Geological Disposal of Radioactive Waste: Elements of a Safety Approach

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1 Foreword

This document has been developed within the general framework of the Franco-Belgian collaboration in the field of nuclear safety and radiological protection. Specific collaboration in the field of the safety approach to disposal in deep geological formations began in June 2000 and led to the creation of a working group made up of the regulatory authorities ASN (*Autorité de Sûreté Nucléaire française*, the French Nuclear Safety Authority) and FANC (Belgian Federal Agency for Nuclear Control), their respective technical supporting organisations, IRSN (*Institut de Radioprotection et de Sûreté Nucléaire*, the Institute for Radiological Protection and Nuclear Safety) and AVN (*Association Vinçotte Nuclear*), and the implementers ANDRA (*Agence Nationale pour la gestion des Déchets Radioactifs*, the French National Agency for the Management of Radioactive Waste) and ONDRAF/NIRAS (Belgian Agency for Radioactive Waste and Enriched Fissile Materials This document results from a common work performed in the framework of the Franco-Belgian collaboration and does not take the place of any regulation and/or normative text.

The progress made in the respective national programmes has enabled the drafting of this common document on the safety approach to disposal in deep geological formations. On the French side, a basic safety rule (RFS III.2.f) [ref. 1] dating from 1991 defines the safety objectives to be applied from the pre-operational phase of a repository project and ANDRA recently issued the "Dossier 2001 – Argile [ref. 2] ” which is a preliminary safety assessment of a repository in an argillaceous host rock in France. ANDRA performs as well studies on the interest of granite formations for disposal of radioactive waste. On the Belgian side, in 2001, ONDRAF/NIRAS published the SAFIR 2 report [ref. 3] (Safety Assessment and Feasibility Interim Report 2) that summarises the knowledge and results obtained in the Belgian programme over the last ten years with respect to the safety and feasibility of disposal of high-level and long-lived radioactive waste in an argillaceous geological formation. In addition to this, the SAFIR 2 report and the "Dossier 2001 – Argile" were both reviewed under the aegis of the OECD/NEA (Organisation for Economic Cooperation and Development/Nuclear Energy Agency), in 2002 and 2003 respectively [ref. 4 & 5].

The progress in the programmes and the recent publications of the ICRP (International Commission on Radiological Protection) [ref. 6 & 7], the IAEA (International Atomic Energy Agency) [ref. 8] and the OECD/NEA [ref. 9 & 10] on long-term safety of disposal has led the ASN and FANC to develop their respective regulatory frameworks. The ASN has started updating of the RFS III.2.f and intends to enhance its ideas, in an international framework, on different elements of the safety approach. The FANC wishes to develop a specific regulatory framework for the disposal of radioactive waste. Regular bilateral meetings have allowed all these ideas to converge and have provided the framework for further consideration of these areas. So the elements of the long-term safety approach contained in this document must be seen as a first stage of the development, intended for being shared with a larger community and for being reviewed.

The present document establishes a link between the protection of man and the environment and the disposal system through the application of safety principles and the identification of safety functions. Being the result of discussions between implementers and regulatory authorities, the document captures their viewpoints and their opinions. This document refers to and takes account of the guidelines formulated by the ICRP as set forth in ICRP Publication 81 [ref. 6] and by the IAEA in the draft Safety Requirements on Geological Disposal (DS-154) [ref. 8]. At a later stage, the intention is to compare the approach described in this document with other national programmes.

2 Introduction

The purpose of this document is to describe, in the context of geological repositories for radioactive waste, the concepts of safety functions, safety principles and radiological protection principles, and to develop a framework for the judgement of the acceptability of safety cases (cf. Chap 3) by regulatory authorities and decision-makers. As the document has been drafted in the context of safety, this judgement of acceptability is also restricted to safety aspects. The aforementioned concepts are described as an integral part of an approach to be taken into account in the development, implementation and in the evaluation of the long-term safety of a radioactive waste repository in deep geological formations. It should be noted that the operational safety does not require the development of the same type of safety approach but the implications of the measures and decisions taken during the operational stage must be identified and taken into account in the long-term safety approach. Furthermore, these measures and decisions must not compromise long-term safety.

The elements of the safety approach are developed in the following chapters. After this introduction that describes the general context, Chapter 3 defines a set of concepts and terms that are necessary in order to understand the document well. In subsequent chapters, the document develops the concepts of "Safety Approach", "Safety Principles", "Radiological Protection Principles", "Primary Safety Functions" and finally “Judgement of Acceptability”. In the Chapter 8, the interpretation of the concept of “Dose” with reference to geological disposal has necessitated the development of a sub-section on safety indicators. In the conclusions a judgement on the level of the progress achieved is made. Appendix 1 contains a comparison of the proposed safety approach with ICRP Publication 81 [ref. 6] and with the draft of Safety Requirements on Geological Disposal of Radioactive Waste of the IAEA [ref. 8]. Some examples of the application of safety functions are given in Appendix 2. In the rest of the document, the term "safety approach" will be used in place of the full expression "elements of safety approach".

In developing the French and Belgian concepts of geological disposal the "concentration and containment" strategy and the principle of precaution are being considered and implemented. The long-term management of solid radioactive waste is based on the “concentration and containment” strategy and therefore this strategy constitutes an essential element of the repository development. Although the principle of precaution is not specific to the problems associated with the geological disposal of radioactive waste, it leads to the prudent practice that underpins the concepts developed. The application of this principle was not subject to any development.

As the essential purpose of this document is to emphasise the concepts that have been subject to additional developments, the well-established principles of radiological protection as defined in ICRP Publication 60 [ref. 11] are not addressed in detail.

In each stage of a repository project, and before the safety case is finalised for the considered stage, the safety approach, which takes account of the regulatory framework, must have been defined by the implementer and submitted to the regulatory authority for its opinion or approval. The safety case must reflect the safety approach followed by the implementer. The regulatory authority assesses the conformity of the safety case at each stage of the programme. Once the safety case is approved, the implementer may continue with its repository programme. The role of the safety case is described in §5.5 of Reference 2.

3 Terminology and Definitions

The Basic Objective of Protection

The protection of man and the environment constitutes the basic objective. This objective must be assured during all stages of disposal.

IAEA Safety Fundamentals

A responsible management of radioactive waste necessitates the application of measures to ensure the protection of man and the environment. The IAEA has formulated a set of principles [ref. 12] that detail these protective measures. These principles refer to general aspects of radioactive waste management. Disposal is only one component of waste management.

Safety Principles

Broadly speaking, safety principles define the basic directions to be followed in the design of a safe geological repository. These directions, which fall within the technical fields of safety, apply to all stages of the development of a geological repository.

Safety Functions

A function can generally be defined as any action that a system or one of its components must carry out in order to achieve a given purpose. The functions of a disposal system contribute to fulfilling the different objectives assigned to it. Safety functions are those which make it possible to comply with the principles of safety and radiological protection as well as with the basic objective of protection during all stages of the life of the facility, while limiting the burden for future generations.

Constraints

Constraints are all of the conditions placed by external actors outside the process of safety assessment or its verification but involved in the decision-making process. Conditions on the choice of sites or the inclusion of reversibility in the development of a concept are examples of constraints.

Safety Case

The safety case integrates all the arguments that support, justify, and, if possible, quantify the safety of the repository and the level of the confidence reached. The safety case contains the assessment of the radiological impact and information on the repository and its implementation, its robustness, its feasibility and the quality of the information and arguments presented. The identification of uncertainties, the incorporation of these and the description of the strategy for their reduction are also constituent parts of the safety case.

The Disposal System and its Environment

The disposal system includes all the components (man-made and natural) that contribute directly or indirectly to the implementation of the "concentration and containment" strategy. The disposal system comprises the conditioned waste packaging, the engineered barriers and the part of the geological formation that perform safety functions.

The biosphere and any other geological formations are not considered part of the disposal system, as they do not participate in the implementation of the "concentration and containment" strategy; they are hereafter referred to the environment of the disposal system.

Robustness

The concept of robustness of a disposal system component means that the component's characteristics associated with its safety function(s) is/are preserved when faced with a spectrum of reasonably foreseeable stresses despite any residual uncertainty associated with the component. The same concept can be extended to a group of components.

When extended to the whole disposal system, the concept of robustness is characterized by the fact that several components can together (complementarity) or in parallel (redundancy) provide a safety function. Therefore the combination of the components' characteristics is such that the capacity of the disposal system to achieve the expected safety performance after being subjected to reasonably foreseeable constraints is assured. Further information on the concept of robustness and its variations can be found in Reference 9.

Reference Value

A reference value is used to establish the acceptable level of impact, without prejudice to the fact that a higher value may be allowed. "Comparison value" is a synonym. A reference value cannot be compared to a "threshold" or "limit" value that cannot be exceeded.

4 Safety Approach

The purpose of this chapter is to describe a safety approach to develop and implement a radioactive waste repository in a deep geological formation. This safety approach is focussed on long-term safety but must be applied during the design and construction stages of the repository and becomes all-important in the post-closure phase. Because long-term safety cannot depend on future human interventions, it must imply the implementation of passive means. This implementation during any given stage has specific repercussions on all subsequent stages.

The safety approach is based on the basic objective of protection (cf. Chapter 3). It implements the safety principles, the radiation protection principles and the safety functions that are developed within Chapters 5, 6 and 7. In this way, it provides a structure for and facilitates the judgement of acceptability developed within Chapter 8.

The principles, as indicated above, establish the orientation and methods that provide a framework for the definition of the strategy for developing a repository. This means that a strategy that is consistent with the safety and protection principles must enable the basic objective of protection to be achieved.

The safety functions and their implementation contribute to the establishment of a strategy for the development of a disposal system; the validity of this strategy is examined in a safety case. The development of a disposal system is an iterative process starting with R&D and evolving to the design and construction of the facility.

Based on these concepts of safety principles and safety functions and taking external design constraints into account, the implementer develops its disposal project, in particular, allocating the safety functions to the different components of the disposal system. To do this, the implementer relies on the known physico-chemical properties of the components it has chosen. This allocation must be supported with arguments and justified in the safety case.

Figure 1 links together the concepts defined above. It illustrates the safety approach in relation to its purpose, which is the acceptance of the safety case by the authorities and decision-makers. This acceptance only refers to an acceptance with respect to safety by the regulatory authority and the decision-makers. In particular, the safety case must describe the adequacy of the allocation of the safety functions to the components and the implementation of the safety and radiation protection principles. It must also demonstrate that this implementation fulfils the basic objective of protection, taking account of the implication of measures to insure the operational safety on long-term safety and of external design constraints such as for example the reversibility and cost of the project.

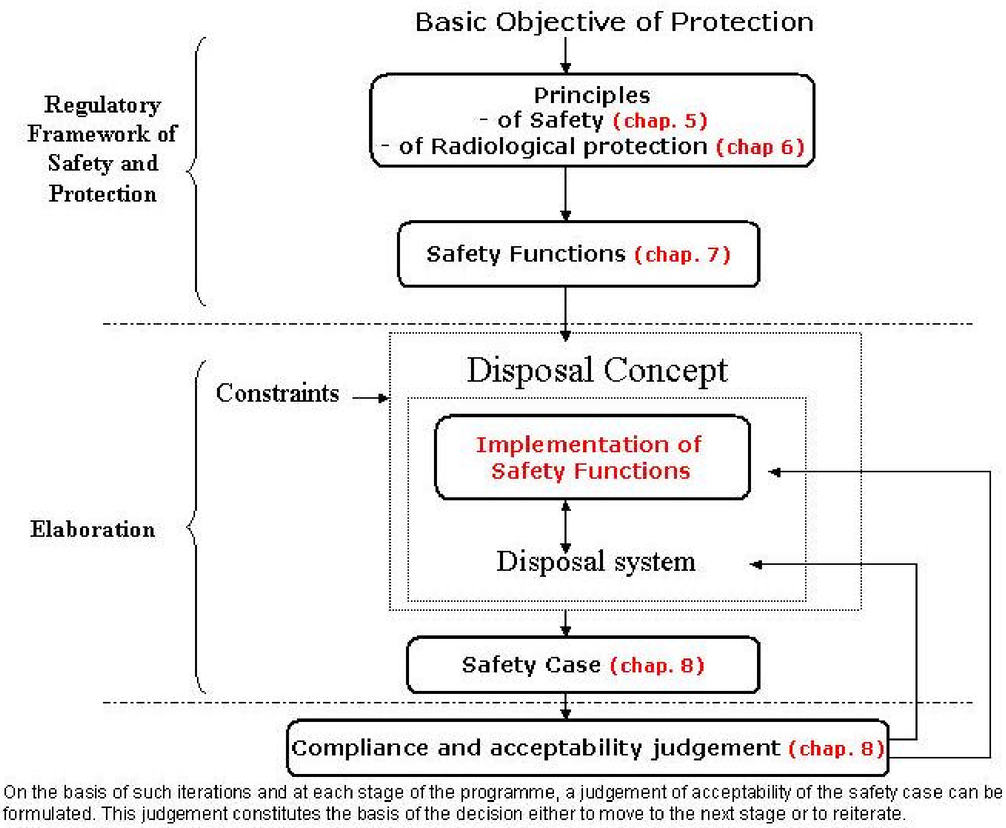

Fig. 1 Illustration of the Elements of the Safety Approach

5 Safety Principles

Having summarised the concepts - relating to the guidelines for the development of a repository – most commonly used in the literature (feasibility, simplicity, robustness, etc.), all of the concepts that are important in terms of the development of a safe repository fall under two safety principles. These principles are the principle of defence-in-depth and the principle of demonstrability.

5.1 Principle of Defence-in-depth

A concept of protection associated with the generation of nuclear power, the principle of defence-in-depth consists of a series of complementary and independent levels of protection with the objective to prevent and/or to limit the release of radionuclides into the environment. One of the aspects in implementing the defence-in-depth principle is to interpose several barriers between ionising materials and the environment (multiple barrier concept).

When applied to a repository in a geological formation, the principle of defence-in-depth implies the implementation of "multiple safety functions". In this case, it is not the number and redundancy of the barriers as such that take on the greatest importance in terms of safety, but the fact of being able to depend on different mechanisms and/or components to provide safety functions (cf. Chapter 7). The safety functions identified are: isolation, containment, limitation and retardation.

One component may fulfil several different functions, stop fulfilling one while continuing to fulfil others, and successively fulfil different functions over different time scales. Several components together (complementarity) or in parallel (redundancy) can perform one function. The aim of designing and developing a repository on the basis of multiple safety functions is that the partial or total loss of one component’s function should not compromise the disposal system’s safety. This is an important element of the robustness of the whole disposal system. However, the total loss of the “isolation” function or “limitation and retardation” function ensured by the geological barrier could seriously compromise the safety of the repository system if this would occur during a period not allowing a significant radioactive decay of the waste inventory. This means that the choice of the geological formation and site must ensure that the total loss of one of the safety functions of the geological barrier is extremely unlikely during the aforementioned period.

5.2 Principle of Demonstrability

The principle of “demonstrability” consists of adopting methods of system development that will make it possible to demonstrate (in the sense of providing a body of convincing arguments) that the functions and performances expected from the repository components will be fulfilled and maintained no matter what reasonably foreseeable disturbance may impact the system (cf. chap 3 “robustness”). This is an element of robustness. Special attention must be paid to the technical feasibility of these components, that is to say, to the qualification of techniques and means of control, in order to ensure the quality of the components’ implementation and, consequently, to gain a sufficient degree of confidence in the capacity of the components to fulfil their functions. Furthermore, the confidence in the findings of the safety assessment will be less if the processes and interactions involve an evolution of components that is difficult to assess. As far as possible, simplicity of design should be sought so that the evolution of the components can be assessed based on sound knowledge of the data and of the underlying processes.

With respect to the presentation of a body of convincing arguments, the principle of demonstrability assumes that the performances expected from the safety functions are based on a passive system.

5.3 Implementation of Safety Principles

The safety principles build upon the different elements described below that define the basic lines of the safety approach. The application of safety principles means integrating these elements to design a repository that complies with the basic objective of protection. During the design stage, the implementer must ensure, by applying the principle of defence-in-depth, that if common modes of failure exist, these are identified and controllable.

The principle of defence-in-depth, when applied, depends on the concept of multiple safety functions and robustness. Similarly, the principle of demonstrability rests on the concepts of robustness, passivity, technical feasibility and simplicity (see §5.3.2 et seq).

In the implementation of the principles, it should be noted that reversibility is not actually a safety concern but it could, however, affect long-term safety. Reversibility is a social and political demand and is an additional external constraint. It affects the development of a repository project and must be taken into account by the implementer.

5.3.1 Multiple Safety Functions

The implementation of multiple safety functions must, on the basis of an iterative process, lead to the elaboration of a design that above all prevents the occurrence of conditions that could lead to the simultaneous failure of one or more repository components. This can be done by analysing the possible causes and consequences of the failure of the functions of repository components. Where these conditions cannot be ruled out, the probability and the impact of the loss of the functions of a component must be limited through compensation. This means that several functions assigned to repository components may intrinsically oppose the release of radionuclides. A prudent approach should be taken, consisting of choosing or designing each component to ensure that it is as effective as reasonably possible taking into account both its role in the overall safety of the repository and the state of the art, available techniques and economic factors.

5.3.2 Robustness

The concept of robustness applies to both the principle of defence-in-depth and the principle of demonstrability. The performance of the repository must be commensurate with the risk posed by the substances contained in the facility and the evolution of this risk with time. To ensure this capacity, it is important that the components of the repository be specified on the basis of conservative assumptions. This means, in the first place, that the characteristics of a component must be such that they can ensure the maintenance of the function(s) of this component in the event of any reasonably foreseeable conditions to which it may be subjected. Secondly, the characteristics and quality of the components should have safety margins with respect to the performance required of the component (the more likely the scenario is that puts the component under stress, the greater the safety margins should be). Thus, the specification of the components, their robustness and that of the repository as a whole should then be able to reinforce confidence in the safety assessment. The choice of a repository component must, therefore, be based on the expected performance of this component over a given period of time, its capacity to maintain that performance over long periods of time and its capacity to integrate in the disposal system as a whole, as well as its robustness.

It seems consistent to extend the concept of robustness in the design through the use of the concept of simplicity, in particular (cf. §5.3.5). The design should be based, in the case of components, on their individual technical and intrinsic robustness and, in the case of the disposal system as a whole, on its overall technical and intrinsic robustness.

5.3.3 Passivity

One specific aspect of the disposal is that human interventions to maintain the effectiveness of the physical barriers are excluded in the post-closure phase. So, in the long term, the safety of the repository relies solely on passive systems. The evolution of the repository over long periods of time is therefore independent of any corrective human intervention or activities since they cannot be relied upon at the moment of the repository development.

5.3.4 Technical Feasibility

The principle of demonstrability asks for consideration of the technical feasibility of the disposal system from the project's initial development stages onwards (to the same extent as data acquisition, experiments and modelling). In order to do this, either proven techniques must be used (the safest method inasmuch as these techniques meet the needs of the project) or new techniques based on qualification tests must be used. In the latter case, new techniques would have to be developed in a time frame that is compatible with the project schedule.

5.3.5 Simplicity

The application of the principle of demonstrability means reducing the possibility for process coupling, limiting, as much as possible, the factors affecting system evolution and the various contrasts and imbalances (e.g. thermal, mechanical, hydraulic, chemical), and working in conditions in which the features, events and processes to be taken into account are clear and straightforward. In this way, the number of key parameters is reduced and simpler models can be used.

6 Radiation Protection Principles

The principles of radiation protection are defined in the ICRP recommendations (ICRP Publication 60 [ref. 11]) and are the bases for radiological protection for all practices. They are thus only alluded to in this document

Their interpretation and application in the context of the long-term safety assessment of a radioactive waste repository are, however, set forth in this document. The results of these considerations define the guidelines on which judgement of acceptability (Chapter 8) is based.

The radiation protection principles (ICRP Publication 60) are:

- The principle of justification of a practice
- The principle of optimisation of protection
- The principle of individual risk and dose limits

ICRP Publications 77 and 81 [ref. 7 & 6] provide recommendations applicable to the disposal of long-lived radioactive waste. In the sense of ICRP terminology, geological disposal falls within the category of practices (ICRP Publication 81, Section 22). The recommendations of Publications 77 and 81 state:

1- By definition, no benefit is derived from waste (ICRP 81, Section 79). Its management and in particular its disposal should, therefore, not be considered a practice as such, subject to justification, but as an integral part of the practice whereby it was produced; it is the practice that generated the waste, such as the production of nuclear energy or the use of radioisotopes for research and medicine, that should be justified taking into account the management of the waste that it produces (ICRP Publication 77, Section 34).

2- The principle of respecting individual dose limits applies to the sum of controllable doses associated with the different practices that generate them (ICRP Publication 60). Disposal is one of the sources of exposure that results from these practices. With regard to the dose limit, ICRP Publications 77 and 81 acknowledge that in the case of radioactive waste disposal, the application of dose limits for long-term safety has intrinsic difficulties. First of all, other possible sources of exposure are unknown. Secondly, deferred impact means that the concept of controllable dose cannot be used. Furthermore, the reason for using dose limits is to ensure that the individual has not received an unacceptable dose; this type of verification a posteriori cannot be carried out in the distant future. In conclusion, ICRP Publication 81 states that the application of the principle of dose limits to the disposal of radioactive waste is not appropriate inasmuch as the principle of optimisation of radiological protection is correctly applied.

3- Optimisation is an essential principle for judging whether the radiological risk presented by a repository is acceptable (ICRP Publication 81, Section 82). The level of the individual dose, the number of individuals exposed, the likelihood of the resulting exposures where these are not certain to be received should be kept as low as reasonably possible taking social and economic factors into account. The principle of optimisation can be applied to all the stages of the project and from the site selection stage in particular. The optimisation process can be deemed to have been achieved if (i) reasonable efforts have been made to limit future exposure at levels that are as low as reasonably possible and to reduce the probability of exposure occurring and if (ii) best practices (sound engineering, quality management and safety culture) were used throughout all stages of development of the programme.

The ICRP issued guidelines in 1990 in ICRP Publication 60 on radiological protection and the limitation of the exposure of members of the public in particular. These guidelines were included in EURATOM Council Directive 96/29 [ref.13]. According to these texts, the effective dose limit for members of the public is set at 1 mSv/year. In order to take account of the possible existence of multiple sources, the doses resulting from a disposal facility must be reduced to a fraction of this limit. The ICRP recommends the maximum dose constraint of 0.3 mSv/year or its risk equivalent of around 10^{-5}/year for natural processes

7 Primary Safety Functions of the Disposal System

The primary safety functions of the disposal system (cf. Chapter 3) are established by the implementer during the design of the disposal system. Subsequently, this allows the implementer to optimise its design in terms of long-term safety through the successive iterations of its safety case. The optimisation of the design can be reinforced by taking into account the characteristics of the environment of the disposal system (cf. Chapter 7) in the safety case. The primary safety functions of the disposal system are identified as the functions of "isolation", "containment" and "limitation and retardation".

During the development of the safety case the iterative process that associates the safety functions to the various components of the disposal system is conditioned by the implementation of the principles defined in Chapters 5 and 6, and by the integration of external constraints imposed on the programme. The application of safety principles (Chapter 5), in particular through the concept of robustness, is one of the driving forces of the iterative process for the association of the safety functions to the components of the system.

In addition to the functions defined above and depending on the design, sub-functions (for example mechanical strength, water tightness, etc.) should also be defined. Because they are design dependent, they are not detailed in this document. In the rest of the document, the term "safety function" will be used in place of the full expression "primary safety function".

Examples of the application of safety functions can be found in Appendix 2.

7.1 Disposal System Safety Functions

This section identifies the main safety functions of the system as a whole with respect to external elements (external functional analysis). The functions considered here result from the chosen management strategy of "concentration and containment".

7.1.1 "Isolation" Function

One of the functions of the disposal system is the long-term isolation of waste from man and the biosphere, in other words, the prevention of direct access to the waste. Disposing the waste in deep geological layers will make this function possible. The disposal system and its environment contribute jointly to this function.

7.1.2 "Containment" Function

Consistent with the strategy of "concentration and containment", another safety function identified for the disposal system is that of the containment of the radionuclides. Containment implies the prevention, as far as possible, of any release of radionuclides from the repository or any part of the disposal system. The containment function cannot, however, be guaranteed over the whole period during which the contents of the repository are considered to present a radiological risk.

7.1.3 Function of “Limitation and Retardation”

In the event of the partial or total failure of the containment function, a function is required that will retard and limit the flux of radionuclides in all parts of the disposal system. The purpose of this function is to attenuate the flux of radionuclides that passes through the disposal system up to the boundaries of the system itself, either by taking advantage of radioactive decay during migration of the radionuclides in the system or by spreading the radionuclide flux over time. The scope of the "limitation and retardation" function depends on the type of radionuclide and the performance characteristics of the components through which they migrate.

7.2 Role of the Disposal System’s Environment

The radiological impact depends on the properties of the disposal system and its environment. The role of the disposal system’s environment is distinguished from the safety functions linked to the disposal system itself by the fact that the environment capacity to reduce the peak flux of the radionuclides is not optimised during the design of the disposal system for two main reasons. First, the objective of the implementer must be coherent with the strategy of "concentration and containment", which makes it essential to design a system that will limit the activity that may reach the biosphere. Second, the characteristics of the disposal system environment, and therefore its role, are an indirect consequence of the site selection process; as such this role is considered to be imposed and cannot be optimised.

The role of the disposal system’s environment can be characterised by its properties of dilution and dispersion. These environmental properties do not correspond to a primary site selection criterion.

7.3 Possible States of the Safety Functions

The interpretation of the results of the safety assessments from the safety function point of view leads to the following conclusions: the safety functions do not all participate at one and the same time in the safety of the disposal system. So, various possible states of safety functions can be considered depending on whether they participate actively or latently in safety, or whether they are considered not to be an effective part of the safety case (reserve safety function).

A "latent safety function" can be defined as a function that becomes partially or totally active only when other safety functions do not or no longer achieve the expected performances.

A "reserve safety function" is a function that, at a given time, is not sufficiently well characterised to be fully relied upon in the safety case, but whose existence contributes to confidence in the overall safety of the repository.

7.4 Roles of the Functions in the Disposal System Development Process

In the disposal system development process, the implementer shall as far as possible ensure that, by virtue of its/their physico-chemical and mechanical properties, the safety function-related component(s) can also provide protection for the components fulfilling other safety functions. The implementer will, as a minimum requirement, ensure that the implementation of a component does not negatively affect other component's safety functions.

Historically, repository designs did not rely on the concept of multiple safety functions but rather on the "multi-barriers" concept.

It is now recognised that the safety of a repository relies more on concepts of the complementarity and redundancy of functions, than on the concept of the redundancy of barriers. These concepts are explained in Chapter 5 "Safety Principles".

Each component of the repository can contribute to fulfilling one or more safety functions with a certain level of performance for each one. The assigning of these functions to different components depends on the choices made by the implementer, the phenomenological knowledge available and the understanding of the functioning of the overall disposal system. Functions are defined in terms of well-known phenomena or characteristics and operate over long periods of time. A component can, at a given time, fulfil a latent safety function, then go on for a certain period of time to fulfil an active safety function and finally reach a point where this is no longer fulfilled. All of the functions together must at all times ensure the protection of man and the environment.

The a posteriori understanding of the disposal system's functioning has made it possible to identify the safety functions as defined above. They have become, on the one hand, a communication tool to describe more easily and succinctly the overall functioning of the disposal system over time. On the other hand, they allow the implementer to analyse the functioning of the disposal system in a more systematic manner.

In the framework of the iterative design approach and in the more advanced stages of the programme, the safety functions could be used in advance for the revision and optimisation of the designs studied.

8 Judgement of Acceptability

Judging the acceptability of a safety case depends, among other things, on the evaluation of the radiological impact and risk that the waste will create in the long-term. The radiological impact is judged on the basis of compliance with the fundamental objective of protection. "Conventional" indicators to quantify the radiological impact are effective dose rate and radiological risk. Therefore, whilst acknowledging these indicators' potential weaknesses and emphasising their strengths, the focus in this chapter is mainly on their use for judging a geological repository's compliance with respect to its radiological impact.

The protection of future generations and their environment from the waste, calls for the implementation of passive systems, in other words systems for which the functioning does not require any scheduled human intervention. Interventions intended to reduce the radiological exposure or to retrieve radioactive material cannot therefore be taken into account in the safety assessments after the final closure of the repository.

For current or envisaged practices, the system of radiological protection (cf. Chapter 6) recommended by the ICRP (see ICRP Publication 60 [ref. 11]) is based on three general principles: the justification of the practice; the limitation of individual doses; and the optimisation of radiological protection (see Chapter 6). This protection system has been adopted in the EURATOM Directive 96/29 [ref. 13].

The optimisation procedure (ICRP Publication 60, paragraphs 112, 121) is generally applied to the total radiological impact but it is limited by an individual dose - a dose constraint –, or an individual risk - a risk constraint - in the case of potential exposure and relies on judgements.

8.1 Bases for the Long-Term Radiological Impact Assessment

The evaluation of the radiological impact of a radioactive waste repository requires the consideration of various exposure scenarios. Usually, the evaluation of radiological impact is based on the identification of a representative critical group and on the evaluation of the individual dose received by a member of this critical group. For safety in the post-closure phase, the impact to be evaluated is associated with potential releases in the distant future. When considering such time periods, the characteristics of the biosphere and the critical group (in particular its eating habits and lifestyle) can only be hypothetical. So, a stylised approach as it has been considered in the BIOMASS project [ref. 15] becomes the most appropriate. It is based on:

- The definition of a reference biosphere,

- The definition of a critical group on the basis of reasonably conservative assumptions,
- An estimate of the effective annual dose received by an individual of the representative critical group using a modelling approach appropriate for these assumptions.

In view of the time scales and the various possible evolutions of the disposal system and its environment, the dose calculated as part of the impact assessment cannot be considered a prediction of future health consequences but only an indicator of the impact associated with a set of particular hypotheses used for the purposes of the evaluation. The value of the information provided by this dose indicator is related to these hypotheses and may vary significantly in accordance with the time scale and the scenario considered, and also depending on the confidence that can be placed in its evaluation. In particular, for some scenarios, it is possible that the evaluation of the impact will consider highly stylised and pessimistic hypotheses on account of the lack of knowledge.

The consideration of uncertainties is a central element of a safety case. It can be undertaken, among other ways, by the use of conventional deterministic or probabilistic uncertainty evaluation tools.

8.2 Bases for the Judgement of Acceptability of the Impact Assessment Results

In accordance with the application of the principle of optimisation, the evaluation of conformity with radiological protection objectives cannot be reduced to a simple comparison of the calculated doses or risks with the dose or risk constraints.

This evaluation of conformity with the basic objective of protection is the result of a process that is based on a judgement and in which the calculated doses or risks are one of the elements to be taken into account in the same way as the following aspects.

- The likelihood of the scenarios and the hypotheses leading to the calculated consequences,
- The overall representativeness of the modelling (basic assumptions, relevance of the models, uncertainty of the parameters and the models),
- The part of the environment affected by the release of activity and the size of the population potentially exposed.

Aspects relating to the time and the duration of exposure are also to be taken into consideration on account of the uncertainties associated with different time scales.

From this perspective, it becomes very important that the impact assessment process makes it possible to analyse the various components of the impact easily and separately. In this respect, the use of risk alone as an indicator combining the radiological consequences and the probabilities of the occurrence of events is insufficient. The separate presentation of the radiological consequences and the probability of occurrence is necessary as it contributes to the comprehension of the safety assessment in the context of a decision-making process.

The individual dose should be preferred to the collective dose (ICRP Publication 81, Paragraphs 26 and 53). Collective doses are not considered relevant in the context of the assessment of the long-term performance of a geological repository as they refer to unverifiable hypotheses concerning the evolution of the size of the populations in the future. A qualitative estimate of the sizes of the populations in question can, however, provide useful information to supplement the results presented in terms of individual doses.

In addition to the above points, best practices must be applied to the engineering, the management and the technical measures implemented (i.e., the application of the principle of defence-in-depth and the principle of demonstrability, quality assurance, training and the qualification of personnel, the flexible and prudent iterative approach) (ICRP Publication 81, Paragraphs 66, 67 [ref. 6] and IAEA Publication DS154 [ref. 8] Paragraph 5.5).

8.3 Application to the Different Types of Scenarios to be taken into Account

The foreseeable evolution of the repository can be represented by one or more reference evolution scenarios. The reference evolution scenarios correspond to the foreseeable evolution of the repository with respect to the most likely effects of certain or very probable events or phenomena. So-called altered evolution scenarios take into account the least likely effects of these events or phenomena and the consequences of events or phenomena that are not integrated into the reference scenario, as the likelihood of occurrence is lower.

The degree of importance that is attached to the calculated dose when judging the acceptability of the impact assessment findings depends on the characteristics of the scenarios considered.

The following approach is recommended:

- As far as the reference evolution scenario(s) is/are concerned, the criterion used is compliance with the dose constraint of 0.3 mSv/yr. In all events, arguments must be set forth to show that uncertainties have been identified and taken into account.

- Where altered evolution scenarios are concerned, the acceptability of the consequences calculated must be appraised on a case by case basis depending on the bounding property of the scenario taken into account, the likelihood of the events and phenomena that are described therein occurring, the degree of conservatism in the hypotheses used in the study, and the level, extent and duration of contamination. The impact calculated can be compared to different references among which the value 0.3 mSv/yr may be considered, without this comparison constituting an absolute acceptance criterion. When the likelihood of occurrence can be evaluated, compliance with a risk constraint can be taken into account as an additional criterion for judging the acceptability of these scenarios. The value of 10^{-5} per year is recommended internationally for the risk constraint.

Some scenarios cannot be considered reference or altered evolution scenarios; these are as follows:

- So called "beyond design limit" scenarios, which, by definition, cannot be used for the repository design. The scenarios that are the result of very unlikely events, for which it appears that it is not reasonably possible to thwart the occurrence or the consequences are classified as a result of an assessment process, as beyond design limit. A safety case (cf. Chap. 3) must contain the justifications relating to the classification of the scenario as being "beyond design limit",

- Imposed or conventional scenarios that are also know as "What if" scenarios for which the occurrence of an event or random phenomenon is postulated although it seems possible to exclude it through design or the level of knowledge available. These scenarios are used mainly for assessing the relative importance of the components of the disposal system for the safety and robustness of the system,

- For scenarios relating to human intrusion, the only ones to be taken into account relate to inadvertent intrusion, most often associated with a loss of memory of the existence of the repository. The incorporation of these scenarios reflects a certain arbitrariness inasmuch as all future human activities that are liable to lead to such intrusions cannot be known or even presupposed. For such scenarios to be analysed, the hypothesis is adopted that the level of technology is the same as it is at the present day. Among the scenarios postulated, taking the regional context into account, are drilling for water, exploratory drilling with the extraction of cores, the operation of a mine near the repository or direct physical human intrusion into the disposal facility. So the consequences are of two different types:
    - 1) Immediate consequences for the intruders when he is in the vicinity of the waste,
    - 2) Deferred consequences associated mainly with the transfer by water in a configuration where one part of the containment barriers has been bypassed and leads to consequences in terms of effective dose for the individuals of the critical group.

  In the first case, the scenario developed is similar to the "beyond design limit" scenarios, that is to say that the doses received could be a priori high and would be difficult to reduce through modification of the design of the repository. These high consequences are closely linked to the strategy of "concentration and containment" selected and comparison of the dose rate received by the intruder with a regulatory limit is not pertinent. One of the acceptance criteria is to minimize the likelihood of the occurrence of such an intrusion by selecting a site that is not rich in natural resources or by means of markers. The depth of the disposal facility is also of primary importance in reducing the likelihood of intrusion.

In the second case, the situation described is comparable to that of an altered evolution scenario leading in all probability to a limited disturbance of the repository. The release of activity should only affect a fraction of the repository and the radiological consequences are assessed in the general framework of the altered evolution scenarios (cf. above). The design must be optimised as far as possible to reduce the consequences associated with this means of transfer relating to an intrusion scenario.

In any event, the objective is to confine the radionuclides for as long as possible. However, beyond a certain period of time, depending essentially on the geological context, the uncertainties are such that the evolution of the disposal system cannot be reasonably foreseen. It is, however, recommended that the system, including the site, be designed and sized so that the evolution of the system can be assessed over a period of time in accordance with radioactive decay deemed sufficient for the radionuclides of the inventory.

A posteriori, after each iteration of the safety case, the classification of each scenario in the aforementioned classes must be reviewed and justified.

8.4 Safety Indicators and Time Scales

Dose is and remains a relevant indicator for the safety assessment. This indicator, which integrates all forms of exposure, is used to assess the direct impact on man. It seems to be well understood and established and internationally agreed upon.

The risk indicator can supplement the dose indicator, for altered evolution scenarios in particular, to the extent that it makes it possible to integrate the probability of the scenarios occurring.

In the medium and long term, dose assessment may be restricted by uncertainties relating to climatic evolution, the evolution of the biosphere and the evolution of the behaviour of individuals and critical groups. Some of these uncertainties may be managed by the use of additional indicators. These should be considered to be complementary tools to aid decision making and to build confidence in the safety assessment. In particular, the activity fluxes from the various barriers of the repository and the radionuclide concentration in the water or in the soil are examples of indicators.

Results of impact calculations for periods of up to several million years after closure of the repository must be considered differently from those relating to the first few thousand years because of increased uncertainty The assumptions made for calculating out over long periods of time become less reliable and, in general, confidence in the results decreases. As an example, the predictability of the geological evolution decreases significantly after the geological stability phase. The appropriate determination of the stability periods (geologic, climatic) and their justifications thereof constitute important elements in judging the acceptability of the site as they provide input to the assessment of the reliability of the geosphere modelling hypotheses and the associated results. Depending on the site, the period of geological stability varies from several thousands of years to several million years. However, whatever the period of geological stability, as a minimum requirement, the safety assessment must be carried out up to a date corresponding to a significant radiotoxicity decay of the waste.

The relevance of the indicators evolves with time. A period of relevance in time can be defined for each indicator. Through a combination of and judicious choice of indicators, it is therefore possible to cover all stages of the life of a repository by associating the appropriate indicator (or indicators) with each stage.

The development of specific arguments for certain periods of time reinforces the relevance of the indicators associated with these periods.

In order to do this, a preliminary agreement is desirable between the implementer and the regulatory authority on the values of comparisons and the associated methodology for the use of safety indicators other than dose or risk in the context of a safety case [ref. 10]. The same is true for the adoption of stylised scenarios. The latter make it possible to better manage the existence of so-called irreducible uncertainties.

9 Conclusions

This document has made it possible to align and structure the positions taken by the Belgian and French operators and regulators on the safety approach of a geological radioactive waste repository and on its constitutive elements: the principles of safety and radiological protection, the safety functions, the safety case and the base of the judgement of acceptability of the radiological impact assessment. Structuring these elements in this document becomes really an added value to the international recommendations of the IAEA and the IRPC.

The acknowledgment of the defence in depth and the demonstrability as safety principles constitutes a major asset of the document. In the proposed safety approach, these two principles integrate and link together a large number of concepts encountered in literature, such as the robustness, the multiple safety functions, the simplicity and the passivity of the disposal system. Their practical application in the case of deep disposal is described in this document.

The elements of the safety approach presented in this document underline the importance of the qualitative argumentation of a safety case for geological disposal. The key role of the safety principles and functions, as well as the importance of a qualitative judgement of the acceptability of the radiological impact, in addition to its quantitative assessment, is particularly worth mentioning.

The schematic presentation of a structured safety approach makes it possible to better explain and communicate the global safety reasoning to different discussion partners. The relatively simple scheme and the limited number of structuring elements are assets of communication and consultation.

This document has been drawn up without referring to a specific type of geological formation although clay constitutes the geological reference formation, both in Belgium and in France. In this respect, the generic character of this safety approach should be confirmed by checking that this approach is also applicable to other types of geological formation. The reasoning that went into this text indicated in particular that this approach should be tested on concrete cases within the scope of a disposal programme, in order to specify the notions developed and obtain a practical and transparent method of supporting the judgement of acceptability. To this end, the approach will be presented and subjected to discussion in a multilateral framework.

10 References

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Appendix 1 Comparison with International Reference Documents

Many of the concepts used in this document are found in international reference documents. However, it appears that the meaning given to some of the concepts may have evolved. In addition, it is worth identifying the contribution that this document represents in terms of the current considerations. Two documents are viewed as being representative of the most successful considerations to date. These are the ICRP guidelines (Publication No. 81) and the "IAEA Safety Standards" referenced DS154 entitled "Geological Disposal of Radioactive Waste" version dated October 2003.

The excellent agreement with the generally accepted concepts used and the synergy obtained by integrating these concepts in a common vision justifies the practical potential of the approach proposed.

- Safety Principles

There is no particular difference between the "Safety Approach" text (i.e. this document) and international texts. The terminology may vary but the same basic concepts are present. For example, the definition of the basic objective of protection corresponds to the principals of radioactive waste management in the document. The principle of the multiple safety function is mentioned in DS154, which does not, however, explicitly mention the principle of defence-in-depth. The principle of demonstrability is mentioned albeit more diffusely in DS154 than in this document. Similar observations can be made for the concurrence between ICRP Publication 81, which explicitly refers to the concept of defence-in-depth. As in DS154, the concept of the principle of demonstrability is more implicit than explicit.

- With respect to "beyond design limit" scenarios,

The concept of “beyond design limit" scenarios is not covered explicitly in either ICRP Publication 81 or DS154. DS154 refers to "events that have the capacity to significantly rupture a repository in a geological formation. For these events, "what if" calculations can be done and precautions can be built into the design so that if such an event were to occur, it would not lead to an overall loss of the safety functions and in this case only a limited part of the disposal facility would be affected." (DS 154, page 12, § 3.16). This last recommendation differs from the treatment proposed for the "beyond design limit" scenarios covered in this document. In this "safety approach" document, these events are characterised by the very low likelihood of their occurring and no evaluation is recommended. On the other hand, acknowledgement of a scenario as "beyond design limit" implies that a preliminary justification must be submitted and approved before the analysis file is compiled.

- Safety Function

The safety functions "limitation and retardation" are not identical to the safety functions "isolation" and "confinement" mentioned in DS154. Recognition of the importance of these functions in the current document makes it possible to take advantage of their optimisation role in the design process.

With respect to the text of "Requirement 7" of DS154, this documents makes a clear distinction between safety functions and the role of the environment.

Appendix 2 Examples of the Application of Safety Functions

Two examples from French and Belgian concepts illustrate the concepts of safety functions, as well as the evolution of their state.

2.1 Andra "HAVL Clay" Project

The following functions are taken from the functional analysis carried out in 2001 by the Andra "HAVL Clay" project. Strictly speaking, it concerns sub-functions chosen because they illustrate simply the generic safety function concept.

The “containment” function can be provided by the engineering around the packages (engineered barrier and cavity plug) and/or by the overpacks of the vitrified waste packages. It is then possible to reason as follows:

- During the first period of time in which structures are not re-saturated, and, consequently, in which the water has still not reached the level of the overpack, the latter is not subject to the function "delaying the arrival of water in contact with the vitrified matrix". During this first period in time, the function "delaying the arrival of water in contact with the vitrified matrix" associated with the overpack is described as **latent**: in other words, although it is potentially possible, the function is not actually used during this period.
- Once the structures are saturated, this function must be provided by the overpack; so it becomes effective for the whole duration of the thermal peak (this function should make it possible to prevent any release of radionuclides in solution while the temperature in contact with the glass exceeds a certain level).
- After several hundred to several thousand years, the overpacks are partially or totally corroded and no longer provide their function of "delaying the arrival of water in contact with the vitrified matrix". Others safety functions then become effective. When the overpack is still leak tight after the thermal peak, this function is then available in reserve.

The main components of the disposal system can provide several functions or sub-functions simultaneously or successively. In the latter case, the example of the seals can be considered; in order to "delay the arrival of water in contact with the waste" one of the necessary functions is that of "isolating the disposal modules from water from overlying geological formations". This function is provided, in particular, by the different seals installed between the packages and the aquifers. Once the overpacks have become corroded and the alteration of waste has begun, these seals contribute to "retarding and limiting the transfer of radionuclides in the disposal system".

2.2 ONDRAF/NIRAS Safety and Feasibility Interim Report 2 (SAFIR 2)

Figure 2 is taken from the ONDRAF/NIRAS SAFIR 2 report. It illustrates the evolution of safety function states over time.

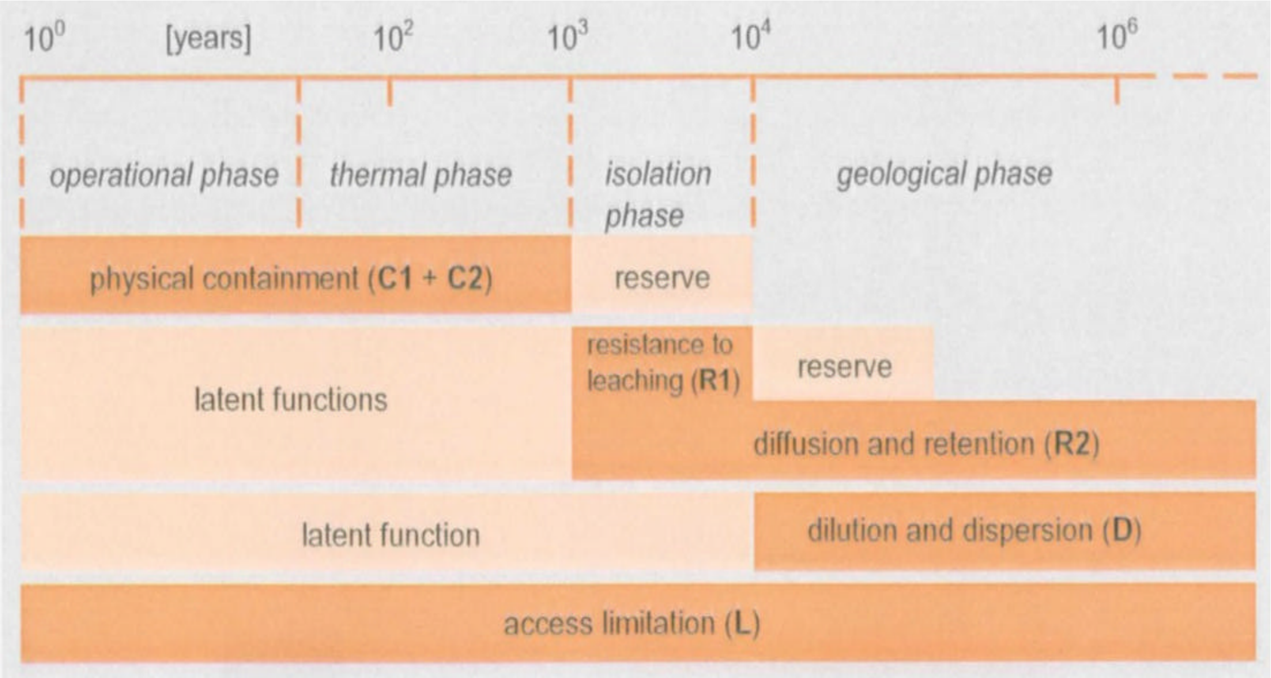

Figure 2 Illustration of the Active, Latent and Reserve States.

The symbols "C1" and "C2" refer to the safety function of the containment. Symbols "R1" and "R2" refer to the "Limitation and Retardation" safety function. The symbol "L" refers to the "Isolation" safety function. The symbol "D" represents the role assigned to the environment of the disposal system. Chapter 2.2.1 of Reference 4 from which the figure is taken gives further information on safety functions.

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