising minister and the various parties involved with a document that will enable them to assess the progress made during the period 1990–2000 with regard to the feasibility and safety of a possible solution for the long-term management of category B and C radioactive waste, that is, its deep disposal into a poorly-indurated argillaceous layer in Belgium. The work done during this period was part of the second phase of its programme of methodological research and development, and mainly concerned the Boom Clay beneath the Mol–Dessel nuclear zone as the host formation and reference site, and, to a much lesser extent, the Ypresian Clays beneath the Doel nuclear zone as an alternative host formation and site. This methodological work in no way implies that a decision has been taken on a location for the implementation of the studied solution. It has benefited from the knowledge and results obtained from the construction and operation of the HADES underground research facility at Mol.

The research and development programme conducted by ONDRAF/NIRAS has taken up most of the recommendations made by the commission set up to evaluate the SAFIR report (1990). It has not, however, been able to implement all of the commission's recommendations on the overall compatibility of the waste with the disposal system and on the acquisition of the required level of knowledge about the waste inventory with a view to its actual disposal.

At present, none of the research findings indicate any prohibitive flaw surrounding the disposal into the Boom Clay of the high-level and long-lived vitrified waste, a fact which reinforces confidence in the studied solution. This confirms that for the waste considered in the SAFIR 2 report, disposal within a poorly-indurated clay remains a viable option. One of the main achievements of the methodological research and development work has been to establish a significant level of confidence in several important aspects. These include the properties of the Boom Clay as a natural barrier, the durability of the glass as a waste matrix, the possibility of excavating the necessary underground facilities, and the methodology used to assess long-term radiological safety. The work also confirms the favourable results of assessments, especially regarding the key contribution to long-term safety made by the host formation, and hence the importance of knowing and controlling the disturbances that are induced in the clay. It also confirms the primary role in the radiological impact of the poorly-retarded or non-retarded radionuclides (^{129}I, ^{36}Cl, ^{79}Se, ^{126}Sn, ^{14}C). The knowledge of the migration of these radionuclides in the clay can be regarded as generally adequate, even though the chemistry of tin and selenium needs to be refined. During preparations for the PRACLAY full-scale in situ demonstration experiment, the research and development work has highlighted the practical difficulties involved in implementing the reference repository design and in fully controlling the interactions among its various components.

Without challenging the basic choice of the Boom Clay, enough issues remain unresolved at the present time, however, for it to be possible to produce a final statement on the technical feasibility of a repository in this host formation, on the long-term and operational safety of such a repository, or on its compliance with environmental standards. This is even more so for the Ypresian Clays. The third phase of the ONDRAF/NIRAS programme of methodological research and development should consider the following priorities with respect to the Boom Clay:

- demonstrating the feasibility of implementing the disposal facilities;
- improving the understanding of the processes of radionuclide retention at work in the Boom Clay and of the evolution of the retention properties in this formation;
- analysing the heterogeneities and discontinuities in the Boom Clay and their effects on groundwater flows and on radionuclide migration;
- analysing the effect on groundwater flows in the Boom Clay of changes in the regional hydrogeological conditions within the surrounding aquifers;
- studying more in detail the aspects of chemical, biological, and physical compatibility of all of the repository materials with the host formation, and of the different disturbances induced by the various waste classes;
- reviewing the choice of material for the packagings/overpacks and developing an integrated approach to defining the engineered barrier system based on preventing corrosion of the packaging/overpack;
- creating a systematic and system-oriented design methodology for the disposal facilities for all waste classes, especially for the most demanding ones;
- analysing the effects on the repository, on the host formation, and on safety of gas generation by the waste (mainly the category B waste), and evaluating ways in which the repository design might address these;
- studying and demonstrating methods that can be used to characterise the waste and to verify and confirm their composition and heat emission. The nature and extent of these operations must be proportionate to the need to apprehend the waste with a view to its deep disposal;
- improving the methodology used to assess long-term safety, in particular as regards identifying and addressing uncertainties and alternative safety and performance indicators, and defining robustness indicators;
- defining and developing a long-term management and transfer system for the knowledge acquired with the chief aims of ensuring the traceability of decisions and technical choices and the transmission, integration, and synthesis of multi-disciplinary information.

The conclusions of this future work, together with information about the feasibility of the repository design generated by the PRACLAY in situ demonstration experiment, will make it possible to prepare, around 2010, a first *Safety and Feasibility Report* on the disposal of category B and C waste into poorly-indurated clays. On completion of the PRACLAY experiment, a second *Safety and Feasibility Report* will be needed to fully exploit the results obtained, especially those aspects connected to increasing confidence in the models and in their predictions. This second report should be produced in around 2017 and would provide a basis for the decision to conclude the methodological research and development phase, and to move on to a pre-project phase, which is specific to a host formation and a site yet to be designated.

Because the issues raised by the long-term management of radioactive waste have to be addressed within a broad context, wider than the strictly technical and scientific aspects, societal and economic dimensions will have to be included in the future programme of ONDRAF/NIRAS in order to support a decision-making process in this matter. Such a process involves a consideration of alternative long-term management options and an analysis of all of the environmental effects of the proposed solution. To address this, ONDRAF/NIRAS proposes to establish documents of the types *Strategic Environmental Impact Assessment* and *Assessment of the Environmental Effects of a Given Facility or Project*. Continuing the work on the Ypresian Clays as an alternative host formation is considered to be advisable, but the level of knowledge about this formation needs not, at this time, match that which has been acquired for the Boom Clay. The degree of knowledge must, however, make it possible to determine whether the Ypresian Clays are a realistic option, either on their own or as a complement to the reference option.

By establishing an inter-disciplinary programme of research and development incorporating aspects that are fundamental, applied, and related to human sciences, and which is in accordance with the priorities listed above, it will be possible to further enhance the confidence acquired in the studied solution. In particular, confidence will be increased by considering management alternatives, developing concrete repository designs, reducing uncertainties, allowing for non-radiological effects, and considering societal aspects.

Annexes

A.1 Figures, tables, and boxes

page

Figures

Tables

Boxes

A.2 Abbreviations, acronyms, and proper names

AFCN/FANC	Federal Nuclear Control Agency (Agence Fédérale de Contrôle Nucléaire / Federaal Agentschap voor Nucleaire Controle) (Brussels, Belgium)
ALARA	As Low As Reasonably Achievable (The ALARA principle, the second of the three fundamental principles of radiation protection, aims to ensure that any dose resulting from an exposure to ionising radiation is kept at as low a level as is reasonably possible, the economic and social factors being taken into account.)
ANDRA	French Agency for Radioactive Waste Management (Agence Nationale pour la Gestion des Déchets Radioactifs) (Châtenay-Malabry, France)
ARCHIMEDE–ARGILE	Acquisition et régulation de la chimie des eaux en milieu argileux pour le projet de stockage de déchets radioactifs en formation géologique (acquisition and regulation of the water chemistry in argillaceous medium for the disposal project of radioactive waste in a geological formation) (European project)
Belgatom	Architect engineer and consulting engineer for the nuclear industry that relies on the technical capabilities of Tractebel Energy Engineering (consulting engineer) and of Belgonucléaire (fuel manufacturer) (Brussels, Belgium)
Belgoprocess	Daughter company of ONDRAF/NIRAS, in charge of most of the operations related to the short-term management of radioactive waste (Dessel, Belgium)
CERBERUS	Control Experiment with Radiation of the Belgian Repository for Underground Storage (European project)
CLIPEX	Clay Instrumentation Programme for the Extension of an Underground Research Laboratory (European project)
COGEMA	General Company for Nuclear Substances (Compagnie Générale des Matières Nucléaires) (Vélizy, France)
EPRI	Electric Power Research Institute (Palo Alto, California, United States)
EURIDICE	Economic Interest Grouping (EIG) European Underground Research Infrastructure for Disposal of Nuclear Waste in a Clay Environment. (The EIG EURIDICE brings together SCK•CEN and ONDRAF/NIRAS for the operation and valorisation of the underground research facility HADES and, in particular, of the PRACLAY project. It replaces the EIG PRACLAY since the end of the year 2000.) (Mol, Belgium)
EUROCHEMIC	European company for the chemical treatment of spent fuel (now Belgoprocess)
EVEREST	Evaluation of Elements Responsible for the Effective Engaged Dose Rates Associated with the Final Storage of Radioactive Waste (European project)
FEP	Features, Events, and Processes
HADES	High-Activity Disposal Experimental Site (underground research facility of SCK•CEN built in the Boom Clay, in Mol)
IAEA	International Atomic Energy Agency (Vienna, Austria)
ICRP	International Commission on Radiological Protection
MOX	Mixed-Oxide Fuel (nuclear fuel made of uranium oxide and plutonium oxide)
NEA	OECD Nuclear Energy Agency (Paris, France)
OECD	Organisation for Economic Cooperation and Development (Paris, France)

ONDRAF/NIRAS	Belgian Agency for Nuclear Waste Management (Organisme National des Déchets Radioactifs et des Matières Fissiles Enrichies / Nationale Instelling voor Radioactief Afval en Verrijkte Splijtstoffen) (Brussels, Belgium)
OPHELIE	On Surface Preliminary Heating Simulation Experimenting Later Instruments and Equipment (instrumented mock-up of the PRACLAY experiment, built in the HADES–PRACLAY hall, in Mol)
PACOMA	Performance Assessment of Geological Disposal of Medium-Level and Alpha Waste in a Clay Formation in Belgium (European project)
PAGIS	Performance Assessment of Geological Isolation Systems (European project)
PAMELA	Pilotanlage Mol zur Erzeugung Lagerfähiger Abfälle (pilot conditioning installation, at Belgoprocess)
PRACLAY	Preliminary Demonstration Test for Clay Disposal (real-scale in situ demonstration experiment)
RESEAL	Large-Scale In Situ Demonstration Test for Repository Sealing in an Argillaceous Host Rock (European project)
SAFIR	Safety Assessment and Feasibility Interim Report
SCK•CEN	Belgian Nuclear Research Centre (Studiecentrum voor Kernenergie / Centre d’Etude de l’Energie Nucléaire) (Mol, Belgium)
SPA	Spent Fuel Performance Assessment (European project)

A.3 Further reading

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A.4 Cross-reference table with the SAFIR 2 report

The table of correspondence below refers, for each section or subsection of the technical overview, to the most relevant corresponding section(s) of the SAFIR 2 report. For clarity, however, it does not mention the numerous links between the first five chapters of the overview and Chapter 13 of the SAFIR 2 report, since this last chapter discusses systematically the main achievements as well as the perspectives and recommendations related to all of the topics covered.

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6 Conclusions and assessment of the confidence

A.5 Final opinion of the Reading Committee of the SAFIR 2 report

The Reading Committee of the SAFIR 2 report was set up following a decision of the Board of Directors of ONDRAF/NIRAS taken during its meeting of 10th December 1999, in order to accompany the finalisation of the SAFIR 2 report. The Reading Committee had two main missions. It had to verify that the SAFIR 2 report reflects truly, entirely, and intelligibly the technical and scientific knowledge acquired during the 1990–2000 period about the possibility of a final repository for high-level and long-lived waste in a poorly-indurated clay layer in Belgium. It also had to verify whether the technical and scientific information presented in the SAFIR 2 report provides enough elements to the authorities to allow them to decide on the future orientation of the research and development programme.

The Reading Committee of the SAFIR 2 report was composed of thirteen members, including its chairman, all of Belgian nationality and none of them a member of ONDRAF/NIRAS. They come mainly from the academic world and are recognised for their expertise in the research fields covered in the SAFIR 2 report.

The Reading Committee expressed its conclusions on the SAFIR 2 report and its recommendations regarding the future priorities for the research and development programme in a final opinion dated July 2001. The text of this final opinion—mainly recommendations—was handed over to the Board of Directors of ONDRAF/NIRAS on 7th December 2001. It is reproduced hereafter, together with its cover letter, signed by the Chairman of the Reading Committee. Both texts are translations of the official Dutch and French versions. (In those texts, the word ‘concept’ must be read as ‘design’ in the meaning given on page 4 of the present document.)

Presentation of the final opinion of the scientific consultative reading committee SAFIR 2

As chairman of the scientific consultative reading committee SAFIR 2 (hereafter called 'reading committee'), set up by the Board of Directors of ONDRAF/NIRAS on 10th December 1999, I am both pleased and honoured to present the final opinion of the reading committee to the Board of Directors.

This presentation officially concludes the activities of the committee, whose task consisted in guiding the final stage of writing the SAFIR 2 report and giving a final opinion on the report.

The composition of the reading committee was approved by the Board of Directors on 17th March 2000 and the first meeting was held on 19th May 2000. The reading committee completed its activities with the formulation of a final opinion at the meeting of 4th July 2001. The reading committee met seven times. During these meetings, all fourteen chapters of the SAFIR 2 report were presented and discussed.

In the course of its activities, the reading committee formulated a large number (about five hundred) written and oral remarks, suggestions and questions related to the draft version of the report presented to the committee (all written questions were answered in writing by ONDRAF/NIRAS). These remarks and suggestions were useful to ONDRAF/NIRAS in improving the quality of the final version of the report, not only regarding transparency, accuracy of wording and structure, but also for establishing further research priorities.

In its final opinion, the reading committee put forward the following three main items:

- First of all, the reading committee finds, on the basis of the information put at its disposal during its activities, that the SAFIR 2 report accurately reproduces the current know-how regarding deep disposal of high-level and long-lived waste in a poorly-indurated clay in Belgium. Furthermore, the reading committee finds that ONDRAF/NIRAS has taken account in its disposal research programme of most of the recommendations formulated by the SAFIR Commission in 1990. The knowledge acquired so far shows no prohibitive problems regarding the feasibility of such a disposal system.

- This conclusion does not alter the fact that the current stage of the methodological research and development programme still holds important uncertainties that require further investigation. To this end, the reading committee formulated a series of technical-scientific recommendations that are to a large extent associated with the items of further research identified in the SAFIR 2 report itself. The conclusions of the final opinion of the reading committee advance ten priorities for further investigation. Generally speaking, the reading committee considers that an important effort will be necessary to raise the level of knowledge for the deep disposal of other waste categories than that of vitrified high-level waste, in order to examine in the short term the possibility of disposing of all the waste of categories B and C in the Boom Clay.

- For the following stage of the disposal programme, the reading committee recommends to extend the scientific and technical section of the SAFIR 2 report—the object of the final opinion—to include the societal and economic aspects. The inclusion of these various dimensions may supply the elements of a well-defined, gradual and flexible decision-making process. In order to prepare the decision-making process, the reading committee considers that the pending options for the long-term management of high-level and long-lived waste should be identified and examined, without compromising research into the reference option (deep disposal in the Boom Clay).

I consider it important to point out that the text of the final opinion of the reading committee was approved by all members of the committee, without exception.

As chairman of the reading committee, I wish to thank all the members and observers of the reading committee for the enormous efforts made during more than a year to accurately and judiciously process the large and very diverse quantities of information. The quality of their work is indisputably reflected in the accurate definition of the research achievements, the pending questions and the priorities of the following stage of the research programme.

Finally, I would like to thank all staff members of ONDRAF/NIRAS and its main partner, SCK•CEN, who assisted in compiling the SAFIR 2 report, for the work accomplished over the years and for the enormous efforts made to synthesize the large quantities of information available and write the report. The quality of their work and their dedication is greatly appreciated by all the members of the reading committee.

Willy Baeyens
Chairman of the scientific consultative reading committee SAFIR 2

(original version signed in Dutch and in French)

Scientific consultative reading committee SAFIR 2

Final opinion

July 2001

1 The SAFIR 2 scientific consultative committee

1.1 Context

Ten years after the publication of the first SAFIR report—Safety Assessment and Feasibility Interim Report—in May 1989, the object of which was ‘to enable the authorities to form an initial opinion as to the qualities of the Boom Clay layer in the region of Mol–Dessel with a view to its selection as host rock for the deep disposal of Belgian conditioned long-lived and/or very high-level radioactive waste’, the Belgian Agency for Radioactive Waste and Enriched Fissile Materials (*Organisme National des Déchets Radioactifs et des Matières Fissiles Enrichies / Nationale Instelling voor Radioactief Afval en Verrijkte Splijtstoffen* or ONDRAF/NIRAS) has now published the SAFIR 2 report. The principal purpose of this report is to present to the authorities, in a structured format, all of the relevant technical and scientific information gathered between 1990 and 2000 relating to the feasibility and acceptability, from technical and safety standpoints, of a deep repository for high-level and long-lived radioactive waste (category B and C waste) in a poorly-indurated clay layer in Belgium.

The report is also intended to intensify interactions and discussions with the nuclear safety authorities (in this case, the *Agence Fédérale de Contrôle Nucléaire / Federaal Agentschap voor Nucleaire Controle* or AFCN/FANC), and to provide a technical and scientific basis for a broad dialogue in the future with the various actors who are now or who will be involved in the long-term management of radioactive waste in Belgium.

Although not a safety report—no licence is being sought—the SAFIR 2 report is structured along the lines of a safety report. This approach makes it easier to identify the technical aspects of a disposal solution and to generally verify those areas or aspects of research where the required knowledge is currently inadequate.

With a view to presenting the SAFIR 2 report to the authorities and its subsequent publication, the Board of Directors of ONDRAF/NIRAS believed that it would be of benefit to have the final phase of the compilation of the report monitored by a scientific consultative reading committee (referred to as the ‘reading committee’ below), made up of Belgian experts in the fields covered by the report.

1.2 Creation

The decision to create the reading committee was taken by the Board of Directors of ONDRAF/NIRAS at its meeting on 10th December 1999. The Board took its decision in accordance with Article 13, Paragraphs 1, 2, and 3 of the Royal Decree of 30th March 1981 determining the tasks and the operating modalities of the public management organisation for radioactive waste and fissile materials.

Again according to the decision of the Board of Directors of ONDRAF/NIRAS, the number of members of the reading committee was limited to twelve plus the chairman. The members, all of whom are Belgian nationals and not employees of ONDRAF/NIRAS, are known for their expertise in the research areas covered by the report (including geology, hydrogeology, geomechanics, radiological protection, waste characterisation, waste repository facilities, risk perception, the physico-chemical interactions between the waste and the repository environment, the safety of nuclear facilities, and international disposal programmes).

The reading committee was chaired by Willy Baeyens, Professor of Chemistry at the VUB and Deputy Chairman of ONDRAF/NIRAS.

1.3 Mission

At the request of the Board of Directors of ONDRAF/NIRAS, the reading committee had to ensure that the SAFIR 2 report correctly, fully, and intelligibly reflects technical and scientific knowledge in the year 2000 relating to the possibility of a repository for high-level, long-lived radioactive waste in a poorly-indurated clay layer in Belgium.

The reading committee was also asked to verify whether the technico-scientific information presented in the SAFIR 2 report provides the authorities with sufficient material as regards the direction of the future research and development programme pertaining to this possibility.

The reading committee was asked to present its conclusions and recommendations on the SAFIR 2 report and the resulting future research and development programme (referred to as the ‘R&D programme’ below) in a final opinion to the Board of Directors of ONDRAF/NIRAS. The members of the reading committee have taken note of the fact that this final opinion and the SAFIR 2 report will be presented to the supervisory authority after they have been discussed by the Board of Directors of ONDRAF/NIRAS and following the decision of the latter to publish the report.

1.4 Members

The members of the reading committee, which had equal language representation, were twelve Belgian experts who were not employees of ONDRAF/NIRAS. These experts were appointed by the agency's management committee—duly mandated for this purpose by the Board of Directors of ONDRAF/NIRAS—on the basis of their expertise in the fields of research addressed in the SAFIR 2 report (see Point 1.2 above). The experts were asked to perform their task as independently as possible of ONDRAF/NIRAS. The members of the reading committee are given in Annex A to this document.

At the request of the Board of Directors of ONDRAF/NIRAS, the supervisory authority of ONDRAF/NIRAS (the Belgian Secretary of State for Energy and Sustainable Development) and the safety authorities appointed observers, Mr Willy Weyns (observer for the Belgian Secretary of State for Energy and Sustainable Development), Mr Luc Baekelandt (observer for the AFCN/FANC) and Mr Patrick Smeesters (observer for the Ionising Radiation Protection Service—Service de Protection contre les Radiations Ionisantes / Dienst voor Bescherming tegen Ioniserende Stralingen or SPRI/DBIS).

1.5 Modus operandi

The following work format was agreed at the first meeting of the reading committee on 19th May 2000: at each meeting, a certain number of available chapters of the report would be presented by the author and/or coordinator of each chapter, and the texts would then be distributed to the members and observers of the reading committee. The questions, comments, and suggestions put verbally by the members at each meeting and afterwards in writing, as well as the written answers and additional information provided by ONDRAF/NIRAS, would be commented on at the next meeting and circulated to the members. It was agreed within the reading committee that the final version of the SAFIR 2 report would be amended as necessary on the basis of the technical and scientific comments and remarks made by the members. The discussions and round tables held during the meetings also made an additional and valuable contribution; this was recorded in the minutes of the meetings and will be incorporated in the final version of the SAFIR 2 report.

To find the amendments that were made to the SAFIR 2 report, the reader is referred to the text of the provisional version and to the answers given by ONDRAF/NIRAS to the questions, comments, and suggestions made about the provisional version; these answers are contained in specific documents.

The reading committee met on 19th May 2000, 11th July 2000, 20th October 2000, 2nd February 2001, 4th May 2001, 26th June 2001, and 4th July 2001. As had been agreed, the general introduction and the thirteen chapters of the SAFIR 2 report were presented to the members of the reading committee at the meetings held up to 4th May 2001. Minutes were prepared for the first five meetings.

All the meetings of the reading committee were attended on behalf of ONDRAF/NIRAS by its general manager, deputy general manager, the director responsible for waste disposal research and the two coordinators of the SAFIR 2 report, as well as the secretary of the reading committee, so as to provide verbal answers to the questions put at the meetings and to provide additional information.

At the meeting held on 20th October 2000, the reading committee was appraised of the current thinking in ONDRAF/NIRAS and of research work outsourced by ONDRAF/NIRAS on the various social and decisional aspects associated with the long-term management of high-level, long-lived radioactive waste. The reading committee took formal note of the fact that the SAFIR 2 report only covers the technical-scientific aspects and found that it has not yet been possible to integrate these aspects with the social aspects.

At the meeting held on 2nd February 2001, it was agreed that the final opinion of the reading committee would pertain as much to the actual SAFIR 2 report as to the future R&D programme, and that it would be built around the following main themes: general themes, the radioactive waste, the geological host formations and their environment, the technical concepts of disposal facilities and their construction, and, finally, safety and protection.

At the meetings held on 4th May 2001, 26th June 2001, and 4th July 2001, the final opinion of the reading committee was finalised in the course of in-depth discussions based on draft texts submitted in meetings.

1.6 Objective, scope, and structure of the final opinion

1.6.1 Objective

Given the mission entrusted by the Board of Directors of ONDRAF/NIRAS to the reading committee, the final opinion of the reading committee and the final version of the SAFIR 2 report will be submitted to the Board of Directors.

1.6.2 Scope

The text of the chapters of the SAFIR 2 report discussed in the reading committee was subsequently amended by ONDRAF/NIRAS on the basis of the comments made by the reading committee. For reasons of practicality, this amended version of the SAFIR 2 report was not subsequently reread by the reading committee. In consequence, the reading committee notes that responsibility for the final version of the SAFIR 2 report, and in particular for the incorporation of corrections and changes made by its members, rests solely with ONDRAF/NIRAS.

The findings and recommendations set out below should therefore be considered within the overall framework of the evolutive process of the writing of the SAFIR 2 report. The reading committee also draws attention to the fact that the text of Chapter 13 ‘Conclusions and Recommendations’ was not submitted until the final phase of this evolutive process, and that this somewhat complicated the framing of the final opinion of the reading committee.

1.6.3 Structure

The final opinion of the reading committee is structured as follows:

- Section 1 introduces the opinion of the reading committee;
- Section 2 describes the decisional context of the long-term management of high-level and long-lived radioactive waste in Belgium;
- Section 3 sets out the general technical-scientific findings of the reading committee;
- Section 4 deals with the main technical-scientific findings, the existing gaps in knowledge and the recommendations of the reading committee for the future R&D programme by major themes (waste, host formation and environment, disposal facility, safety, protection, and economic assessments);
- Section 5 presents the general conclusions of the reading committee, and specifically the priority areas for future R&D.

The findings of the reading committee that relate both to the acquired knowledge and to the identified gaps in that knowledge are shown in ‘normal’ text in Sections 2 to 4 below. The recommendations of the reading committee are shown as numbered items (R1, R2, etc.).

Annex B of the final opinion lists the documents that were made available to the reading committee.

2 Decisional context of the long-term management of high-level and long-lived waste

Over the past twenty-five years, the problems of the long-term management of high-level and long-lived waste have been the subject of regular discussion at the highest levels both in Belgium (Government, Parliament) and internationally, in particular on the following occasions:

- the publication of the report by the Nuclear Energy Assessment Commission (*Commission d’Evaluation en Matière d’Energie Nucléaire / Evaluatiecommissie voor Kernenergie*) (1976);
- the publication of the report ‘Elements for a New Energy Policy’ (*Eléments pour une Nouvelle Politique Energétique / Elementen voor een Nieuw Energiebeleid*) by the Ministry of Economic Affairs (1979);
- the work of the Parliamentary Commission on Nuclear Electricity Generation Following the Chernobyl Accident (*Commission Parlementaire sur la Production Electronucléaire après l’Accident de Tchernobyl / Parlementaire Commissie over de Elektronucleaire Productie na het Ongeval van Tsjernobyl*) (1987);

- the work by the SAFIR Evaluation Commission (*Commission d'Evaluation SAFIR / Evaluatiecommissie-SAFIR*) (1990);
- the publication of the report by the Nuclear Safety Information and Enquiry Commission (*Commission d'Information et d'Enquête en Matière de Sécurité Nucléaire / Informatie- en Onderzoekscommissie inzake Nucleaire Veiligheid*) (1991);
- the work by the Commission on MOX Fuel and the Options for the Management of Spent Nuclear Fuel (*Commission Concernant le Combustible MOX et les Options de Gestion du Combustible Nucléaire Usé / Commissie inzake MOX-Kernbrandstof en de Opties voor het Beheer van Verbruikte Kernbrandstof*) (resolution of 22nd December 1993);
- the publication of the 'Resolution of the Council of the European Union Relating to the Management of Radioactive Waste' (19th December 1994);
- the publication of the 'Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management' (IAEA, Vienna, 1997), signed by Belgium in December 1997;
- the publication of the report by the Commission for the Analysis of Methods of Electricity Production and Energy Redeployment (*Commission pour l'Analyse des Modes de Production de l'Electricité et le Redéploiement des Energies / Commissie voor de Analyse van de Productiemiddelen van Elektriciteit en de Reoriëntatie van de Energievectoren*) — AMPERE (2000) and the Assessment of the Ampère Commission Report by an International Peer Review Group (2001).

The reading committee finds that, on each occasion, the major options regarding the research and development of a safe and preferably final solution were confirmed or that recommendations for future research were formulated. More specifically, the merits of the disposal option have been reaffirmed, in particular the fact that within the Belgian programme, disposal into a deep poorly-indurated clay layer remains a very valuable option that must be studied further and enjoys much scientific confidence at international level.

The SAFIR 2 report can also be set within this context.

Although twenty years have already passed since the problem was first posed, many more years will have to pass before a phase of industrial implementation can be embarked upon.

Moreover, society also changes over such long periods of time, that correspond to several human generations. Scientific positivism which still prevailed in the fairly recent past is now no longer seen as the main component of decisions involving choices by society over the very long term. Increasingly, the process of taking decisions on these matters is being guided by the precautionary principle, the fundamental aim of which is to advance step by step and in accordance with a structured and transparent process, and to take conclusive account of every type of implication and uncertainty.

The choices that society makes are increasingly guided by long-term considerations consistent with the concept of sustainable development.

R1 The reading committee considers that the scientific and technical facets upon which it has been called to express an opinion must be broadened by incorporating the social and economic aspects. This enlargement will make it possible to supply the elements of a decision-making process whose broad phases are well defined (decision in principle on the long-term management of waste, choice of site, authorisation, closure, etc.). The subsequent R&D programmes must therefore be developed in a structural and interdisciplinary manner that supports society's decision-making process. The reading committee also believes that a decisional process that is well defined, progressive, and flexible offers a guarantee of safety in the long term.

R2 The reading committee believes it is necessary to identify and examine the options open for the long-term management of high-level and long-lived waste (e.g., disposal in a national or international context, prolonged storage, separation and transmutation, whether or not within a strongly developed and sustainable nuclear programme), with a view to preparing the decisional process.

R3 The reading committee considers that a 'Strategic Environmental Impact Assessment', as is currently being defined and discussed at European level[1], is an indispensable tool for the definition and management of the political option (options) and future activities.

R4 The reading committee is of the opinion that concentrating the R&D work of ONDRAF/NIRAS on a reference option, i.e., disposal in the Boom Clay at Mol–Dessel, is justified in the light of the limited human and financial resources and of the results obtained to date. This is currently the option that appears to be the most realistic for the waste that has already been studied.

R5 Even so, it is advisable to examine alternative host formations, though to a lesser degree of detail but still in such a way that research on an alternative host formation could be undertaken rapidly should future studies conclude that the Boom Clay is not a satisfactory solution after all. The study of the Ypresian Clays at Doel represent the beginnings of such an approach and must focus exclusively on the crucial points (see Section 4.2.3) in the subsequent phase of the programme.

R6 The reading committee finds that the SAFIR 2 report does not address the aspect of 'sustainable development' and recommends that ONDRAF/NIRAS give this aspect the necessary attention within the framework of the programme of long-term radioactive waste management.

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[1] Common position EC No. 25/2000 of the Council of 30th March 2000; within the Flemish Region, steps are also being taken to prepare a draft for a new *MER* decree (*milieueffectrapportage* or environmental impact assessment) which distinguishes a *MER plan* (strategic plan) from a *MER project* (specific to a given project). The *MER plan* is equivalent to the Strategic Environmental Impact Assessment at European level.

3 General findings and recommendations of the reading committee

On the basis of all of the information made available directly and indirectly during the course of its work (see Annex B), the reading committee considers that the SAFIR 2 report correctly reflects the fundamental knowledge relating to the different components of the disposal system in a poorly-indurated clay and its environment as well as to their long-term evolution, that has been acquired by ONDRAF/NIRAS during the period 1990–2000. The knowledge gathered from research confirms that the option of 'disposal' into poorly-indurated clay remains a potential option for the waste types considered in the SAFIR 2 report, even though significant uncertainties remain, as explained in the SAFIR 2 report itself and in this document. These uncertainties must be examined further and adequately reduced before the actual implementation of disposal could be envisaged.

The reading committee finds that the report deals in the main with high-level vitrified waste and, to a lesser extent, conditioned spent fuel assemblies, i.e., types of waste that impose the most severe radiological and thermal constraints on the disposal system and its environment. Conditioned spent fuel assemblies also make additional demands in regard to non-proliferation and the heterogeneity of the waste matrix. However, the performance of the system can also be affected by other constraints of a chemical or bacterial nature for instance, in particular as regards the compatibility of waste embedded in a bitumen matrix with the disposal system.

R7 The reading committee believes that it is necessary in the short term to make a similar research effort for the other classes of waste, in particular conditioned spent fuel assemblies and bituminised waste, so as to verify the suitability of the Boom Clay as a host formation for these classes of waste.

R8 The reading committee wishes a systematic analysis be undertaken of all of the constraints imposed on the disposal system by the different classes of waste.

R9 The reading committee also believes that clear conclusions should be formulated as soon as possible in regard to the compatibility of the different classes of waste with the host formation(s). Specifically, the reading committee reminds the parties involved of the recommendations of the SAFIR Commission (1990) on bituminised waste.

The reading committee also finds that besides the knowledge that is still to be acquired, not all of the data gathered so far has yet been fully exploited, and that part of this data has not been used for the various assessments, in particular as regards the integrated interpretation of data associated with the earth sciences.

R10 The reading committee recommends the deployment of the means necessary for this purpose so that the data obtained can be used and reported in an integrated manner.

The reading committee also believes that most of the recommendations of the commission that was created to evaluate the SAFIR report (1990) have been clearly followed. However, the reading committee finds that ONDRAF/NIRAS has only been able to act on part of the recommendations of that commission relating to the overall compatibility of the waste with the disposal system and the acquisition of the depth of knowledge of the waste inventory[2] that is required in order to be able to proceed with the actual disposal.

R11 Although it is correct that this situation is a function of the current R&D stage of the disposal programme, the reading committee urgently recommends the development and implementation of a quality system relating to the overall compatibility of the waste with the disposal system and the acquisition of the depth of knowledge of the waste inventory that is required to proceed with the actual disposal. This quality system must be defined and developed to respond to the specific demands on quality that are to be defined within the framework of a global and actual disposal system. This quality system must be put into practice as soon as possible; the gradual implementation of this system must proceed hand in hand with the progress achieved in the research and development of an actual disposal system. In addition, the quality system must be regularly reviewed in the course of its progressive implementation. It is essential for the foundations of this system to be laid in the next phase of the R&D programme if the very credibility and legitimacy of the disposal concept itself are not to be compromised.

The reading committee finds that the R&D programmes that have been conducted to date have focused to a large extent on the assessment of the long-term radiological safety of the repository and the phenomena that contribute to safety; the information and results obtained in this area are significant and satisfactory, and allow to undertake a number of complementary steps.

R12 The reading committee believes therefore that the applied research must now focus on the aspects that are directly linked to the practical implementation of the technical disposal concept and hence concentrate on feasibility and demonstration (an activity of technical engineering). So far as possible, these aspects must be framed in a balanced fashion by a ‘validation’ and verification of the models and scenarios, which is more of a long-term scientific activity. This balance and the systematic feedback between demonstration, ‘validation’, and verification will boost confidence in the technical solutions. The study of natural analogues may also furnish additional information and knowledge.

R13 Stress must be placed on the architecture of the repository and on the possible interactions between its various elements so as to be able to correctly assess their operation and deduce their strengths and weaknesses.

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[2] The term ‘waste inventory’ refers to all of the relevant characteristics of the waste to be placed in a repository, e.g., the volumes, the physico-chemical characteristics, radionuclide activity, heat emissions, etc.

R14 Special attention must also be given to the influence of retrievability and monitoring on aspects such as the safety, the robustness, and the costs of the repository.

R15 The reading committee considers that the assessments of the radiological impact should be extended to other environmental effects as is required in an environmental impact assessment[3].

The reading committee finds that significant methodological progress has been made on the way in which the disposal system must be developed in terms of safety, i.e., the introduction of safety functions and the identification of the various elements of the disposal system which contribute to safety in the different phases of a disposal system. These safety functions are important for establishing the design bases of the system, and are an effective means of scientific discussion, collaboration with the relevant players, and popularisation; they also represent a necessary complement to the safety studies in which the overall radiological impact of the disposal system is assessed.

R16 The reading committee recommends that the significance and use of these safety functions be developed further in close cooperation with the safety authorities.

The work done by ONDRAF/NIRAS and the organisations with which it cooperates, notably the Belgian Nuclear Research Centre (Centre d'Etude de l'Energie Nucléaire / Studiecentrum voor Kernenergie or SCK•CEN) and the EIG EURIDICE[4], represents a whole which can be valorised from a scientific and technical viewpoint.

R17 The reading committee judges it is important, first, for the acquired knowledge to be valorised and shared, especially at European level, and, second, for the continuity of the R&D programme to be preserved.

R18 As already recommended by the SAFIR Commission (1990), the reading committee believes that a certain independence of research from the waste producers continues to be desirable.

It must be emphasised that the duration of the work by ONDRAF/NIRAS poses difficulties for the control and traceability of the knowledge acquired.

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[3] See Recommendation R3 for a strategic assessment of environmental effects; see European Directive 97/11/EC for an assessment of environmental effects of a specific project or facility.

[4] *European Underground Research Infrastructure for Disposal of Nuclear Waste in Clay Environment*, an economic interest grouping set up by ONDRAF/NIRAS and SCK•CEN.

R19 The reading committee therefore urges ONDRAF/NIRAS to develop an appropriate system for managing knowledge and documentation over the required periods of time to ensure that this knowledge remains accessible and can be actively used for future requirements. This implies the necessity for a synthesis and integration tool and the need to reinforce the interdisciplinary approach. Its first objective must be to be capable of managing the relevant data from each sub-field and each discipline, while limiting the future research and development challenges to what is essential. The second objective must be to furnish the decision-makers with the information they require in an intelligible manner so that they can make the necessary choices and take the necessary decisions when the time comes and in full knowledge of the facts.

The reading committee notes that the structure used for the preliminary version of the SAFIR 2 report does not make it possible to form an overall view, due particularly to subjects or related disciplines being dealt with in separate chapters.

R20 The reading committee believes that for future progress reports on the safety and feasibility of a repository, ONDRAF/NIRAS should adopt a structure that combines all of the aspects proper to a particular discipline within a single chapter. From the same viewpoint, the reading committee suggests that the chapter devoted to long-term safety assessments be limited to these assessments (methodological aspects, scenarios, models, results, etc.) and that the scientific bases and margins of uncertainty on which these assessments are based be reported in separate chapters.

4 Specific technical scientific themes of the final opinion

4.1 The radioactive waste

The reading committee notes that significant progress has been made on the waste inventory by giving the necessary attention to the classification and characterisation of the waste. By identifying all of the waste streams, it is possible to gather the information required to inventorise the waste and improve this knowledge in the future.

The reading committee also notes that the General Rules for the Acceptance of Waste and the acceptance criteria represent a significant improvement on the situation reported in the SAFIR report (1989). However, this aspect has not been dealt with sufficiently in the SAFIR 2 report.

R21 The reading committee considers that it must be possible to make public the information already gathered and still to be acquired on the waste inventory in a manner that is traceable and transparent (basic assumptions, calculation codes, measurements carried out, etc.).

R22 The reading committee considers that it is appropriate to further confirm the activity of critical radionuclides in the different waste classes as well as the quality of the waste matrix as a barrier and the compatibility of the conditioned waste with the host formation, by establishing an overall quality system (see Recommendation R11). This system must include procedures and methods for accepting the waste in a disposal facility based on the acceptance criteria applied by ONDRAF/NIRAS according to the General Rules. In particular, measurement methods which can be used to confirm as soon as possible the characteristics of the waste with a view to their disposal should be identified and studied.

R23 The reading committee believes that an appropriate knowledge of the waste inventory is an essential basis for the development of a disposal system. This knowledge must include not only the radiological component but also the other physico-chemical characteristics (such as the release of heat and the presence of heavy metals).

Within this framework, the reference scenarios used for nuclear waste production must take greater account of any future changes in the production of energy and the overall management of the fuel cycle (minimum and maximum scenarios of, e.g., waste production).

R24 It is the opinion of the reading committee that ONDRAF/NIRAS must monitor the scientific and technological changes taking place in waste conditioning, specifically as regards alternative matrices for high-level vitrified waste.

4.2 The host formations and their environment

4.2.1 Reference formation and alternatives

The reading committee takes note of the present status of the various argillaceous formations studied or considered in the Belgian programme and the reference locations for R&D. It considers this status to be justified for historical reasons given the results obtained so far and the human and financial resources available. This status can be summarised as follows:

- the Boom Clay at Mol–Dessel as the reference for the methodological studies;
- the Ypresian Clays at Doel as an alternative (as recommended by the SAFIR Commission—1990).

The following two options can also be considered:

- the schists (considered at the start of the programme but not studied);
- possible international alternatives (not considered at present).

The reading committee also notes that no final choice has been made yet as to the host formation or disposal site, the programme being in a phase of methodological research at the present time.

R25 As already mentioned (see Recommendation R5), the reading committee considers that it is necessary to maintain the studies relating to other potential host formations so as to have an alternative should the Boom Clay prove unsuitable. It is therefore necessary to analyse and document the possible alternatives in order to be able to take a decision on this matter in full knowledge of the facts and within a reasonable period of time. The reading committee therefore recommends that work continue on the Ypresian Clays but considers that the level of knowledge to be achieved for these clays as an alternative option need not at the present stage attain the same level as that which exists for the Boom Clay.

R26 Similarly, the reading committee recommends that the 'schists' option be made the object of an orientation study aimed at establishing the potentials of these rocks as a host formation.

4.2.2 The Boom Clay at Mol–Dessel

R27 On a general level, the reading committee notes that since the Boom Clay is the most important barrier in the studied disposal system, it is essential to pursue the R&D work being conducted to understand this clay's properties and their changes over time as well as disturbances to those properties caused by the presence of the waste and the repository. As part of these studies, it will also be important to assess case by case the opportunities for transferring the acquired knowledge to the Ypresian Clays (see also Recommendation R51).

4.2.2.1 Geoscientific characterisation

As to the Boom Clay, the reading committee notes that in recent years a significant amount of geoscientific data has been gathered on the total thickness of the formation, whether regarding geophysics (seismic reflection and high-resolution logging providing increased knowledge of the detailed lithostratigraphy of the clay and of the discontinuities which affect it), hydrogeology (permeability tests on different scales), geomechanics (excavation of the second shaft), or certain migration characteristics (tests on cores taken over the full thickness of the formation, analysis of the mobility of the naturally present radionuclides, etc.). These data meet the recommendations of the SAFIR Commission (1990) and constitute a database for an integrated interpretation of the geoscientific knowledge of the Mol–Dessel site.

R28 All of the geoscientific data that is available on the host formations and their environments must be systematically processed in order particularly to be able to indicate precisely the origin and quality of the data (exact location of samples, quality controls carried out, etc.). This should make it possible to differentiate the conclusions that relate to all of a formation or to a part of it. This recommendation obviously applies to all of the host formations studied.

R29 The reading committee believes that the systematisation and integrated interpretation of all of the geoscientific knowledge about the Mol–Dessel site is a priority for the future programme.

The reading committee finds that there are many places in the SAFIR 2 report which assert the homogeneity of the Boom Clay; this assertion merits some refining.

R30 Consequently, the reading committee considers that, in future, it will be important to give greater attention to those aspects associated with the homogeneity and/or spatial heterogeneity of the Boom Clay. In particular,

- knowing the precise location of all of the examined samples relative to the lithological column (texture, organic matter, carbonates, etc.) of the Boom Clay is essential for a detailed knowledge of this column for the whole of the region studied; this will ensure that measurements are interpreted correctly;
- the same applies to determining the usable thickness of the Boom Clay layer;
- on the basis of the measured parameters and the studies recommended above, and with a view to continuing the safety studies, the Boom Clay will have to be divided into sub-layers that are defined by envelope values for the relevant characteristics.

This will also make the data more transparent for assessment purposes.

4.2.2.2 Mining aspects

The reading committee finds that the current programme has demonstrated the possibility of sinking the shafts and excavating the galleries necessary for a deep repository into the Boom Clay. The reading committee notes that ONDRAF/NIRAS has already embarked on studies with a view to resolving the uncertainties about the origin of the fractures observed in the Boom Clay at the base of the second shaft.

R31 The reading committee asks ONDRAF/NIRAS to continue its work on the practical aspects of excavating underground facilities (minimising disturbances, junction of galleries, geometry of the facility, especially in regard to the mining requirements, thermal load, etc.).

R32 The reading committee recommends that the origin of the fractures observed in the Boom Clay during the excavation of the second shaft be explained. It is not yet clear whether these fractures are due to a mechanical effect associated with the excavation or to the reactivation of existing natural discontinuities.

R33 Within this framework, the ‘validation’ of the models of the long-term mechanical behaviour of the clay, in particular as regards the self-healing of fractures, calls for more sustained attention.

4.2.2.3 Hydrogeology and migration

The reading committee notes that a major effort has been made in recent years on measuring the permeability of the Boom Clay straight beneath Mol–Dessel on different scales. However, the reading committee believes that the flows of water within the Boom Clay are still not well enough understood to be able to exclude the possibility of advective movements that are more significant than those hitherto measured.

R34 The reading committee recommends that the uncertainties on the large-scale permeability of the Boom Clay be resolved, specifically as regards the spatial variability of the permeability, the flows of water in the siltiest zones of the formation or within the faults crossing the clay on the regional scale.

R35 The reading committee also recommends that the inconsistency found between the values measured locally of the permeability of the Boom Clay and the values produced by regional hydrogeological modelling be resolved.

R36 In this same context, the reading committee considers that although the aquifers are not part of the disposal system and have therefore no barrier function, a greater knowledge of the aquifers beneath the Boom Clay is necessary (division into sub-layers) with a particular view to calibrating the regional hydrogeological model.

R37 Similarly, the reading committee wishes the sensitivity of the hydrogeological system to disturbances caused by pumping to be analysed.

R38 Given the timescales involved, the reading committee considers that it is important to analyse the possible changes in water movements in the Boom Clay and in its overlying and underlying layers due to changes in environmental conditions (e.g., climate changes leading to glacial or periglacial conditions—permafrost—or to an increase in temperature and a subsequent rise in sea levels). The hydrogeochemical consequences of such changes (including those relating to migration parameters) will also have to be considered. Consequently, it will be important to be able to show that changes in regional hydrogeological conditions will not cast doubt on the role of the Boom Clay as a barrier.

R39 Regarding the long-term safety assessments, and in particular with a view to minimising some of the uncertainties associated with transport (flow of water and radionuclide migration), the reading committee believes that special attention should be given to the use, on significant scales of time and space, of the transport data acquired locally and/or over limited periods (upscaling, i.e., the gradual increase in scales of time and space).

R40 Depending on the results of the above studies, the reading committee considers that it will be necessary to adapt the hydrogeological modelling, in particular by considering (should this prove necessary),

- the aquitards in an explicit manner;
- the spatial variability of the permeability in the Boom Clay (using stochastic models for instance);
- any elements that conduct water within the Boom Clay (e.g., using a double porosity approach);
- the dependency on time of climate changes, especially when analysing the impact of pumping.

R41 The reading committee requests that the local character of the outlets of the radionuclide transport pathways between the Boom Clay and the biosphere be confirmed, in particular by attempting to incorporate into the safety assessments the transport of radionuclides in the Boom Clay and within the aquifers surrounding it.

R42 The reading committee also stresses the importance of the iterative development of hydrogeological modelling compared with the evolution in knowledge acquired elsewhere.

The reading committee finds that the SAFIR 2 report has not addressed the geochemical and hydrogeochemical aspects in depth. However, it notes that the radiochemical characterisation of the Boom Clay has yielded some very interesting initial results.

R43 The reading committee considers therefore that these geochemical and hydrogeochemical aspects deserve a more sustained effort. Among the points to be resolved, one might cite the origin, age, and change in chemistry of the interstitial water of the Boom Clay and surrounding aquifers, the origin and behaviour of the chlorine and sulphur compounds in the Boom Clay, and the coupling between flows and hydrogeochemistry for the aquifers. A palaeohydrogeological approach and the use of inert gases as tracers could prove useful in this effort.

The reading committee also urges ONDRAF/NIRAS to pursue the radiochemical characterisation studies, taking particular account of the interstitial water in the Boom Clay and the impact of the surrounding aquifers.

The combined results of all of these studies will serve to establish a coherent view of the hydrogeochemical system and its evolution. They will have to be considered during the assessment of the durability of the engineered barriers, the stability of the geochemical conditions, and the migration parameters in particular.

R44 The understanding of the physico-chemical processes in the Boom Clay which are responsible for radionuclide retention (speciation, sorption, complexation with the organic components, precipitation/dissolution, etc.) should be improved to make it possible to interpret the laboratory and in situ migration experiments in detail.

4.2.2.4 Disturbances caused in the host formation and the aquifers

R45 Generally speaking, the reading committee considers that it would be advisable to pursue the work being done on understanding and, as appropriate, on limiting the disturbances caused in the host formation by the presence of the repository (e.g., excavation, oxidation, alkaline front, nitrates, gas production, and migration).

R46 More specifically, the reading committee recommends that the thermal impact on the clay and the aquifers be studied in greater detail (especially in the absence of any standards in this area).

R47 The reading committee recommends that the work on combining the thermal, mechanical, and hydraulic aspects (THM) which has so far been conducted for the near field be expanded to include chemical aspects as well (THCM).

4.2.3 Ypresian Clays at Doel

The reading committee finds that the geoscientific data acquired on the Ypresian Clays at Doel following the recommendations of the SAFIR Commission (1990) have not yet been fully utilised.

R48 The reading committee therefore believes that it is essential to finalise and document the interpretation of the data gathered so far at Doel as rapidly as possible.

R49 The reading committee considers that the lateral and horizontal variability in the lithological facies of the Ypresian Clays makes it essential to reference each measurement/data relative to a precise location and lithostratigraphic unit in order to avoid making global interpretations of the Ypresian Clays based on information that is only representative of one specific unit or location.

R50 The reading committee recommends that a limited series of complementary tests/analyses intended to give accurate answers about the value of the Ypresian Clays alternative as compared with the reference option should be designed on the basis of the interpretation referred to above and the knowledge acquired on the Boom Clay regarding deep disposal. The crucial points to be verified would include, in particular,

- the reason for the high salinity of the interstitial water and the impact of the chloride levels on the choice of materials for engineered barriers and on the migration of radionuclides; the origin of the high chloride levels should be understood as part of an assessment of the history of the interstitial water (origins, mixtures, changes) on a regional scale;

- the possibility of excavating such a clay, given its mechanical characteristics and the high concentration of swelling minerals;
- its significant lateral variability;
- the hydrogeological role of the observed faults and discontinuities;
- its safety potential (as a natural barrier) by means of a preliminary assessment of long-term safety.

In the light of the points listed above, the reading committee believes that the transferability of the knowledge acquired about the Boom Clay to the Ypresian Clays is far from self-evident. Specifically, the difference in depth between the Ypresian Clays at Doel (approximately 325 to 440 metres at right angles to the Doel-1a borehole) and the Boom Clay at Mol–Dessel (approximately 190 to 290 metres at right angles to the Mol-1 borehole) could affect not just the excavation of underground infrastructures in the former clay formation, but also the geological evolution scenarios of the site (e.g., glaciation).

R51 The reading committee therefore recommends that ONDRAF/NIRAS undertake an analysis of the transferability of the knowledge acquired about the Boom Clay to the Ypresian Clays as soon as possible, this analysis forming an essential link in the assessment of the potential of the Ypresian Clays as an alternative host formation.

4.3 Development and construction of the disposal facility

4.3.1 Diversity of the waste classes

The category B waste (which accounts for a significant proportion of the waste to be placed in a repository) and the category C waste are conditioned in a variety of forms according to their source or period of production.

R52 The reading committee considers that a technical concept fully suited to the disposal facility must be developed for each class of waste (or homogeneous group of classes), taking into account the specifics of the class or group of classes (the physico-chemical characteristics of the waste and its conditioning—specifically the heat production and the potential for gas generation—, the radioactive and non-radioactive inventory, the quantities, etc.).

R53 The reading committee finds that priority has so far been given to the waste classes that contain the highest level of activity, and asks the necessary actions be taken to catch up for the waste classes whose compatibility with the clay is still uncertain.

4.3.2 Uniqueness of the disposal site

The reading committee finds that ONDRAF/NIRAS starts from the working hypothesis that all of the category B and C waste will be disposed of on the same site. Only the prohibitive incompatibility between a waste class and certain characteristics of the disposal system, the natural properties of the host formation in particular, could be legitimate grounds for re-conditioning this waste or looking for a more suitable site or an ethically justified international disposal solution. These two latter aspects also apply should there prove to be insufficient disposal capacity.

R54 The reading committee believes that verifying the compatibility of each waste class with the considered host formation is an important step in the development of any technical concept for a disposal system, and that it is therefore necessary to finalise the studies of the compatibility of the bituminised waste (including Eurobitum) with the argillaceous medium, supported by clear conclusions. These studies must also be extended to include an assessment of the impact of the full radiological and non-radiological inventory (to include actinides and heavy metals). In time, research must also be conducted on developing corrective management measures.

4.3.3 Development of technical concepts for the disposal facility

The reading committee finds that only the technical disposal concept for high-level vitrified waste has so far been examined in detail. This waste class will impose more severe constraints in the event of the direct disposal of conditioned spent fuel assemblies, especially MOX fuel assemblies.

R55 The reading committee therefore recommends that the technical concepts for the disposal of high-level vitrified waste as well as for the disposal of conditioned spent fuel assemblies be put at the same level as soon as possible. To do so, the obvious synergies that exist between the solutions to be implemented for each class should be used, while advancing the search for a uniform concept so far as possible and clearly addressing the specific demands which the different waste classes pose in terms of protection.

The reading committee regrets that ONDRAF/NIRAS has as yet been unable to address the development of technical concepts for the category B waste that represents a significant proportion of the quantities of waste to be disposed of. This waste is divided up into a relatively large number of classes with sometimes very diverse specific characteristics.

R56 The reading committee recommends that ONDRAF/NIRAS selects from among the category B waste at least one waste class that is regarded as penalising, and begins to develop an appropriate technical concept for that class as a matter of priority.

The study of the technical concept for high-level vitrified waste, currently the most advanced of the studies, has made it possible to include in the SAFIR 2 report an appropriate list of technological questions that need an answer.

The reading committee finds that it is impossible, from the available results of corrosion studies on the types of reference steel chosen for the overpack, to draw clear conclusions as to the compatibility of these materials with the disposal conditions.

R57 The reading committee recommends that the study of the corrosion consistency of the overpack and the options for preventing its corrosion under disposal conditions should be an important priority in the future R&D programme. The necessary attention must therefore be given to the appropriate choice of all the materials (mainly the backfill materials) that are present around the overpack. The choice of the types of steel or other materials that may have to be studied must also be reviewed in this regard.

R58 Of the other unanswered questions, the reading committee believes that priority in the future R&D programme must be given to

- limiting the rise in temperature in the near field, the clay, and the aquifers;
- the aspects of mining engineering;
- limiting the mechanical and chemical disturbance of the clay rock during the construction and operational phases;
- studying the self-healing of the fractures caused in the Boom Clay during the excavation of the galleries and shafts (see also Recommendation R33).

R59 The reading committee recommends that satisfactory design solutions to the remaining unresolved technical questions about the high-level vitrified waste should be found as rapidly as possible without neglecting the search for possible technological alternatives. This is because the PRACLAY[5] demonstration experiment which is currently in preparation has little meaning unless it is based on a technical concept that is sufficiently representative of the concept that will actually be implemented.

R60 The reading committee believes that the dismantling and analysis of the results of the OPHELIE[6] mock-up must be organised in a way that derives the maximum amount of information from it both technically and in terms of understanding the phenomena at work in part of the near field during the hydration phase and the thermal phase. So far as the problems of corrosion are concerned, it is important to explain the relatively high chloride concentrations found in the mock-up.

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[5] *Preliminary Demonstration Test for Clay Disposal.*

[6] *On Surface Preliminary Heating Simulation Experimenting Later Instruments and Equipment.*

R61 It is the opinion of the reading committee that ONDRAF/NIRAS should incorporate the priorities mentioned above in a timetable for the review of the technical disposal concept for high-level vitrified waste and the development of technical concepts for the other waste classes intended for disposal in deep clay layers. In particular, this affects, first, the conditioned spent fuel assemblies which can represent a very restricting waste class owing to their inventory of fission and activation products and actinides, and their heterogeneous composition, and, second, the bituminised waste given the relatively large quantities involved. Sufficient account must also be taken of the anticipated and possible waste production scenarios.

4.3.4 Methodology for the development of technical concepts for disposal facilities

R62 The reading committee believes that ONDRAF/NIRAS must implement, starting from an engineering vision, the methodology which it proposes in the SAFIR 2 report for the development of technical concepts. This methodology is based on a systematic approach that encompasses all of the elements of the disposal system. It must be based on a structured study of the major interactions between each component of the disposal system and at the same time establish the constraints and the conditions whereby each component exists and functions. However, the necessary balance with fundamental research must not be lost from sight in this overall approach.

The reading committee notes that several decades will elapse before a disposal solution is actually implemented, and that the development of technical concepts is therefore an iterative process of continuous improvement during which the latest knowledge and information acquired will be taken into account (new scientific data, technological progress, etc.). This continuous improvement process must be conducted within reasonable limits.

The reading committee reminds that the multi-barrier approach remains the design basis of any disposal system in deep formations, especially as regards the periods of time involved. It is an approach that must not ignore the additional robustness and safety which can be afforded by the barriers that were overlooked in the long-term safety studies. The uncertainties that remain as to the characteristics of the conditioned waste (heat emission, radionuclide inventory, etc.) and its behaviour in the disposal system have decisive significance for the assessment of this additional robustness and safety.

R63 The reading committee believes that ONDRAF/NIRAS must give overriding priority to developing technical concepts for disposal facilities

- whose feasibility, established on the basis of experience or a specific demonstration, is no longer in doubt;
- which are simple and whose quality and performances are easy to demonstrate;
- which are robust and which have a low sensitivity to uncertainties;

- which are flexible and easy to adapt to the specifics of the different waste forms and to changes in the initial parameters.

4.3.5 Methodology for the assessment of technical concepts for disposal facilities

R64 The reading committee considers that the various technical concepts that make up the disposal system will have to be further developed to enable the system to satisfactorily fulfil its assigned functions. The new approach, which takes as its basic assumption the functions of the disposal facility at each period in its life, seems to be a suitable methodological tool for assessing the technical concepts. These functions have so far been focused on the long-term safety. ONDRAF/NIRAS must therefore extend this approach to include all the functions of the facility at each period of its life in order to develop the technical disposal concepts on clear bases.

R65 The development and improvement of a quality assurance system that can be applied to the design, construction, and operation of the disposal facility must be based on specific quality needs. These needs must be progressively defined within the overall concrete disposal system (see also Recommendations R11, R22, and R23).

4.3.6 Waste retrievability

The reading committee finds that no particular demand for waste retrievability has been made so far. Nevertheless, the current technical concepts for the disposal of category C waste already provide a certain level of intrinsic retrievability. For a certain length of time, it is indeed possible to take back the primary waste packages as they have been placed. Retrieving waste after the gradual closure of the main galleries and access shafts remains possible, but obviously becomes increasingly complex.

R66 The reading committee believes that it is important for the development of technical concepts to in future take account of the possibility, for a period to be defined, of retrieving buried waste under safety conditions equal to those that prevailed when the waste was buried.

R67 The retrievability devices that are meant to be incorporated in the disposal system must not compromise the system’s performance and safety. The impact of these devices on long-term safety must be closely examined.

R68 For safety and feasibility reasons, it can be assumed that the opportunities for waste retrieval will become fewer as the decision-making process advances. It is therefore recommended that the length of the period of retrievability should be limited in time and that it should be adapted to the type of waste and to the type of disposal facility. This period should be defined.

R69 Aside from the technical and safety aspects of retrievability, the reading committee recommends consideration of the ethical and economic implications of retrievability as well.

4.3.7 Monitoring

The reading committee finds that the role and precise content of monitoring in the successive phases of a disposal facility are areas in which a significant amount of information is still lacking.

R70 The technical requirements (definition of parameters, instrumentation, etc.) of monitoring after the closure of the disposal facility must be specified. The reading committee recommends that the necessary degree of attention be given to this aspect, especially during the demonstration phase.

R71 The reading committee recommends that the role of monitoring should be clarified from the viewpoints of waste retrievability and the durability of measuring instruments.

R72 On a more general level, the reading committee believes that the demands made from the viewpoint of safeguards for monitoring and retrievability must be assessed.

4.4 Safety and protection

The reading committee finds that one of the important experiences of the 1990–2000 period covered by the SAFIR 2 report relates to the general methodology for safety assessments. This methodology is predicated on a broad international basis for which acceptability by society is a major challenge. The reading committee finds however that the approaches used in the safety assessments so far undertaken (models, input data, deterministic analyses versus probabilistic, basic assumptions and points of departure, etc.) do not favour the transparency of the results obtained.

R73 The reading committee believes that additional work will have to be done during the coming phases of the R&D programme to further enhance the safety assessment methodology, specifically as already indicated in the SAFIR 2 report, by using alternative safety indicators and indicators of robustness, and by identifying, assessing, and, if necessary, reducing the various sources of uncertainty.

Attention given to long-term safety cannot be to the detriment of factors that determine safety during the initial phases of a disposal facility (construction, operation, period of institutional control).

R74 The reading committee also recommends that future safety assessments should be undertaken on more transparent and comparable bases (models, input data, deterministic analyses versus probabilistic, basic assumptions and points of departure, etc.).

The previous research programme confirmed the dominant and determining role of the Boom Clay as a barrier. The other barriers are eclipsed by the Boom Clay.

R75 The reading committee believes that this cannot in any way imply that these other barriers should not be reinforced so far as possible. This way, they can be kept as a safety reserve, significantly enhancing the robustness of the disposal system.

Through constructing and using conservative models and hypotheses, the role of some of these barriers is underestimated and even totally neglected in the safety assessments. From this viewpoint, the detailed study of certain barriers can be terminated sooner than for other barriers which have been explicitly considered.

R76 The reading committee believes that—as pertinently indicated in the SAFIR 2 report—all of the barriers must be considered together on the basis of the waste inventory in order to determine the overall safety of the disposal system. Such an integrated approach implies that the interfaces between the different barriers and between the barriers and the environment must be studied closely and accurately in order to properly understand the interactions between the barriers. The reading committee considers that the PRACLAY demonstration experiment offers an opportunity to study not just the various interactions between the waste and the barriers but also the disturbances caused by these interactions. In this case, it will be possible to test models in full scale that have so far only been verified on a laboratory scale.

R77 The reading committee considers that the Boom Clay as the most important barrier justifies a more in-depth study of certain priority aspects that must reduce certain uncertainties and gaps in knowledge:

- the uncertainties that remain about the migration of retarded radionuclides in the Boom Clay;
- the water flows in the Boom Clay (and the coupling with the observed heterogeneities and discontinuities) (see also Recommendations R30 and R40);
- the assessment of the disturbance of the disposal system (and mainly the clay host formation) by the production of gas for some classes of category B waste. Any conceptual solutions to be given to these disturbances will also have to be analysed.

Safety assessments for periods of time that can extend to several tens of thousands of years naturally depend on the scenarios that are used to represent the most likely changes in the disposal system and its environment. There are a number of difficulties surrounding the use of such scenarios.

- Current international thinking on climate change and the human impact on it is a good indication that safety assessments must not lose sight of this aspect. Modified climatological conditions such as permafrost and glaciations will also have an effect on water flows.
- The study of the geochemistry of the Boom Clay and the aquifers must provide enough information to ensure proper confirmation of the non-dependence on time of the radionuclide migration in the Boom Clay as currently considered.
- Assessing the radiological impact over such periods of time calls for a complex interpretation of the dose as a safety indicator on the one hand, and on a concentration of resources on enhancing the technical robustness of the different barriers on the basis of other indicators on the other hand.

R78 Given these considerations, the reading committee recommends

- that future safety assessments take account of the various possible scenarios in terms of climate change and their effects on the operation of the disposal system and the relevant characteristics of the environment;
- that priority be given to an in-depth study of the geochemical stability of the host formation and of the aquifers surrounding it;
- that the important scenario of groundwater pumping from the subjacent aquifer be better defined, particularly as regards the uses of the water that is pumped up;
- that priority be given to developing and applying indicators for quantifying the long-term impact and the robustness of the disposal system.

R79 The reading committee believes that in the future, the programme's current focus on the radiological impact will have to be broadened to consider all of the possible impacts that must be addressed in a strategic or project-specific environmental impact assessment (see Recommendations R3 and R15). This could entail a number of new R&D activities that will help to generate all of the information needed to undertake an environmental impact assessment in due course (e.g., defining the reference situation, thermal and chemical impact on the environment of the disposal system and more specifically on the aquifers, required alternatives, etc.).

The reading committee notes that a number of references are made to documents of the ICRP (International Commission on Radiological Protection), the OECD (Organisation for Economic Cooperation and Development), and the IAEA (International Atomic Energy Agency) in connection with radiological protection. The reading committee insists on the fact that these documents are recommendations only.

R80 The reading committee believes that ONDRAF/NIRAS and the competent safety authorities should act in concert on the application of these recommendations to the disposal of radioactive waste, without however compromising the independence of the safety authorities.

R81 The reading committee also believes that an effort will have to be made in the future development of the disposal concept to elaborate and apply the basis for optimisation.

R82 The reading committee is of the opinion that the importance of the collective dose as a tool for safety optimisation during the successive phases of a disposal facility (safety during the operational phase and long-term safety) must be precisely evaluated. The reading committee notes however that the importance of the collective dose as a long-term safety indicator is low given the huge and inevitable technical and social uncertainties during its assessment.

R83 The reading committee believes that future safety assessments must systematically include all aspects relating to criticality.

R84 The reading committee also believes that the aspect of safeguards (non-proliferation) in geological disposal, especially the geological disposal of conditioned spent fuel assemblies, must be developed further at international level in accordance with the international conventions that are in force.

4.5 Economic assessments

The reading committee considers that the economic assessments of long-term waste management are an important aspect, one of their primary aims being to establish the tariffs to be applied when waste is accepted.

R85 The reading committee therefore believes that ONDRAF/NIRAS must ensure transparently and with regular assessments that all of the foreseeable costs that could arise in the long term are covered. This recommendation applies in particular to costs incurred by failures of the waste to satisfy disposal requirements found during periodical inspections.

R86 The reading committee considers that it would be interesting to make an international comparison of the costs and tariffs estimated or applied by the various countries, bearing in mind local specifics.

R87 The economic effect on waste management of future reference and alternative scenarios in terms of waste production must also be studied, and the impact on the financing of waste management must be properly taken into account.

5 General conclusions of the reading committee

On the basis of all of the information made available directly or indirectly in the course of its work (see Annex B), the reading committee considers that the SAFIR 2 report correctly reflects the fundamental knowledge gathered by ONDRAF/NIRAS in the period 1990–2000 relating to the different components of the disposal system in a poorly-indurated clay and its environment, and to the long-term evolution of those components.

The reading committee also believes that most of the recommendations of the commission that was created to assess the SAFIR report (1990) have been clearly followed. However, the reading committee finds that ONDRAF/NIRAS has only been able to act on part of the recommendations of that commission relating to the overall compatibility of the waste with the disposal system and the acquisition of the depth of knowledge of the waste inventory that is required in order to be able to proceed with the actual disposal.

None of the results of the research work currently indicates any prohibitive problem concerning the disposal of high-level and long-lived vitrified waste into the Boom Clay, and this strengthens the confidence in the researched solution. This confirms that deep disposal within a poorly-indurated clay remains an entirely conceivable option for the waste discussed in the SAFIR 2 report. However, there are still major uncertainties that require more in-depth research.

The reading committee regards it as a priority to intensify the R&D programme on the other classes of waste intended for deep disposal, especially the conditioned spent fuel assemblies and the category B waste (in particular the bituminised waste), the object being to verify the capacity of the Boom Clay to receive all of the category B and C waste. To this end, the reading committee believes that clear answers to the questions about the compatibility of the various waste classes with the studied disposal system must be found as soon as possible. It also believes that the consistency of the acceptability criteria with the disposal system as developed must be periodically verified.

Most particularly, the reading committee draws attention to the following issues which should form priorities in the future R&D programme of ONDRAF/NIRAS:

1. Concentration on aspects directly linked to the feasibility and practical implementation of technical disposal facilities, and hence on the aspects of demonstration; this ‘architect/engineer’ approach will have to be supported by the validation and verification of models and hypotheses, which are exercises in more fundamental research.

2. Deepening the understanding of the processes of radionuclide migration retardation in the Boom Clay, and of long-term changes in the geochemistry and retention properties of this formation.

3. Analysis of the heterogeneities and discontinuities of the Boom Clay and of their effects on radionuclide migration.

4. Analysis of the water flows in the Boom Clay (lithological or structural discontinuities) and of the influence on these flows of changes in regional hydrogeological conditions in the surrounding aquifers.

5. Greater consideration for aspects of the chemical, biological, and physical compatibility of all of the materials in the presence of the host formation; specifically, the study of chemical, biological, and physical disturbances caused by the presence of waste (e.g., the nitrates and heavy metals present in the Belgian government's bituminised waste, the swelling of bituminous matrices, the matrix cement, the backfill and lining materials, microbial corrosion) must be continued.

6. Review of the choice of overpack materials and development of an integrated approach to defining all of the engineered barriers based on the prevention of overpack corrosion, as a function of the specifics of the host rocks.

7. Analysis of the impact of the production of gas by the waste (mainly category B) on the repository, on the host formation, and on safety, and of the conceptual answers that may be given in response.

8. Study and demonstration of the methods used to characterise the waste and to verify and confirm its composition and heat emission. The nature and extent of these operations must be in proportion to the waste knowledge required with a view to its deep disposal.

9. Improvement in the methodology of long-term safety assessments, particularly as regards the identification and handling of uncertainties, alternative safety and performance indicators as well as indicators of robustness.

10. Definition and development of a system for the long-term management and transfer of knowledge, in particular to enable the traceability of decisions and technical choices and the transmission, integration, and synthesis of multi-disciplinary information.

The reading committee finds that the problems of the long-term management of radioactive waste must be viewed in a wider than strictly technical/scientific context. Therefore, it recommends that the future R&D programme of ONDRAF/NIRAS should include without delay both technical/scientific and societal and economic aspects. An interdisciplinary programme of this type must also be structured in a way that supports the decisional process in matters concerning the long-term management of radioactive waste by affording this process the best possible scientific footing (especially as regards the consideration of all types of uncertainty) and with a view to applying the precautionary principle.

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The reading committee also notes that taking decisions on matters of radioactive waste involves a consideration of long-term management alternatives (e.g., the various host formations, the institutional options for an international repository—without jeopardising the present national R&D programme on waste disposal—, separation and transmutation, whether as part of a strongly developed and long-term nuclear programme or not) and of all of the environmental impacts of the proposed solution. The reading committee therefore urges ONDRAF/NIRAS to initiate the studies needed to establish documents of the ‘Strategic Environmental Impact Assessment’ type and of the ‘Environmental Impact Report’ type for a given facility or project, if possible within a broad international collaborative effort.

The reading committee therefore recommends the continuation of the work being done on the Ypresian Clays as an alternative host formation, but believes that, at the present stage, the level of knowledge required for these clays need not necessarily be the same as for the Boom Clay. Nevertheless, this level of knowledge must be sufficient to determine whether the Ypresian Clays constitute a realistic option either alone or as an addition to the reference option, i.e., the Boom Clay.

The reading committee notes that ONDRAF/NIRAS, within the scope of its mission, is the only organisation in Belgium running a systematic major research and development programme on the long-term management of radioactive waste. The reading committee also finds that, according to the legal mechanism for financing the activities of ONDRAF/NIRAS, this R&D programme must be developed in consultation with the waste producers. The reading committee insists that this consultation must make it possible to establish an R&D programme that covers the priority research topics referred to above and, if possible, all of the scientific, technical, and societal issues deemed to be relevant by ONDRAF/NIRAS and its independent advisers. The reading committee restates the request made by the SAFIR Evaluation Commission (1990) for independent research to be conducted and for the necessary funds to be made available to the scientific world for this purpose. It also insists on the fact that international collaboration and the development of international networks are major factors in the success of such a project. The reading committee therefore urges ONDRAF/NIRAS to draw upon the widest possible expertise and to enhance the value of its knowledge at both national and international level.

The reading committee is convinced that the creation of an interdisciplinary R&D programme (fundamental aspects, applied aspects, and aspects relevant to human sciences) that is consistent with the priorities referred to above will help further strengthen the confidence acquired in the studied solution, in particular by developing specific technical disposal concepts for all classes of waste, by reducing uncertainties, by taking account of non-radiological effects, and by considering social aspects.

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Annex A: Members of the SAFIR 2 scientific consultative reading committee

Chairman:

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Professor of Chemistry at the Vrije Universiteit Brussel (VUB)

Members:

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Lecturer—Director of the Chemical Engineering Department at the Université Libre de Bruxelles (ULB)

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Professor of Applied Geology and Hydrogeology at the Universiteit Gent (UG)

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Professor of Physics at the Facultés Universitaires Notre-Dame de la Paix in Namur (FUNDP)

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Professor of Metallurgy and Corrosion at the Katholieke Universiteit Leuven (KUL)

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Adviser to the Board of Directors and Representative of *Integratie Humane Wetenschappen* (Integration of Human Sciences) SCK•CEN, Visiting Professor of Radiological Protection at the Vrije Universiteit Brussel (VUB)

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Annex B: List of documents made available to the reading committee

- SAFIR—Safety Assessment and Feasibility Interim Report (1989, in French and in Dutch) [*] and its summary report (1989, in French, in Dutch, and in English).
- Final report of the SAFIR Evaluation Commission (1990, in French and in Dutch).
- Version 1 of the SAFIR 2 report. General introduction and Chapters 1–13 (distributed between May 2000 and April 2001, mixed French + Dutch text).
- Minutes of the meetings of the reading committee (including copies of transparencies from presentations given at meetings, mixed French + Dutch text).
- Compilation of verbal and written questions put by the members of the reading committee and the answers provided by ONDRAF/NIRAS (mixed French + Dutch text):
  - on Chapters 0–3: ONDRAF/NIRAS memo 2000–4470 (plus attachments, i.e., ONDRAF/NIRAS memos 2000–2747 and 2000–3220, and ACTUA No. 36–37 of May 2000);
  - on Chapters 4–8: ONDRAF/NIRAS memo 2001–0270 (plus attachments);
  - on Chapters 9–13: ONDRAF/NIRAS memo 2001–2665 (plus attachments).
- *Géologie de la Campine — Essai de synthèse / Geologie van de Kempen — Een synthese* (L. Wouters and N. Vandenberghe), NIROND 94–12 / NIROND 94–11, 1994.[*]
- *Rayonnements ionisants — Effets de faibles doses / Ioniserende straling — Effecten van lage dosissen* (H. Vanmarcke, L. Baugnet-Mahieu, J.-P. Culot, P. Govaerts, L. Holmstock), NIROND 96–03, 1996.[*]
- *Analogies naturelles en milieu argileux — Essai de synthèse bibliographique / Natuurlijke analogieën in klei — Een bibliografische synthese* (Th. De Putter and J.-M. Charlet), NIROND 94–13 / NIROND 94–14, 1994.[*]
- *Analogies naturelles et archéologiques — Géologie et altération de surface / Natuurlijke en archeologische analogieën — Oppervlaktegeologie en oppervlakteverwering* (Th. De Putter et al.), NIROND 97–9 / NIROND 97–10, 1997.
- Information file on ONDRAF/NIRAS (in French and in Dutch).

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[*]: Documents made available to be examined on site or on request.

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