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.

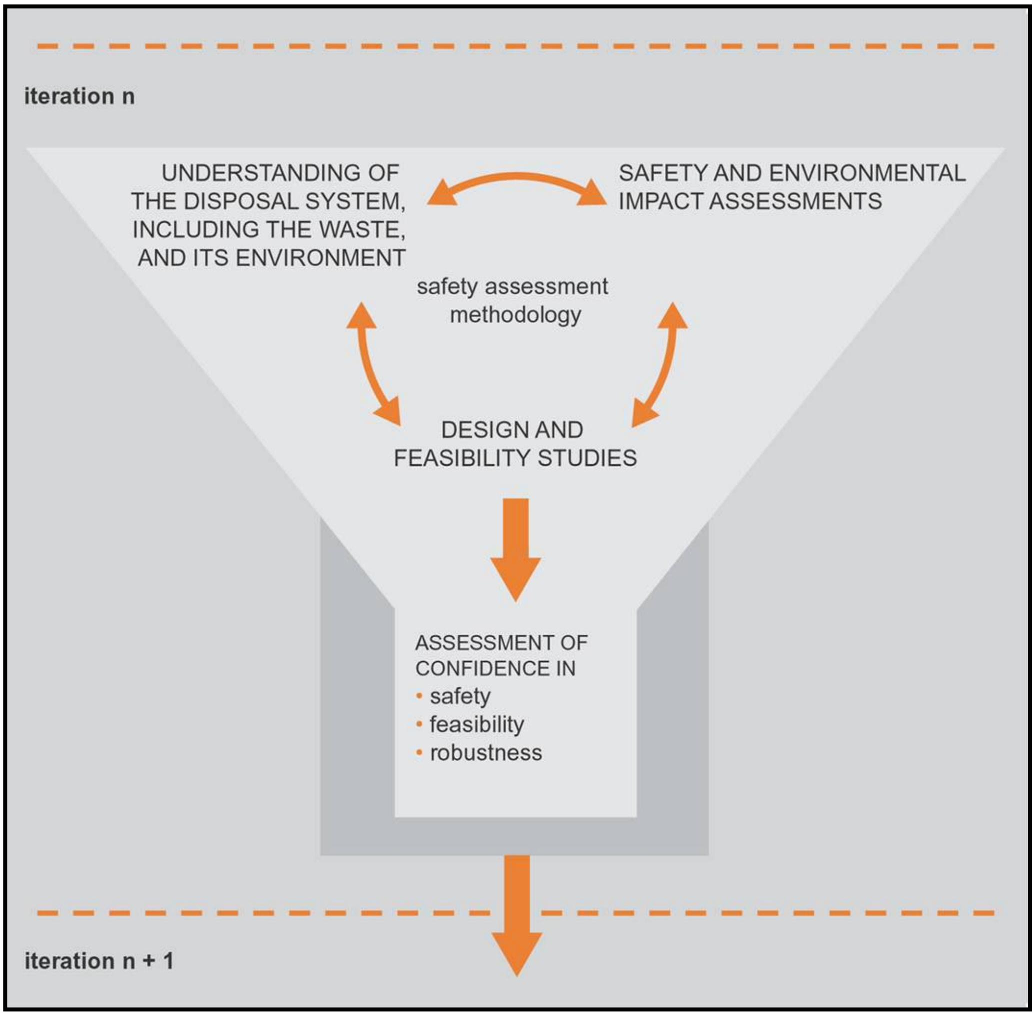

Figure 1.1 General approach taken by the Belgian methodological research and development programme into deep disposal (see also Fig. 2.2).

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.

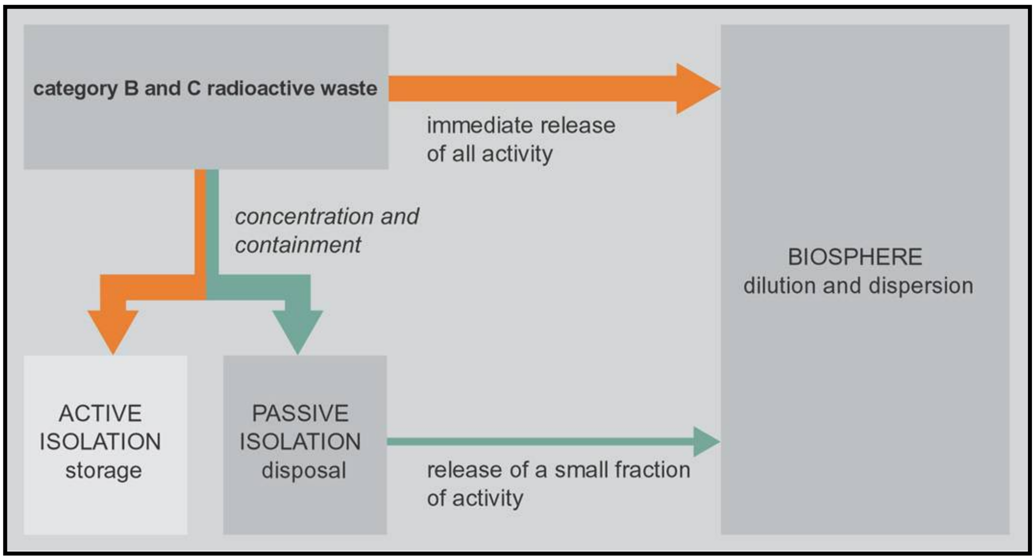

Figure 2.1 The potential options for the long-term management of radioactive waste. The option studied by ONDRAF/NIRAS for the management of category B and C waste is the concentration and containment of the waste by disposal.

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.

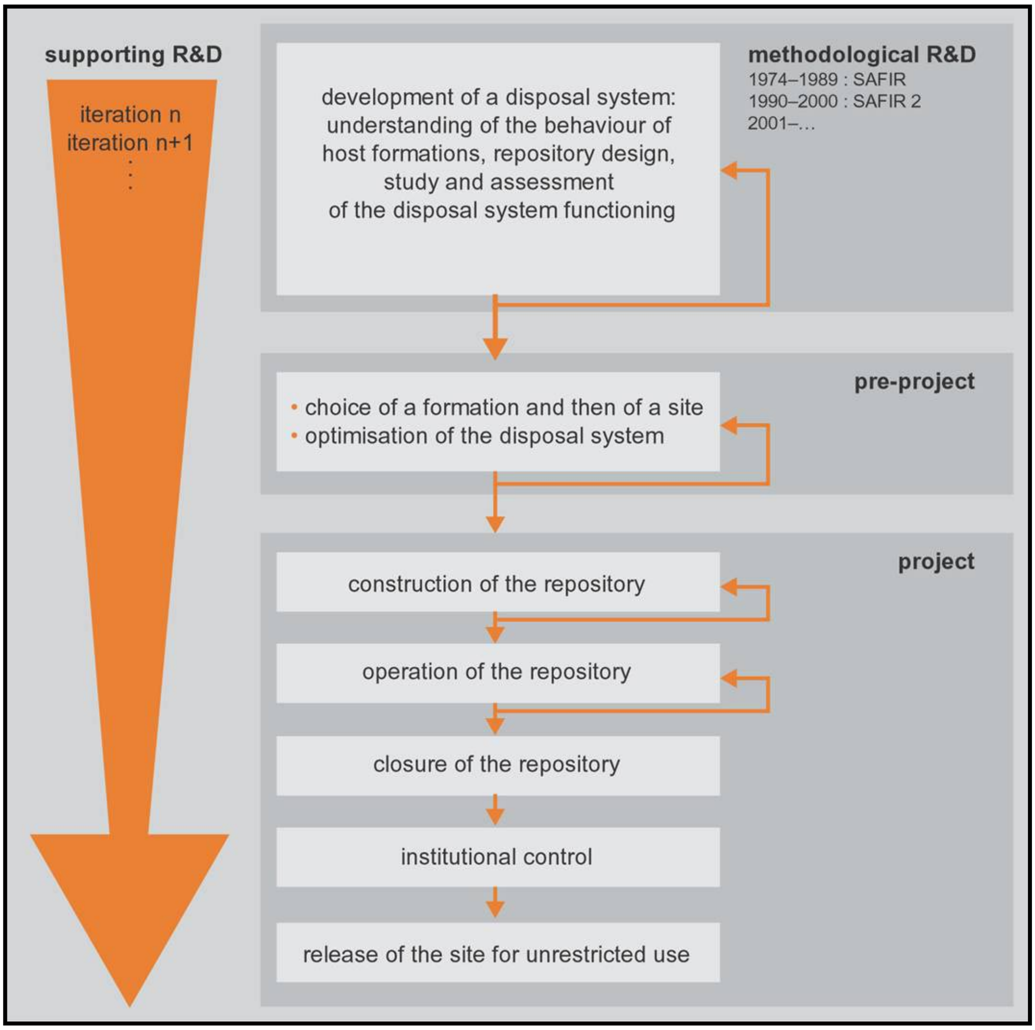

Figure 2.2 The main phases of the stepwise implementation of a disposal system. The approach is flexible and iterative, with the iterations involving making adjustments and, if necessary, looking back within the same phase or to a prior phase (see also Fig. 1.1). Successive safety assessments also contribute 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.

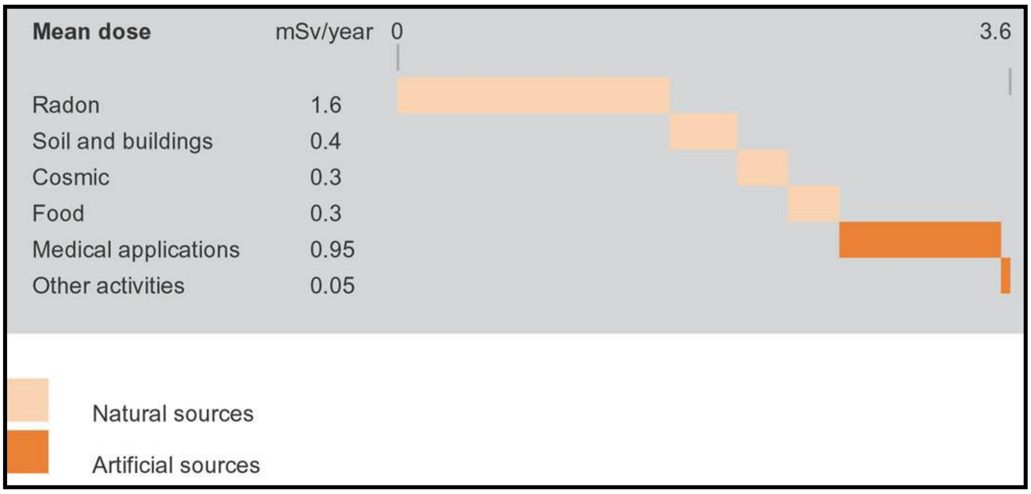

Figure 2.3 Mean annual exposure to ionising radiation in Belgium. 72 % of the mean exposure of 3.6 mSv per year is due to natural sources and 26 % to artificial medical sources.

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.

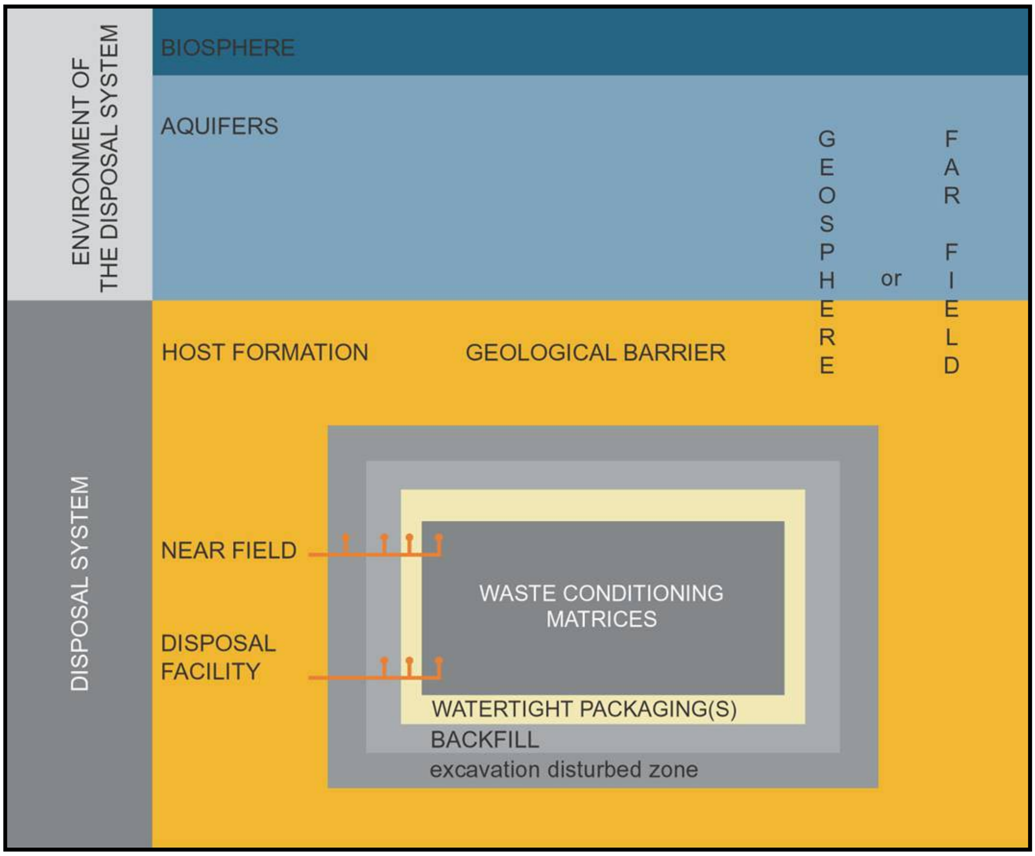

Figure 2.4 Schematic of a deep disposal system and its environment, and related terminology.

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.

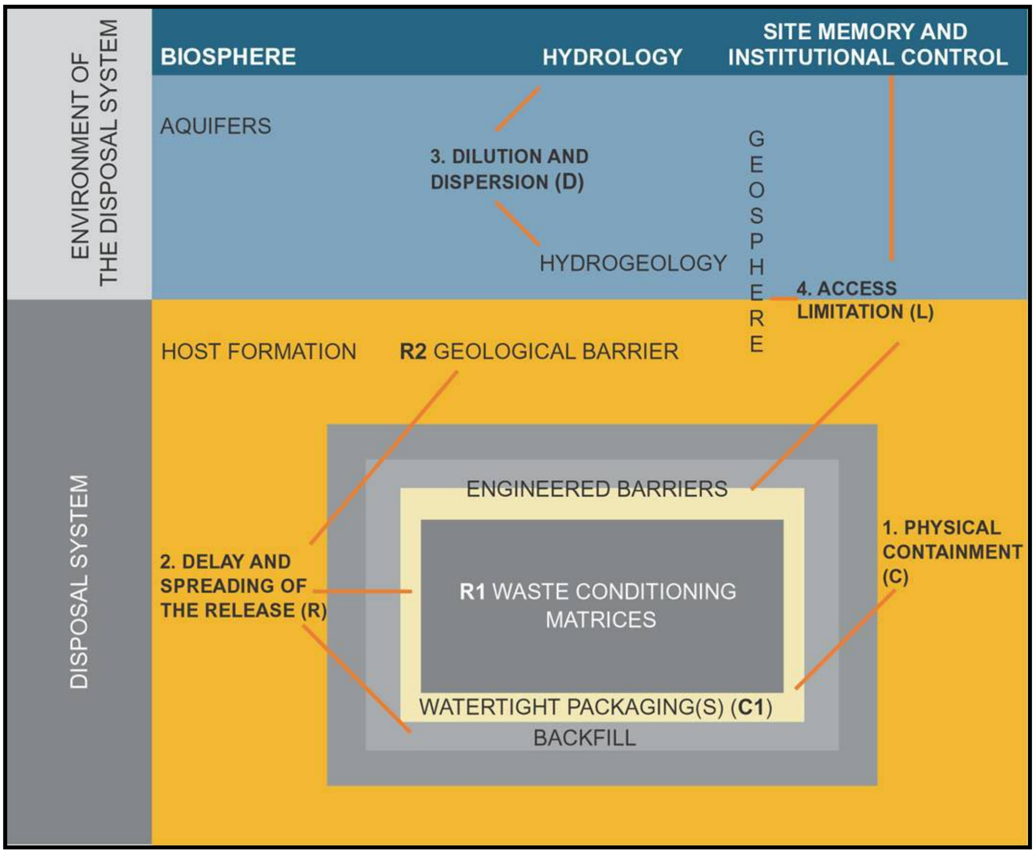

Figure 2.5 The long-term safety functions of the deep disposal system under study that are considered in the long-term safety assessments for the normal-evolution scenario. The various components of the system may perform other safety functions not taken into account in the assessments (see also Section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

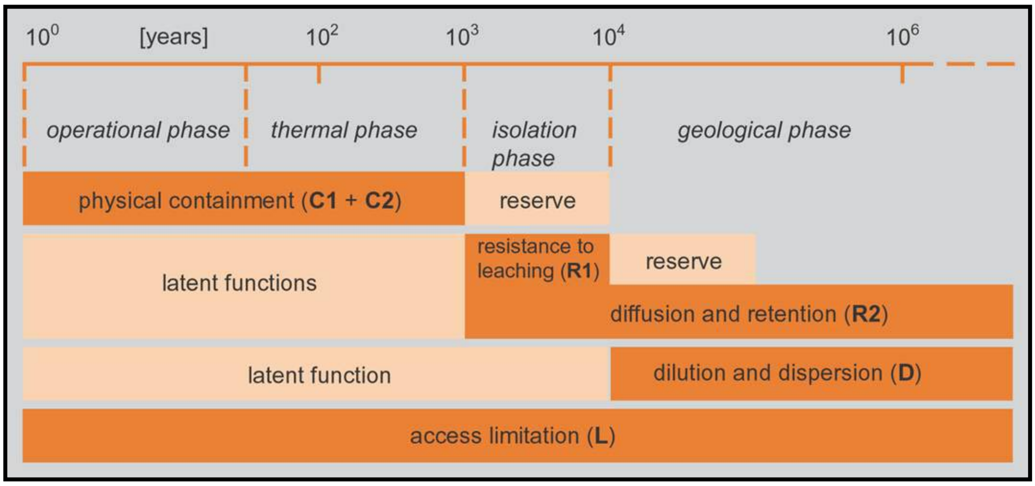

Figure 2.6 The four phases in the normal evolution of a deep disposal system for category C waste, the most demanding waste in terms of radiation and heat emission, i.e., the vitrified waste and spent fuel (see Section 3.1), and the corresponding long-term safety functions.

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

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.

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.

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).