Development of Safety and Performance Indicators

OPERA-PU-NRG7311

Radioactive substances and ionizing radiation are used in medicine, industry, agriculture, research, education and electricity production. This generates radioactive waste. In the Netherlands, this waste is collected, treated and stored by COVRA (Centrale Organisatie Voor Radioactief Afval). After interim storage for a period of at least 100 years radioactive waste is intended for disposal. There is a world-wide scientific and technical consensus that geological disposal represents the safest long-term option for radioactive waste.
Geological disposal is emplacement of radioactive waste in deep underground formations. The goal of geological disposal is long-term isolation of radioactive waste from our living environment in order to avoid exposure of future generations to ionising radiation from the waste. OPERA (OnderzoeksProgramma Eindberging Radioactief Afval) is the Dutch research programme on geological disposal of radioactive waste.
Within OPERA, researchers of different organisations in different areas of expertise will cooperate on the initial, conditional Safety Cases for the host rocks Boom Clay and Zechstein rock salt. As the radioactive waste disposal process in the Netherlands is at an early, conceptual phase and the previous research programme has ended more than a decade ago, in OPERA a first preliminary or initial safety case will be developed to structure the research necessary for the eventual development of a repository in the Netherlands. The safety case is conditional since only the long-term safety of a generic repository will be assessed. OPERA is financed by the Dutch Ministry of Economic Affairs, Agriculture and Innovation and the public limited liability company Electriciteits-Produktiemaatschappij Zuid-Nederland (EPZ) and coordinated by COVRA. Further details on OPERA and its outcomes can be accessed at www.covra.nl.

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Title: Development of Safety and Performance Indicators
Authors: E. Rosca-Bocancea, and T.J. Schröder
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Summary

This report presents an overview of safety and performance indicators and their use for communicating the outcome of assessments on the long-term safety of radioactive waste disposal. The objective of this report is to propose a selection of safety and performance indicators for OPERA Safety Case. In order to do so, safety and performance indicators considered in previous European projects and research programmes were evaluated.

The selection of indicators for the OPERA Safety Case was carried out in two consecutive steps. Firstly, a list of criteria was defined on basis of IAEA and NEA recommendations and international projects. Secondly, potential indicators suitable for the Opera Safety Case were identified.
Based on the collected information a selection of indicators to be used for the OPERA Safety Case is proposed. The report concludes with an overview of the selected safety and performance indicators. The outcome forms the basis for further interaction with other OPERA Tasks. A more detailed description, including the mathematical formalism used, compartment definitions and graphical representation will be provided in a subsequent milestone report M7.3.2.

Samenvatting

Dit rapport geeft een overzicht van zgn. 'safety and performance indicators', die een belangrijke rol spelen in de communicatie van de resultaten van veiligheid evaluaties betreffende lange termijn veiligheid van het opbergen van radioactief afval in de diepe ondergrond. De doelstelling van dit rapport is om tot een voorstel voor 'safety and performance indicators' te komen, die binnen het OPERA programma toegepast kunnen worden. Hiervoor zijn voorgaande projecten op dit gebied geëvalueerd, en werden internationale aanbevelingen geraadpleegd.

De selectie van indicatoren voor de OPERA Safety Case is uitgevoerd in twee opeenvolgende stappen. In de eerste stap wordt een lijst van criteria gepresenteerd, gebaseerd op criteria voorgesteld in internationale projecten en in IAEA en NEA documenten. In de tweede stap zijn potentiele indicatoren voor de OPERA Safety Case geïdentificeerd.

Een samenvatting van de voorgestelde lijst van indicatoren voor de OPERA Safety Case is gegeven in hoofdstuk 5. Een gedetailleerdere beschrijving, inclusief wiskundig formalisme, definities van de compartimenten en een grafische presentatie is voorzien in M7.3.2.

1. Introduction

1.1. *Background*

The five-year research programme for the geological disposal of radioactive waste –OPERA- started on 7 July 2011 with an open invitation for research proposals. In these proposals, research was proposed for the tasks described in the OPERA Research Plan.

1.2. *Objectives*

The present report has been developed within task 7.3.1 'Safety and Performance Indicators calculation methodology' of the OPAP-I project. OPAP-I covers all six tasks of WP7 tendered in the 1st Call of the OPERA research programme and forms a consistent package that efficiently addresses the links between all tasks. The main outcome of the OPAP-I project will be a set of graphical representations of safety and performance indicators and their accompanying probability distributions, calculated for all scenarios. This list enables a statement on the long-term safety of a future disposal of radioactive waste in Boom Clay.
This report presents an overview of safety and performance indicators and their use in the assessment of long-term safety of radioactive waste disposal. The safety and performance indicators proposed in previous projects and research programmes were evaluated. Based on the results of this evaluation, a set of safety and performance indicators for the OPERA Safety Assessment is proposed.

1.3. *Realisation*

Next to international guidelines and recommendations [IAEA, 1994], [IAEA, 2003], [IAEA, 2006], [IAEA, 2013], [NEA, 2013], NRG has reviewed the indicators of the EC-funded projects *Testing of Safety and Performance Indicators* (*SPIN)* and *Performance Assessment Methodologies in Application to Guide the Development of the Safety Case* (*PAMINA),* the recent Nuclear Energy Agency's (NEA) project *Methods for Safety Assessment* (*MeSA)*, and information on the current Belgian approach provided by SCK·CEN. A preliminary list of safety and performance indicators suitable for the OPERA Safety Case is proposed and documented in the present report. The report will be provided as input to Task 1.2.2 to allow the ENGAGED project to evaluate to what extent the list addresses societal expectations. The report will also be discussed and iterated with Task 1.3.1 and Task 1.2.2 to gain a coherent list of indicators that fit consistently in the communication strategyA more technical report M7.3.1.2 will be prepared that works out the exact presentation of the indicators and describes the underlying calculation methods in detail in a way that it can serve as input for the integrated modelling environment developed in Task 7.2.4 and other tasks involved in the definition of modelling approaches.

1.4. *Explanation contents*

In Chapter 2, general concepts and terminology of safety and performance indicators for the assessment of long-term safety of radioactive waste disposal are summarized. Chapter 3 gives an overview of the safety and performance indicators considered in the project SPIN and the FP6 project PAMINA. Additionally, the indicators applied currently in the safety assessments of a disposal concept in Boom Clay in Belgium are summarized. In Chapter 4 the indicators are reviewed to evaluate their usefulness for the OPERA Safety Assessment. New indicators are proposed where necessary. A preliminary list of safety and performance indicators applicable for the OPERA Safety Assessment is summarized and briefly described in Chapter 5.

2. Types of indicators and terminology

2.1. General considerations

The concept of geological disposal of radioactive waste in deep geological formations is based on the multi-barrier concept and implies redundant safety functions for each of the individual barriers in order to compensate for the uncertainties in long-term performance. The most important task in the process of implementing such a disposal system is to assure the safety for man and environment.

Key to the safety assessment are the post-closure radiological impacts. This requires analysis of the long-term evolution of a disposal system and its components, quantification of the performance of the engineered barriers and evaluation of radiological dose and/or associated risk as end-points of the assessment. The calculated dose and/or risk are compared to regulatory defined limits in order to demonstrate the 'safety' of the system.

In the last years, NEA has promoted the concept of a safety case, where a safety case is a formal compilation of evidence, analyses and arguments that quantify and substantiate a claim that the repository will be safe [NEA 2013, p.12]. Within the concept of a safety case, an *indicator* is a characteristic or consequence of a disposal system that can be measured or calculated and eventually compared to rigid or more loosely defined measures or 'yardsticks' in order to formulate such arguments [IAEA, 2003, p. 5]. A number of related purposes for using indicators in a safety case have been identified [NEA, 2012, p.24]:

- supporting safety case structure and multiple lines of reasoning;
- increasing the transparency of safety case arguments;
- assessment of repository safety and presenting impacts in the content of the natural environment;
- assessment of sub-system performance;
- assessment of safety functions;
- scenario identification;
- addressing uncertainty and the assessment of repository safety in different timeframes; and
- helping with communication, especially to non-technical audiences.

Additional purposes for indicators in the wider scope of repository development programmes that have been identified [NEA, 2012, p.25]:

- supporting site selection;
- aiding selection of the repository design options and engineering optimisation; and
- repository monitoring and performance confirmation.

Several classification schemes for indicators exist. An important distinction is made between *primary* and *complementary* indicators [NEA, 2012]. A *primary indicator* is one that is compared to a legally or regulatory defined radiological constraint. All other indicators that are used in a safety case are referred to as *complementary indicators*. It is recommended that complementary indicators should feature in all safety cases. At the same time, it is important to give careful thought to choosing and applying those indicators. More specifically, the indicators should be consistent with [NEA, 2012, p.92]:

- the regulatory context;
- the assessment context;
- the assessment methodology;
- the stage in the repository development programmes; and
- the intended audiences for the safety case.

Regardless of the classification scheme adopted, it is important that indicators are clearly defined and described and are applied in a manner consistent with the assessment context and methodology [NEA, 2012, p.24]. The following list of 'desirable characteristics' of potential indicators is defined in [IAEA, 1994, p.9]:

- *reliable*: they should be based on well-established principles and be applicable over a wide range of situations;
- *relevant*: they should relate to the important safety and environmental features of the repository;
- *simple*: they should be simple and not overly complex otherwise they will be less used and take more time and effort to apply. Simple indicators can facilitate communication;
- *direct*: the indicators should be as closely linked to some primary system property as possible and should involve the minimum of computation for translating available information to the format of the indicator;
- *understandable*: users should know exactly what the indicators represent and how to determine its value. This links with the needs of simplicity and directness;
- *practical*: the data and the tools or models needed should be available and well based.

A general distinction that should be made is between *safety indicators* and *performance indicators,* following the recommendations of the IAEA made in 2003. Besides, some organisations define *safety function indicators* related to explicit safety functions of individual repository components. These safety function indicators can be considered as a special case and application of performance indicators.

Indicators can also be categorised, without implying any hierarchy, with respect to the character of the indicators and what they measure or illustrate. Most of the commonly used indicators fall into three main groups:

- *'content and concentration'* related indicators (radioactivity/toxicity concentration/abundance in wasteform, radioactivity/toxicity concentration/abundance in engineered barrier system, radioactivity/toxicity concentration/abundance in geosphere, radioactivity/toxicity concentration/abundance in biosphere, power density in groundwater);
- *'flux'* related indicators (radioactivity/toxicity flux from the engineered barriers to the geosphere, radioactivity/toxicity flux from the geosphere to biosphere, integrated radioactivity/toxicity flux from geosphere to biosphere over time, radionuclide molar flow);
- *'status of barriers'* related indicators (groundwater age, container lifetime, transport times through the engineered barrier system components and the biosphere, state of stress in the near-field rock, swelling pressure in buffer and backfill, ionic strength in geosphere groundwater).

These groups can be related to the main compartments in a typical repository concept as illustrated in Fig. 2-1.

	Compartment			
Indicator Type	Wasteform	Engineered barriers	Geosphere	Biosphere
Concentration and content indicators	✓	✓	✓	✓
Flux indicators	→	→	→	
Status of barrier indicators	✓	✓	✓	

Figure 2-1 An alternative approach to classifying indicators [NEA, 1012, p. 33]

An additional group of performance indicators refers to specific THMC properties of the engineered and natural barriers. Examples of this type of performance indicators are:

- temperature at different locations in the EBS and near-field host rock;
- porewater pressure at different locations;
- fractures in near-field host rock;
- clay composition of (e.g. montmorillonite or illite) host rock;
- ground level;
- etc.

This indicator group relates to the 'status of barriers' related indicators.
In the next sections, the different types of indicators are discussed in more detail.

2.2. *Performance indicators*

In [IAEA, 2003, p.3] the following definition of performance indicators has been introduced:

> *"A performance indicator provides measures of performance to support the development of system understanding and to assess the quality, reliability or effectiveness of a disposal system as a whole or of particular aspects or components of a disposal system."*

The EC's PAMINA project built on the outcome of the SPIN project recommended slightly different definition of the term [Becker et al., 2009, p.10]:

> *"A performance indicator is a quantity, calculable by means of appropriate models, that provides a measure for the performance of a system component, several components or the whole system."*

Because performance indicators provide a measure of the behaviour of an individual repository component or sub-system, they are usually more concept or site-specific than safety indicators. Performance indicators may be compared with independent quantities, known as indicator criteria, although these are not essential for their application and often, no meaningful indicator criteria may be available for comparison with a performance indicator. Where these are available, indicator criteria may be derived from independent modelling, laboratory studies or, occasionally, natural analogue studies (e.g. to provide a measure of long-term metal corrosion rates) [NEA, 2012, p.5].

Performance indicators can be divided into groups based of their nature and the information they provide. Each group of indicators can be applied to one or more relevant compartments of a repository concept. It should be noted that these groups are not independent if the status of one of the barriers could have a significant impact on the flux of radionuclides across it and, consequently, the content of radionuclides in the compartments on either side. As consequence, a certain redundancy in information exists

2.3. *Safety indicators*

In [IAEA, 2003, p.3] following definition of a safety indicator has been introduced:

> *"A safety indicator, which may be regarded as a special type of performance indicator, is used to assess calculated performance in terms of overall safety."*

A slightly different definition of the safety indicators was used in the EC project PAMINA [Becker et al., 2009, p.9]:

> *"A safety indicator is a quantity, calculable by means of suitable models, that provides a measure for the total system performance with respect to a specific safety aspect, in comparison with a reference value quantifying a global or local level that can be proven, or is at least commonly considered, to be safe."*

Following types of safety indicators are identified:

- *'dose-rate'* related indicators (individual dose rate, collective dose rate, dose rate to animals and plants);
- *'risk'* related indicators (individual risk, societal risk);
- *'concentration'* related indicators (concentration in groundwater, concentration in biosphere water, concentration in soil, concentration in air);
- *'flux'* related indicators (radiotoxicity release).

The safety indicators must be compared with independent quantities, known as *reference values*, which represent some minimum measure of safety that is generally considered to be acceptable [NEA, 2012, p. 12].

A widely used and generally accepted safety indicator is the 'effective dose rate', and is often considered as the *basic safety indicator*. With respect to the above characteristics, it was recognized in [IAEA, 1994, p.10], that a single indicator cannot be expected to meet all of these desirable characteristics. It was suggested in [IAEA, 1994, p.7] that dose related indicators should be supplemented by 'intermediate quantities' which rely less on assumptions about future conditions. These indicators are considered useful if they can be compared to some known data based on natural processes.

However, the derivation of appropriate reference values is identified as one of the major difficulties in the use of safety indicators [Becker et al., 2002], [Becker et al., 2009], [NEA, 2012]. There is only a limited number of universally applicable reference values that may be used in all safety cases. In most cases site-specific reference data are used, because these provide the most relevant situational context. The derivation of reference values for the safety indicators in OPERA Safety Case is performed within OPERA Task 1.2.2 (ENGAGED), however, as will be discussed in Ch. 4, the ability to derive meaningful and generally accepted reference values is an important consideration in selecting safety indicators.

2.4. Safety Function Indicators

In some national disposal concepts, as well as in the OPERA Research Plan [Verhoef et al.,2011], safety functions are defined that can be attributed to individual repository components. In [NEA, 2012, p.5], it is mentioned that some organisations define a set of indicators that can be related to these safety functions. These indicators are called *Safety function indicators* or *Performance indicators based on safety functions*. These are measurable or calculable properties that indicate the extent to which the system components achieve their safety function. Safety function indicators are usually compared with indicator criteria which define the quantitative limits (maximum or minimum conditions) that are the boundary conditions under which the matching safety function may be maintained. These are generally derived from independent studies.

2.5. Reference values and indicator criteria

In order to evaluate the safety relevant aspects of a repository system and to judge whether these aspects have been met, it is often useful to compare the indicators to appropriate 'yardsticks'. Such a yardstick may:

- provide a direct test of the ability of the overall system, or a system component;
- relate to a property that a system component should fulfil in order either to be effective itself as a barrier; or
- provide a suitable environment for the operation of other parts of the system [IAEA, 2003].

In [NEA 2012, p. 77-78] three different types of yardsticks have been identified, consistent with the definitions of safety indicators, performance indicators and safety function indicators:

- *Reference values* must be used in combination with a safety indicator, and they are comparative values used to establish the acceptable level of impact for their corresponding indicators. To evaluate the calculated results for safety indicators, the results of a safety assessment must be compared with established reference values that indicate an adequate and acceptable level of safety. If a safety indicator is below the corresponding reference value, it can be stated that the repository is 'safe' with regard to the particular safety aspect being considered. Without a reference value, safety cannot be judged and, therefore, a reference value is a requirement when using safety indicators. Most complementary safety indicators and their reference values generally have no formal regulatory character and so may be defined by the safety assessor, although there are a few examples when they are specified by regulators.
- *Indicator criteria* are used in combination with performance indicators, although there is no requirement to have a criterion for each performance indicator. Performance indicators comprise a great variety of different types of indicators. For some performance indicators, relative comparisons may be of value, for example the same performance indicator may be calculated for alternative design options, to allow their comparative performance to be evaluated and compared. Such comparisons can lead to enhanced system understanding without defining any yardsticks and are often used in performance assessment during the phase of concept development and model setup. Less often, performance indicators may be used to present the results of calculations for specific scenarios for established designs and systems, such as the fluxes or concentrations outside of the engineered barriers. For this purpose, comparisons with yardsticks are more illustrative. Some performance indicators are defined by a ratio, e.g. the ratio of transport time of a radionuclide to its half-life or the ratio of the rate of advection of a radionuclide to its rate of diffusion or Péclet number, For this particular form of performance indicator, the yardstick is an implicit part of the definition.

  Safety function indicator criteria are used in combination with safety function indicators. These criteria define the quantitative limits (maximum or minimum conditions) that are the boundary conditions under which the matching safety function may be maintained, and will generally be derived from independent studies.

With respect to the use of yardsticks, it can be concluded that with respect to safety indicators, reference values are an intrinsic part of a safety indicator (see definition in the previous section). Note that the definition of suitable reference values is not part of this project, but Task 1.2.2 (project ENGAGED). For the performance indicators, it can be concluded, that criteria are not compulsory, and although considered beneficial in general, currently such criteria are not available (see also next chapters).

2.6. *Treatment of timescales*

In order to address uncertainty in the value of the safety indicators, it was proposed to distinguish between three timescales [IAEA,1994, p.18]:

- closure - 10^4 years
- 10^4 - 10^6 years
- beyond 10^6 years

with the demarcation times of 10^4 and 10^6 years only indicatively.

For the first period, it is recognized that information about the repository is expected to be kept at least several hundreds of years after closure. In tectonically stable areas, significant natural changes in the geological environment are unlikely within the first 10000 years. The biosphere can be assumed to be comparable to present day conditions (i.e in the form in which it has been shaped by man since the introduction of agriculture 10000 years ago), and it “does not seem unreasonable to suppose that there will be an interest in maintaining conditions close to the present ones, i.e. favourable to agriculture” [IAEA 1994, p.18]. Although considerable uncertainty may exist during this time period, it is assumed to be reasonable to make quantitative estimates for the indicators to be used in that period, e.g. dose rate, by defining ranges of biosphere conditions and emphasize that such calculation results are not accurate predictions of future repository performance but general indications.

In the time frame of 10^4 to 10^6 years, long term natural changes in climate will occur with glacial or periglacial conditions present for a substantial portion of the time. The impacts of these natural phenomena, e.g. a sea level could drop by up to 140 m, can be evaluated by generic modelling of processes on continental scale. In general, major tectonic changes are not expected during this time frame, thus no large impact on the general transport routes form radionuclides from deep geological repositories is expected. On the other hand, possible biospheric conditions and human behaviour might be changed too much to allow reliable modelling of biospheric transport, uptake and exposure. However, calculations can be performed assuming present conditions for illustration, with indicative dose rates.

Beyond 1 million years, uncertainty increases, and beyond 10 million years, unpredictable large scale changes take place, e.g., mountain building, continental drift, and massive erosion. It is concluded that little credibility can be attached to assessments beyond 10^6 years.

3. Evaluation of indicators

In this chapter, the indicators considered in the projects SPIN and PAMINA are discussed. Furthermore, a summary is provided on the indicators applied in the Belgian programme.

3.1. *Indicators considered in SPIN*

The objective of the *Testing of Safety and Performance Indicators* (SPIN) project was to identify suitable safety and performance indicators and to test them on different performance assessment studies in order to show their applicability and to identify their specific advantages and disadvantages in practical use, leading to a general assessment of all tested indicators. Assessment criteria have been defined to allow a systematic assessment. For each indicator a conclusion was drawn concerning its possible use in future safety cases.

The SPIN project identified and tested seven safety and fourteen performance indicators. The safety indicators have been mainly identified by evaluating the open literature whereas the performance indicators have been identified through systematic approaches. The indicators have been tested by re-calculating existing performance assessments of disposal systems for high level waste in crystalline formations in Spain, Germany, Finland and Switzerland. The results have been compared and assessed in view of the general applicability of the specific indicators

One of the objectives of the SPIN project was also to develop indicative reference values for the safety indicators being tested. The reference data have been taken from literature and from documents made available by project participants and from the IAEA Coordinated research Programme '*The use of selected safety indicators in the assessment of radioactive waste disposal*'. These data have been used to develop indicative reference values[a] for the safety indicators. The reference values were based on a limited set of data and therefore, no statistical analysis of the data was possible [Becker at al., 2002, p. 33].

Safety indicators

Seven safety indicators as given in Table 3-1 have been selected.

Table 3-1 Safety indicators selected for the SPIN project [Becker et al., 2002, p. 43-47]

Safety indicator name	***Unit***
Effective dose rate	Sv/a
Radiotoxicity concentration in biosphere water	Sv/m^3
Radiotoxicity flux from geosphere	Sv/a
Time-integrated radiotoxicity flux from geosphere	Sv
Radiotoxicity outside geosphere	Sv
Relative activity concentration in biosphere water	-
Relative activity flux from geosphere	-

All safety indicators selected for use in the SPIN project had to meet a number of requirements. The requirements were deduced from the definition of the indicators and are presented in Table 3-2. Based on the results of the first assessment, a second assessment scheme has been applied, which considered all the advantages and disadvantages of each of the indicators. On this basis, the usefulness of each indicator was assessed and its most appropriate use was determined.

[a] The derived reference values for the safety indicators were only intended for use as indicative values in SPIN.

Table 3-2 Requirements and assessment criteria used in selection of safety indicators [Becker et al., 2002, p. 74].

Categories	*Requirements and Criteria*
Basic requirements	• provide a measure of the safety of the whole system, • safety-relevant reference values available, • safety relevant weighting scheme available, • calculable using performance assessment models,
Assessment criteria	• easy to understand, • added value compared to other indicators, • biosphere pathways excluded, • dilution in aquifer excluded.

Next to the effective dose rate as the basic safety indicator, two other indicators were found to provide significant benefits and may therefore be used to complement the effective dose rate. The three proposed safety indicators and their preferred time frames of application are:

- *Effective dose rate*: most relevant to early time frames and represents the annual effective dose to an average member of the critical group affected by the repository;
- *Radiotoxicity concentration in biosphere water*: preference for medium time frames and is a measure of the radiological consequences resulting from the ingestion of water from biosphere which is contaminated by radionuclides from the waste;
- *Radiotoxicity flux from geosphere*: preference for late time frames and is a hypothetical measure of the annual radiological impact caused by ingestion of all radionuclides from the waste as they are released from the geosphere to biosphere.

Performance indicators

The assessment of the performance indicators in SPIN was less restrictive than that of the safety indicators and the selection of the performance indicators depended mainly on the problem to be investigated. The basic requirements and assessment criteria are summarized in Table 3-4. A key assessment criterion is whether one indicator provides added value compared to others.

Table 3-3 Requirements and criteria for performance indicators as developed and used in the SPIN project [Becker et al., 2002, p. 77]

Categories	*Requirements and Criteria*
Basic requirements	• measure for the performance of the system or subsystem, • allow a comparison between options or with technical criteria, • weighting scheme available, • calculable using performance assessment models
Assessment criteria	• easy to understand • added value compared to other indicators

The project results allowed to conclude that several performance indicators can be used to show different aspects of the functioning of the individual compartments of the multi-barrier system. These indicators and their preferred applications are:

- *Inventories in compartments*: showing where the radionuclides are at different points in time, and the retention of radionuclides from the biosphere;
- *Inventories outside compartments*: showing the retention capability of all inner barriers;

- *Fluxes from compartments*: showing the decreasing release rates from successive compartments, including radioactive decay and ingrowth, and the delayed release ;
- *Concentrations in compartment water*: showing the decrease of concentration by dilution, dispersion and decay in successive compartments ;
- *Transport times through compartments*: showing the potential importance of individual radionuclides to the release of radiotoxicity by comparing them to their half-lives.

For investigations related to the total radionuclide spectrum, use of performance indicators based on radiotoxicities can be recommended. For the investigation of the behaviour of different types of radionuclides, indicators based on activity were considered appropriate.

Safety function indicators
The indicators given above can also be identified by considering the basic safety functions of the repository's multi-barriers system and can be used to demonstrate how these safety functions are fulfilled. Three other performance indicators have been developed to show exclusively the safety functions '*physical confinement*', '*decay during the delayed transport*', and '*dispersion and dilution*':

- *Proportion of waste not completely isolated for a given time period*: physical confinement function;
- *Time-integrated flux from compartments divided by initial inventory*: decay during delayed transport function;
- *Concentration in biosphere water divided by concentration in waste package water*: dispersion and dilution function.

These indicators have been defined in such a way that low numbers indicate a good performance of the disposal system.

Table 3-4 Performance Indicators and safety function indicators evaluated in the SPIN project [Becker et al, 2002, p. 82-83]

Performance indicator name	*Unit*
Activity in compartments	Bq
Activity outside compartments	Bq
Activity flux from compartments	Bq/a
Radiotoxicity in compartments	Sv
Radiotoxicity outside compartments	Sv
Radiotoxicity flux from compartments	Sv/a
Activity concentration compartment water	Bq/m^3
Radiotoxicity concentration compartment water	Sv/m^3
Transport time through compartments	a
Proportion of not totally isolated waste	-
Time integrated flux from geosphere/initial inventory	-
Concentration in biosphere water / waste package water	-

The definition of performance indicators has been related to compartments rather than to barriers. Each of the performance indicators in Table 3-7 can be applied to different compartments or groups of compartments. Comparing the indicators calculated for different compartments of a disposal system is often very illustrative for demonstrating the functioning of the system. Compartments can represent natural subsystems, buildings, engineered components or even physically independent phases in specific regions. In SPIN, seven compartments have been selected, though it was not considered useful to calculate each performance indicator for each compartment. The selection of compartments considered for the different indicators are summarized in Table 3-5.

Table 3-5 Selection of Compartments for Types of Performance Indicators [Becker et al., 2002, p. 13]

Compartments	*Amount in*	*Amount outside Flux from Time-integrated flux from*	*Concentration in water*	*Transport time through*
Waste form	x	x		
Precipitate	x			
Waste package		x	x	
Buffer	x			x
Near-field		x		
Geosphere	x	x		x
Biosphere	x		x	

3.2. *Indicators evaluated in PAMINA*

As part of the 6th European framework programme, the project PAMINA (Performance Assessment Methodologies in Application to Guide the Development of the Safety Case) addressed methodological questions in relation to performance assessment. Based on the outcome of the SPIN project, in PAMINA Work Package 3.4, additional work on safety and performance indicators was performed, with three principal objectives [4]:

- achieve a common understanding for the terms safety indicators and performance indicators,
- test appropriate safety indicators and performance indicators for the three host rock types (clay, granite, and rock salt) considered within the EU for deep geological repositories, and
- determine adequate reference values for the considered safety indicators.

The specific definitions for the safety and performance indicators established for the purpose of the SPIN project [Becker et al, 2003, p.9] have been refined and used within the PAMINA project [Becker et al, 2009, p. 5-7] and are adopted for the present project.

For PAMINA WP 3.4 six repository systems were defined: three systems in clay formations (ENRESA, NRG, SCK·CEN), two systems on rock salt formations (GRS, NRG), one system in a granite formation (NRI). Only the indicators selected for the systems in clay will be presented and discussed in the present report.

Safety indicators

In PAMINA four safety indicators were considered (Table 3-6). The use of complementary indicators next to the primary indicator *effective dose rate* was found beneficial because it contributes to a higher confidence in the safety statements given by a post-closure safety analysis. The complementary safety indicators ‘radiotoxicity concentration in biosphere water’ and ‘radiotoxicity flux from the biosphere’ are identical with the safety indicators applied in the SPIN project. The ‘power density in ground water’ indicator is a new proposal. This indicator is independent of any assumptions on biological effects, i.e. no correction for the - relative to its decay energy - stronger biological effects of ingested α-sources on species is made. Instead, the activity is directly multiplied by decay energy in order to derive the power density indicator.

Table 3-6 Safety indicators used in the PAMINA project [Becker et al.,2009, p. 34]

Safety indicator name	***Unit***
Effective dose rate	Sv/a
Radiotoxicity concentration in biosphere water	Sv/m^3
Radiotoxicity flux from geosphere	Sv/a
Power density in biosphere water	$MeV/s{\cdot}m^3$

Performance indicators

Five types of performance indicators of interest for a disposal concept in clay have been distinguished in PAMINA:

- *Inventory or concentration* related indicators;
- *Flux* related indicators;
- *Integrated flux* related indicators;
- *Safety functions* related indicators;
- *Transport times* related indicators;

Indicators of the first four types can be calculated for a single radionuclide (fission or activation products), for a decay chain or for a weighted sum over all radionuclides in terms of radiotoxicity. All indicators aim at illustrating the functioning of the repository system. The third and fourth types of indicators are specifically used for quantifying the contributions of the components or the safety functions of a repository system. Indicators of the fifth type are calculated for chemical elements and compared with the half-lives of the corresponding radionuclides. They are used for repository systems in granite and clay.

A performance indicator additional to those from SPIN project [Becker et al, 2002, p. 12]], was proposed:

- *Concentration in biosphere water / waste package water*

In addition SCK•CEN defined *performance indicators based on the safety functions* that contribute to the confinement of the radionuclides in the repository system. These indicators are also listed in Table 3-7 below, and are treated more extensively in Section 3.3 on the indicators applied in the Belgian case.

Table 3-7 Performance indicators considered in PAMINA project [Becker at al., 2009, p. 48-49].

Performance indicator name	***Unit***
Performance indicators based on inventories or concentrations:	
Activity in compartments	Bq
Activity outside compartments	Bq
Radiotoxicity in compartments	Sv
Radiotoxicity outside compartments	Sv
Activity concentration in compartment water	Bq/m^3
Radiotoxicity concentration in compartment water	Sv/m^3
Concentration in biosphere water / waste package water	-
Indicators based on fluxes:	
Activity flux from compartments	Bq/a
Radiotoxicity flux from compartments	Sv/a
Performance indicators based on integrated fluxes:	
Time-integrated activity flux from compartments	Bq
Time-integrated radiotoxicity flux from compartments	Sv
Performance indicators based on safety functions:	
Containment factor (C)	-
Limitation of release (R1)	-
Retardation factor (R3)	-
Performance of the integrated repository system (PI)	-
Performance indicators based on transport times:	
Transport time through compartments	a

In PAMINA, slightly different definitions of compartments were used than in SPIN. Table 3-8 shows the compartments considered in PAMINA for three different repository systems in clay.

Table 3-8 Compartments considered in PAMINA WP3.4 for the repository systems in clay (adapted from [Becker et al., 2009, p. 51])

Compartment	***ENRESA***	***SCK-CEN***	***NRG***
Waste matrix	x	x	x
Waste package		x	x
Waste package water	-	-	x
Precipitate	x	x	-
Buffer	x	x	x
Host formation		x	x
Overlying rock	x	x	x
Biosphere	x	x	x

In the PAMINA project, two evaluations of safety and performance indicators were performed on a disposal concept in Boom Clay, one by NRG [Schröder et al., 2009] and one by SCK·CEN [Marivoet et al., 2009]. The NRG study focussed on the abandonment scenario, while the SCK·CEN study focused on the normal evolution scenario. The indicators evaluated by NRG are shortly summarized in Appendix 1.

For the evaluated safety indicators, it was concluded by NRG [Schröder et al. 2009, p.84*f*] that the three complementary indicators provide significant benefits in terms of completeness and consistency of the safety evaluation in addition to the basic safety indicator *effective dose rate*. For the performance indicators tested, in [Schröder et al. 2009, p.80*f*] it was concluded with respect to the different indicators:

- *The activity-based indicators* are found not to have additional benefit compared to the radiotoxicity-based indicators.

- *Radiotoxicity in different compartments* is found a particular useful indicator giving a good overview over the distribution of the radiotoxicity over different compartments in time.

- *Radiotoxicity flux from compartments* gives a good overview on the impact of different barriers when these are arranged in a hierarchical way. It was noted that for the repository system studies, however, it should be defined in certain cases more explicit to which compartment the flow is directed. E.g. in certain scenarios, radionuclides can migrate from the clay (back) to the gallery, potentially leading to negative fluxes or fluxes difficult to explain to non-experts.

- *Time-integrated radiotoxicity flux out of different compartments* and *Normalized time-integrated radiotoxicity flux out of different compartments* are useful indicators to estimate which part of the radionuclides in the waste has passed the different barriers, but since both indicators give equivalent information, only one of them should be applied, with no clear preference given in that study.

- *Radiotoxicity concentration in disposal cell and biosphere water* and *Radiotoxicity concentration in biosphere water divided by concentrations in disposal cell water* are based on the same information, but preference is given for the first one because of its larger information content.

- For the *Transport time through compartments* two different representations are chosen, with the first based on a commonly used generic approach. It was found that this representation is less sensitive in an abandonment scenario and does not provide the opportunity to compare the travel time for different scenario's within the same repository design. The alternative presentation was somewhat less straightforward to understand, but allows a conservative estimation of different scenarios and inventories.

- *Containment factor (Host rock retention factor)* was defined differently by the various PAMINA contributors. NRG defined *containment* relative to the time-dependent inventory in the host formation (radiotoxicity released divided by radiotoxicity in the host formation). This was found more useful for the abandonment scenario. To avoid confusion with other, similar named indicators, this indicator will be addressed in this report as Host Rock Retention Factor.

3.3. Indicators currently considered for a geological disposal in Belgium

Based on the European projects SPIN and PAMINA an updated list of safety function indicators was developed by SCK·CEN, with some differences with the lists evaluated in the above-mentioned projects.

Safety indicators

Three selected safety indicators, i.e. the effective dose rate and two complementary safety indicators were considered:

- *Effective dose rate*
- *Radiotoxicity concentration in biosphere water*
- *Radiotoxicity flux released from the host formation*

Performance indicators

An additional performance indicator to those from the SPIN project [Becker at al. 2002, p.83], is proposed in PAMINA [Marivoet et al. 2010, p. 12], which quantifies the effectiveness of the confinement provided by the integrated repository system:

- <u>*Confinement factor*</u>: total amount of radionuclides released from host formation/ total amount of radionuclides in the disposed waste

Furthermore, a transport times related indicator was proposed as performance indicator ('<u>*Transport times through compartments*</u>') and a performance indicator related to the defined safety function indicators (see below) was considered ('<u>*Contribution of each safety function*</u>')

In total, eleven performance indicators were considered:

- *Activity in compartments*
- *Radiotoxicity in compartments*
- *Activity flux from compartments*
- *Radiotoxicity flux from compartments*
- *Time-integrated activity flux from compartments*
- *Time-integrated radiotoxicity flux from compartments*
- *Activity outside host formation*
- *Radiotoxicity outside host formation*
- *Activity released from host formation / Activity in disposed waste*
- *Transport time through compartments*
- *Contribution of each safety function to the overall safety*

The indicators and compartments considered are summarized in Table 3-10.

Table 3-9 Compartments considered for the different performance indicators

Compartments	***Amount in***	***Flux from or Time-integrated flux from***
Waste matrix	x	
Precipitate	x	
Waste package		x
Buffer	x	x
Host formation	x	x
Aquifer	x	x
Biosphere	x	

Performance indicators based on safety functions

In line with the Belgian safety concept a set of performance indicators based on safety functions (Figure 3-1) are defined. The considered set of safety functions is the one that has been defined within the Belgian radioactive waste disposal program [De Preter, 2007], and were identified in the safety strategy [ONDRAF/NIRAS, 2009] to contribute to the confinement of the radionuclides in the repository system in the case of the reference scenario. The following four additional performance indicators were considered:

- *Containment (C):* activity in waste package at time of overpack failure (T_1)/ initial activity in waste package (T_0= time of disposal);

- *Limitation of release (R1):* time-integrated (up to time t) activity flux released from waste package/activity in waste package at time of overpack failure (T_1);

- *Retardation due to migration through buffer and host formation (R3):* time integrated activity flux released from host formation/time-integrated (up to time t) activity flux released from waste package;

- *Performance of the integrated repository system (equivalent to the confinement factor):* time integrated activity flux released from host formation / initial activity in waste package (T_0= time of disposal).

Results and discussions on the application of these indicators in the Belgian safety assessment calculations can be found in [Marivoet et al., 2010] and [Weetjens et al., 2010].

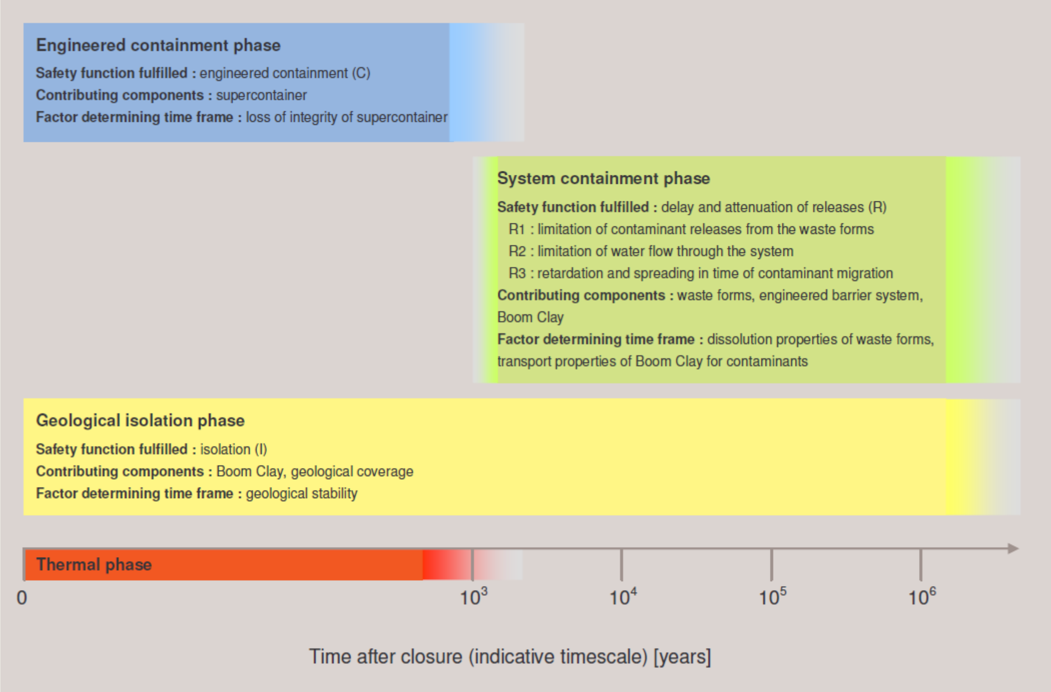

Figure 3-1 Safety functions provided by the main components of the disposal system for heat-generating waste (category C waste) in Boom Clay, its geological coverage, and the time frames over which they are expected to be fulfilled [ONDRAF/NIRAS, 2009, p.31].

4. Selection of indicators for OPERA

In order to provide a reasoned selection of indicators for the OPERA Safety Assessment, three consecutive steps are followed. Firstly, a list of criteria for the selection of safety and performance indicators is presented, based on the international projects and IAEA and NEA documents discussed in Chapter 2. Secondly, it is evaluated which of the indicators proposed for the Belgian Safety Case is applicable for the OPERA Safety Case, considering the principal differences between the Belgian and Dutch case. Based on the safety and performance indicators discussed in Chapter 3 additional indicators were proposed where necessary.

4.1. Selection criteria

In [NEA, 2012], a number of potential sources for the derivation of indicator criteria or reference values are given (Fig 4-1). The figure is found useful when considering potential sources for the definition of safety and performance indicators in OPERA, too:

- International recommendations
- PA calculations as performed in national safety assessments or European projects SPIN or PAMINA can provide useful insight in which type of indicator is practical and meaningful
- System understanding, partially based on PA calculations and uncertainty analysis, provide insight in the relevance of indicators
- Data from natural systems help to define 'natural', undisturbed conditions that may be helpful in defining indicators expressing the effect of waste disposal on the environment
- Social values and expectations may result in the need of additional indicators

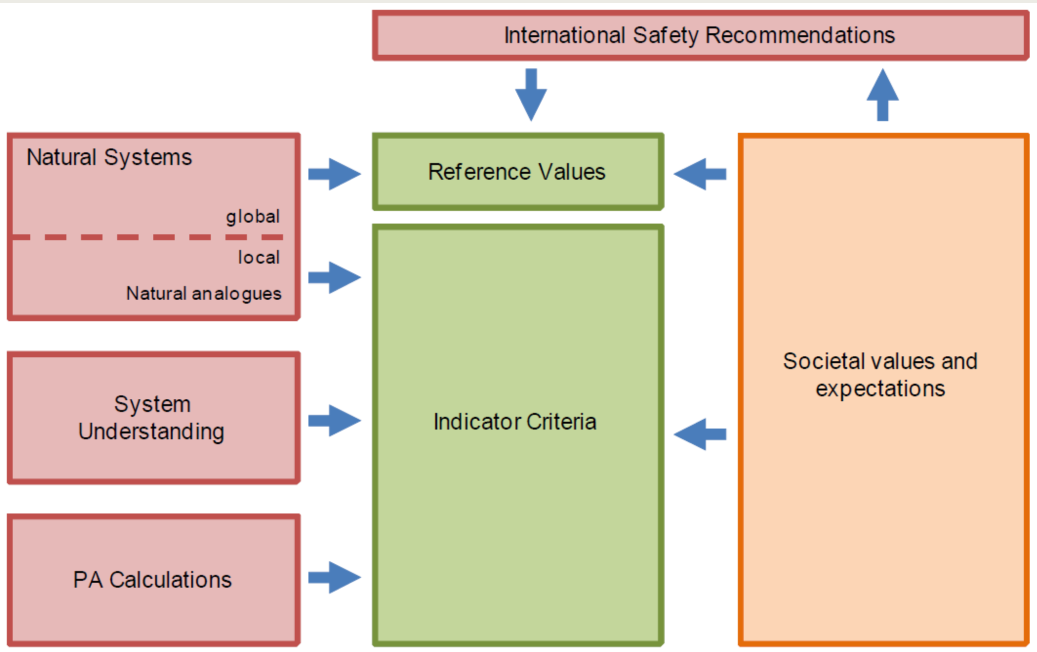

Figure 4-1 Sources of references values and indicator criteria [NEA, 2012, Fig. 15, p.79]

From the four sources discussed above, the first three are used in this report, and the fourth is taken into account as far as information on this was provided in the projects and international recommendations discussed in the previous section. For the last aspect, input may be provided from the OPERA Task 1.2.2. (ENGAGED), and may be integrated in the milestone report M7.3.1.2.

Following the definition of indicators in [NEA, 2012], indicators should be either:

- directly measurable characteristics of the disposal system,
- characteristics derived from system understanding, or
- characteristics derived from calculations of the long term evolution of the disposal system

With respect to safety indicators, more specific requirements are taken from [Becker et al.,2002, p.9]. Indicators should:

- provide a measure of the safety of the whole system,
- allow a comparison with a safety-relevant reference value,
- take into account the contributions of all radionuclides,
- be calculable using performance assessment models

and for our judgement of the practical applicability and meaningfulness of the indicators, we followed the assessment criteria defined in *SPIN* [Becker et al.,2002, p.74]:

- easy to understand
- added value compared to other indicators
- biosphere pathways excluded
- dilution in aquifer excluded

Besides the specifications discussed in Section 2.1, with respect to the communication with non-technical audiences, some considerations for the definition of beneficial complementary indicators are given in [NEA, 2012]:

- <u>local context</u> is related to presenting the potential impacts of the repository in terms of the local environment;
- <u>comprehensible timescales</u> means applying indicators over the assessment timescales that most people are concerned with, which rarely extends beyond the lifetime of the next few generations (their children and grandchildren);
- <u>impact significance</u> means presenting the potential consequences of the repository using units and measures that people understand;
- <u>two-way engagement</u> is related to working with public and stakeholders to ask them what complementary indicators they would like to see in a safety case.

The last group of selection criteria goes beyond the scope of this report. With respect to these aspects, potential input from Task 1.2.2 (ENGAGED) and Task 1.3.1 (CIP) will be integrated in the next Milestone report M7.3.1.2.

Although the OPERA disposal concept in Boom Clay is comparable to the current Belgian Supercontainer disposal concept, there are notable differences between the Belgian and Dutch safety cases, that are considered in the present analysis:

- amounts and characteristics of the waste in the OPERA concept are different:
  - the radionuclide inventory is smaller (<10% of the Belgian inventory);
  - all LILW, (TE)NORM, and HLW is disposed of in the deep clay formation while in Belgium, they are planning for a separate surface disposal for short-lived LILW;
  - HLW in Belgium consists of larger fractions of spent fuel, while from the Dutch NPP, only vitrified waste is considered;
  - the period of interim storage in the Netherlands is longer;
- the OPERA concept differs in the chosen dimensions (smaller containers, shorter disposal drifts) reflecting differences in amounts and characteristics of the waste;
- retrievability of the waste is a requirement of the Dutch policy on waste disposal;

- the Dutch waste is foreseen to be disposed of at greater depths (500 m) to account for deep erosion during glacial periods;
- the effects of delay and dilution of radionuclides in the geosphere are expected to be much larger for the OPERA reference concept: expected travel times in the geosphere are about 10 000 years for the Dutch case[b];
- in Belgium the research on geological disposal and the safety assessment methodology is in a more advanced state, with the Safety Case driving concrete political choices and decisions: the objective of the Safety and Feasibility Case 1 (SFC1, with was originally planned for 2013) was to obtain a "go for siting" decision from the Belgian government.

4.2. *Evaluation of safety indicators*

One of the conclusions of [NEA, 2012, p.94] is that most safety indicators are transferrable between repository concepts and host geological environments because they provide an integrated measure of total safety [NEA, 2012, p.94-95]. Therefore, in spite of the notable differences between the Belgian and Dutch disposal concepts, the safety indicators proposed for the Belgian disposal concept are also of interest in the OPERA Safety Assessment. These indicators have been tested in the SPIN and PAMINA projects by NRG and SCK·CEN and consistent results have been found that all these indicators increase the confidence in the outcome of the safety analysis.

Table 4-1 Safety Indicators proposed for the OPERA Safety Assessment

Safety Indicator	NRG	SCK·CEN	recommended for OPERA
Effective dose rate	x	x	+
Radiotoxicity concentration in biosphere water	x	x	+
Radiotoxicity flux from geosphere	x	x	+
Power density in the groundwater	x		o

o = potential candidate parameter

Effective dose rate is the basic indicator used to determine the safety of nuclear practices worldwide and is internationally accepted as the main indicator for assessing the safety of a repository system. The application of this indicators is well established and found in the PAMINA project useful by NRG and SCK·CEN. It is based on the best safety-relevant weighting scheme for the present biosphere with reference values defined in national regulations. The indicator has been found useful for all time frames, but it is recommended to give a higher preference for early time frames to limit the uncertainties of the evolution of the biosphere and upper geosphere.

Radiotoxicity concentration in biosphere water is an indicator that attempts to avoid the uncertainty associated with future development of biospheres, it is still affected by the uncertainty in the dilution in the considered water body and the aquifer system. A safety-relevant weighting scheme is available and safety-relevant reference values can be developed. The indicator is found useful by NRG and SCK·CEN. The indicator can be applied for all time frames, but a higher preference for early and medium time frames should be given. Reference values can be obtained for instance by computing the natural radiotoxicity of groundwater, based on the actual concentrations of naturally-occurring radionuclides.

Radiotoxicity flux from geosphere is defined without using dilution in aquifers or rivers and, therefore is less dependent on uncertainties related to the evolution of the upper

[b] based on first internal discussion in the RAMROCK project (OPERA WP6.2).

geosphere. A safety-relevant weighting scheme is available and safety-relevant reference values can be developed, although complicated by the fact that fluxes cannot be measured directly but are derived from measured concentrations and assumptions about the relevant hydrogeological setting, thus introducing another type of uncertainty. The indicator was found useful by NRG and SCK·CEN. The indicator is preferential for late time frames.

The indicator *Power density in biosphere* is a purely physical based parameter independent of any specific biological assumptions on effects. Because radiological effects cannot be assessed by this indicator, it has only a limited relevance for safety compared to the other presented safety indicators. Still, this indicator gives complementary information in the NRG calculation (but was not considered by SCK·CEN) and therefore judged as beneficial. With respect to the criteria defined in Section 4.1, one may ask if the indicator can be judged as based on “well-established principles” (there is no established reference value), and the impact significance might be lower due to the abstract unit provided ($MeV/s \cdot m^3$). We therefore decide not to add the indicator to the list of recommended indicators for the OPERA Safety Case, but put it on a list of ‘potential additional candidate indicators’.

4.3. Evaluation of performance indicators

Performance indicators provide a way to evaluate how individual barriers behave and contribute to the overall safety performance of a repository design which makes them specific to the repository design and geological environment, and so are not readily transferrable between different concepts and assessments [NEA, 2012, p.94-95]. However, the Dutch and Belgian concepts for clay show sufficient similarities to allow a combined analysis.

Table 4-2 Performance indicators **proposed for the OPERA Safety Case**

Performance Indicator	**NRG**	**SCK·CEN**	**recommended for OPERA**
Activity in compartments	x	x	-
Activity flux from compartments	x	x	-
Time-integrated activity flux from compartments	x	x	-
Normalized time-integrated activity flux from compartments	x		-
Radiotoxicity in compartments	x	x	+
Radiotoxicity flux from compartments	x	x	+
Time-integrated radiotoxicity flux from compartments	x	x	+
Normalized time-integrated radiotoxicity flux from compartments	x		-
Activity concentration in compartment water	x		-
Radiotoxicity concentration in compartment water	x		+
Activity concentration in biosphere divided by concentration in disposal cell	x	x	-
Radiotoxicity concentration in biosphere divided by concentration in disposal cell	x		-
Transport time through compartments	x	x	+
Host rock retention factor	x		+
Contribution of each safety function		x	+

The *activity-related indicators* were judged by NRG to be less relevant than their radiotoxicity-based counterparts: although the activity is based on less assumption (i.e. no dose conversion factor is involved), the relevance of radiotoxicity is higher since it provides information related to radiological consequences, that can be compared to other outcomes. SCK·CEN considers the use of activities for the analysis of single radionuclides, and the use of radiotoxicities, if groups of radionuclides are assessed [Marivoet et al., 2009, p.28ff]. For purpose of internal consistency checks as part of QA, the use of activity-based indicator has an added value, although these are not foreseen for external communication.

Radiotoxicities in compartments show the retention capability of the different barriers and the decrease of radiotoxicity in time as function of the natural decay of radionuclides. Both Belgian and Dutch studies found this type of indicators applicable and we recommend the use for the OPERA Safety Case.

Indicators that relate to *radiotoxicity fluxes from compartments* show the evolution of the transport rates of radionuclides between successive compartments, including radioactive decay and ingrowth. They have been found useful to show decreasing release rates from compartment to compartment and the retention function of each compartment of the disposal system. Their applicability is not dependent on any of the differences between the two considered concepts and the use is recommended for the OPERA Safety Case. However, as discussed in Section 3.3, attention should be paid to the definitions of compartments in order to avoid misinterpretations of the indicator in certain scenarios.

Time-integrated radiotoxicity flux out of different compartments was found a useful indicator by NRG and SCK·CEN to estimate which part of the radionuclides in the waste has passed the different barriers. We recommend the use of this indicator in the OPERA Safety Case.

The *Normalized time-integrated radiotoxicity flux out of different compartments* is not recommended for the use in the OPERA Safety Case, since it contains similar information as the previous indicator. In some presentations normalisation is useful, but the choice of the radiotoxic inventory of the waste to normalise the flux is somewhat arbitrary and should be explained.

Radiotoxicity concentration in compartment water is recommended as indicator for the OPERA Safety Case, since it gives additional information on the mobility of radionuclides with respect to the *radiotoxicity in compartments* indicator.

Radiotoxicity concentration in biosphere divided by concentration in disposal cell is not recommended as indicator for the OPERA Safety Case because it gives information similar to the previous indicator, and while it gives some information on the overall performance of the system, it is not specifically enough linked to a safety function like the comparable indicator *Performance of the integrated repository system* (see Section 4.4).

The indicators based on transport times provide information on how much the radionuclide decay during its transit through a compartment and therefore indicates the importance of individual radionuclides for long-term safety. The indicator is applicable in the OPERA Safety Case. Several potential representation of this indicator exists, and their application depends on the purpose. I.e., in order to make a first section on which radionuclides are of relevance at all, a simple representation as provided by NRG [Schröder et al., 2009, Fig. 48, p.72], SCK·CEN [Marivoet et al., 2009, Fig. 6.28 and 6.29 on p.48] or ENRESA [ENRESA, 2009, Fig. 4.32 and 4.33, p.47] might be sufficient, because it allows to identify which radionuclides has, compared to the travel times, half-life's that are short enough that no relevant amount will leave the host rock. However, as discussed in [Schröder et al., 2009, p.70ff], when looking more into detail, the indicator does not allow to exclude long-living radionuclides on basis of their small inventory (i.e. the amount that may leave the host rock are too small to represent a relevant hazard). In order to address this, NRG provided a more elaborated representation of the transport time indicator [Schröder et al., 2009, Fig.49, p.74], that however can be considered as a complex, less straight-forward indicator. We recommend to consider the use of this indicator for the OPERA Safety Case. Note that this indicator is basis of the OPERA Task 1.1.2 and may be developed the further in order to increase applicability.

The Host rock retention factor (*Containment factor))*, represented by NRG as *radiotoxicity released divided by radiotoxicity in the host formation* in PAMINA, is found a better indicator for the overall performance of the disposal system than *Radiotoxicity concentration in biosphere divided by concentration in disposal cell*, because the latter indicator is difficult to interpret since it does not account for the transport times of the radionuclides (i.e. the two concentrations are "out of phase" by an unlnown, nuclide dependent time shift). We therefore recommend the use of the *Host rock retention factor* indicator for the OPERA Safety Case, because it provide meaningful, non-redundant information.

The general concept of the performance indicator *Contribution of each safety function* is found useful in evaluating the relevance of each barrier to the overall safety. However, in the Dutch case, due to the longer travel times of radionuclides in the geosphere, it is expected that the geosphere provides significantly more to the overall safety than in the Belgian case. Moreover, different geo-hydrological settings are possible in the Netherlands, and it would make sense to provide an indicator that allows to evaluate such an influence in a later stage. The use of radiotoxicities is preferred above activities, while the performance indicator *Contribution of each safety function* proposed by SCK·CEN is based on activities (see section 3.3).

4.4. Evaluation of performance indicators related to safety functions

It is a logical and sound approach to use performance indicators that relate directly to the safety functions. As such, these indicators as presented in Section 3.3 are strong candidates.
However, indicators using summed activities of different radionuclides are not related to radiological impact. Therefore, for the OPERA safety assessment qualitatively the same indicators are proposed, but these proposed indicators reflect the radiotoxicity. To emphasise the difference, the indicators are annotated with RT.

Also, to take advantage of the very slow groundwater movement at the depth of the repository, an additional geosphere indicator R4-RT is proposed.

- *Containment (C-RT):* radiotoxocity in waste package at time of overpack failure (T1)/ initial radiotoxocity in waste package (T0= time of disposal);

- *Limitation of release (R1-RT):* time-integrated (up to time t) radiotoxocity flux released from waste package/radiotoxocity in waste package at time of overpack failure (T1);

- *Retardation due to migration through buffer and host formation (R3 - RT)*: time integrated radiotoxocity flux released from host formation/time-integrated (up to time t) radiotoxocity flux released from waste package;

- *Retardation due to migration through geosphere (R4 - RT)*: time integrated radiotoxicity flux released to biosphere / time integrated radiotoxicity flux released from host formation

- *Performance of the integrated repository system (PI-RT*): time integrated radiotoxocity flux released from host formation / initial radiotoxocity in waste package (T0= time of disposal).

For purpose of internal consistency checks as part of QA, the use of activity-based indicator has added value.

5. Overview of the indicators proposed for OPERA

In this chapter, an summarizing overview is given on the indicators proposed for the OPERA Safety Case, complemented by a short verbal description of the indicators. Note that a more detail description, including mathematical formulation, compartment definitions and graphical representation will be provided in M7.3.2. Table 5-1 gives an overview of the proposed indicators.

Table 5-1 Safety and performance indicators recommended for OPERA

Safety Indicator	
Effective dose rate	+
Radiotoxicity concentration in biosphere water	+
Radiotoxicity flux from geosphere	+
Power density in the groundwater	o
Performance Indicator	
Radiotoxicity in compartments	+
Radiotoxicity flux from compartments	+
Time-integrated radiotoxicity flux from compartments	+
Radiotoxicity concentration in compartment water	+
Transport time through compartments	+
Host rock retention factor	+
Contribution of each safety function	+
Performance indicators based on safety functions	
Containment (C-RT):	+
Limitation of release (R1-RT):	+
Retardation due to migration through buffer and host formation (R3 - RT)	+
Retardation due to migration through geosphere (R4 - RT)	+
Performance of the integrated repository system (PI-RT)	+
Activity based indicators (C, R1, R3, R4, PI)	0

o = potential additional candidate parameter

5.1. *Safety indicators*

Effective dose rate

The safety indicator “Effective dose rate in the biosphere” relates to the long-term potential exposure of the population due to the release of radionuclides from a radioactive waste repository. The individual dose rate represents the annual effective dose to an average member of the group of the most exposed individuals. It takes into account dilution and accumulation in the biosphere, different exposure pathways as well as living and nutrition habits. The effective dose rate is internationally accepted as the main indicator for assessing the safety of a repository system.

Radiotoxicity concentration in biosphere water

This indicator represents the radiotoxicity of the radionuclides in 1 m^3 of biosphere water. It also can be understood as the dose which is received by drinking of 1m^3 of biosphere water. For the computation of the radiotoxicity concentration in the biosphere water no exposure pathways need to be defined. The radiotoxicity concentration is thus independent of the biosphere, and can therefore be regarded as a more robust indicator for longer time frames. However, aquifer dynamics may considerably change on the long-term. This uncertainty is still inherently present. In comparison to the individual dose rate the safety statement of this indicator is restricted in a way that it assesses only the integrity of the drinking water from the contemplated aquifer with respect to human health.

Radiotoxicity flux from geosphere
Radiotoxicity flux from geosphere represents the radiotoxicity of the radionuclides released from the geosphere to the biosphere in a year. It can also be understood as the annual dose to a single human being who would ingest all radionuclides released from the geosphere to the biosphere. This indicator can be defined without using dilution in aquifers or rivers. However, whereas the calculated indicator is less dependent on uncertain data, the uncertainty is transferred to the estimation of relevant reference values that can be used for comparison. It is also very important to clearly define the extent of the geosphere, in order to avoid confusion. The radiotoxicity flux eliminates the uncertainty from the dilution in this water body, but it has only a weak relation to human health. It is preferably applicable to long time frames. The safety statement of this indicator is that there is no significant influence of the repository on the radiotoxicity of the water body (for instance the water in an upper aquifer or a river).

Power density in ground water
The indicator “power density in groundwater” is a physical parameter independent of any specific biological species. It is composed of the contribution of all radionuclides and can be seen as a criterion for the impact of hazardous radionuclides on biota in general. But since the radiological consequences cannot be assessed by this indicator, it has only a limited relevance for safety compared to the other presented safety indicators

5.2. *Performance indicators*

Radiotoxicity in compartments
The indicator represents nuclide-specific radiotoxicities as well as the total radiotoxicities in the compartments at different points in time.

Radiotoxicity flux from compartments
The indicator represents the radiotoxicity flux from compartment *i* for single radionuclides as well as summed over all radionuclides. Indicators that relate to fluxes from compartments show the evolution of the transport rates of radionuclides between successive compartments, including radioactive decay and ingrowth. They are also a measure of the barrier function of the components of the disposal system.

Time-integrated radiotoxicity flux from compartments
The indicator presents the cumulated radiotoxicity flux from the geosphere to the biosphere for single radionuclides as well as summed over all radionuclides. It can also be understood as the cumulated radiological impact due to continuous ingestion of all radionuclides released from the geosphere to the biosphere. It shows the retention capabilities of each compartment of the disposal system and is independent of the biosphere model and dilution. For individual radionuclides this indicator allows the quantification of the fraction of the inventory that decays or is finally retained in each compartment.

Radiotoxicity concentration in compartment water
This indicator represents nuclide-specific radiotoxicity concentrations as well as the total radiotoxicity concentrations in the water of the compartments and shows the dilution in successive compartments.

Transport time through compartments
In its simplest form, transport times through compartments are calculated for single nuclides without taking radioactive decay into account. To make the indicator useful, it must include a measure the potential radiological impact, i.e. it must be translated to radiotoxicity and the waste inventory. An attempt will be made to elaborate this indicator in milestone report M7.3.2.

Host rock retention factor
This indicator quantifies the effectiveness of the confinement provided by the integrated repository system and represents the radiotoxicity of radionuclides released from host formation / radiotoxicty of radionuclides in the disposed waste.

5.3. Performance indicators based on safety functions

The performance indicators based on safety functions consist of a set of five indicators related to the safety functions defined in the OPERA Research plan, and are closely related to the safety functions considered in the Belgium programme. The last indicator can be derived by multiplication of the other four.

- *Containment (C-RT):* radiotoxocity in waste package at time of overpack failure (T_1)/ initial radiotoxocity in waste package (T_0= time of disposal);

- *Limitation of release (R1-RT):* time-integrated (up to time t) radiotoxocity flux released from waste package/radiotoxocity in waste package at time of overpack failure (T_1);

- *Retardation due to migration through buffer and host formation (R3 - RT):* time integrated radiotoxocity flux released from host formation/time-integrated (up to time t) radiotoxocity flux released from waste package;

- Retardation due to migration through geosphere (R4 - RT): time integrated radiotoxicity flux released to biosphere / time integrated radiotoxicity flux released from host formation

- *Performance of the integrated repository system (PI-RT):* time integrated radiotoxocity flux released from host formation / initial radiotoxocity in waste package (T_0= time of disposal).

For purpose of internal consistency checks as part of QA, the use of activity-based indicator has added value.

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Appendix 1 Indicators tested by NRG within PAMINA

In line with the overall set considered in PAMINA, the following safety indicators were tested by NRG:

- *Effective dose rate*
- *Radiotoxicity concentration in biosphere water*
- *Power density in the biosphere water*
- *Radiotoxicity flux from geosphere*

Table 1 gives a detailed overview of the combination of indicators and compartments that were calculated by NRG.

Table 1 Performance indicators and compartments analysed by NRG

<table>
<tr><th rowspan="2">Performance Indicator</th><th colspan="8">Compartments</th></tr>
<tr><th>waste containers</th><th>concrete buffer</th><th>gallery</th><th>clay</th><th>biosphere</th><th>waste package</th><th>disposal cell</th><th>host formation</th></tr>
<tr><td>Activity in compartments</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td></td><td></td><td></td></tr>
<tr><td>Activity flux from compartments</td><td>x</td><td></td><td>x*</td><td>x*</td><td></td><td>x</td><td>x</td><td>x</td></tr>
<tr><td>Time-integrated activity flux from compartments</td><td>x</td><td></td><td></td><td></td><td></td><td>x</td><td>x</td><td>x</td></tr>
<tr><td>Normalized time-integrated activity flux from compartments</td><td>x</td><td></td><td></td><td></td><td></td><td>x</td><td>x</td><td>x</td></tr>
<tr><td>Radiotoxicity in compartments</td><td>x</td><td></td><td>x</td><td>x</td><td>x</td><td>x</td><td></td><td></td></tr>
<tr><td>Radiotoxicity flux from compartments</td><td>x</td><td></td><td></td><td></td><td></td><td>x</td><td>x</td><td>x</td></tr>
<tr><td>Time-integrated radiotoxicity flux from compartments</td><td>x</td><td></td><td></td><td></td><td></td><td>x</td><td>x</td><td>x</td></tr>
<tr><td>Normalized time-integrated radiotoxicity flux from compartments</td><td>x</td><td></td><td></td><td></td><td></td><td>x</td><td>x</td><td>x</td></tr>
<tr><td>Activity concentration in compartment water</td><td></td><td></td><td></td><td></td><td>x</td><td>x</td><td></td><td></td></tr>
<tr><td>Radiotoxicity concentration in compartment water</td><td></td><td></td><td></td><td></td><td>x</td><td>x</td><td></td><td></td></tr>
<tr><td>Activity concentration in biosphere divided by concentration in disposal cell</td><td colspan="8">x</td></tr>
<tr><td>Radiotoxicity concentration in biosphere divided by concentration in disposal cell</td><td colspan="8">x</td></tr>
<tr><td>Transport time through compartments</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>x</td></tr>
<tr><td>Containment factor (Radiotoxicity released divided by radiotoxicity in the host formation)**</td><td colspan="8">x</td></tr>
</table>

* to geosphere

** NRG defined containment relative to the time-dependent inventory in the host formation (radiotoxicity released divided by radiotoxicity in the host formation). This was found more useful for the abandonment scenario. To avoid confusion with other, similar named indicators, this indicator will be addressed in this report as Host Rock Retention Factor.

In order to exclude long-living radionuclides on basis of their small inventory, NRG provided a more elaborated representation of the transport time indicator [Schröder et al., 2009, Fig.49, p.74], that however can be considered as a complex, less straight-forward indicator.

Figure 1 shows the radionuclide inventory as function of the nuclide half-life (grey diamonds). In the same figure a group of lines is added, derived from the relative flow rates, but now inverse in terms of a dilution factor: a given reference value (here the radiotoxicity flow in geosphere of 60 Sv/a) divided by the relative flow rate. In other words, each curve represents the initial inventory of a radionuclide that would be necessary to realize a radiotoxicity flow out of the repository of 60 Sv/a (the reference value). The dashed lines extend the minimum values of the curves horizontally in time to the right, to reflect the assumption that radionuclides with a half-life longer than the maximum travel time will leave the repository with the maximum relative flow rate.

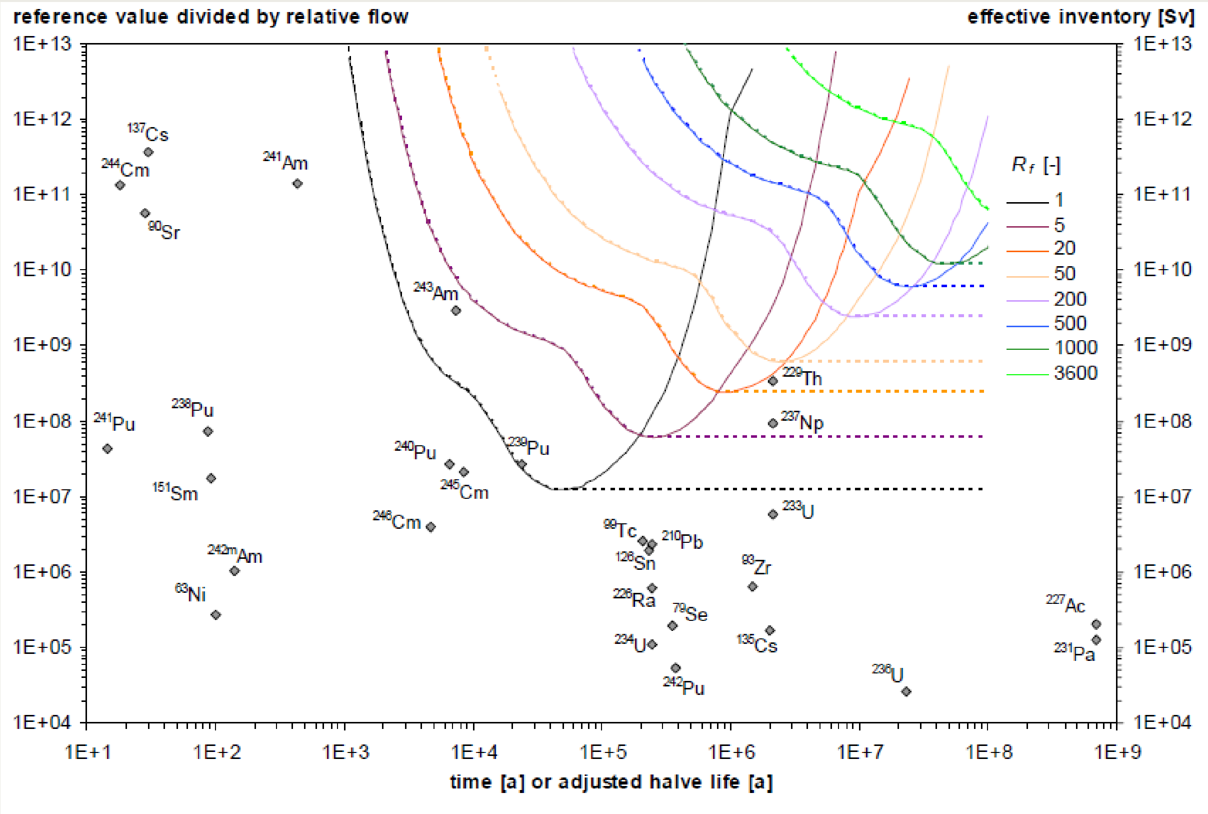

Figure 1 Reference value divided by relative flow rate and radiotoxicity inventory as function of radionuclide half-life for the "average" parameterization. The inventory is based on 3000 Supercontainers [Schröder et al., 2009, Fig. 49, p.74]

The figure shows that most nuclides will not cause a significant radiotoxic flux through the geosphere (compared to the reference value 60 Sv/yr), but that in particular the nuclides 243Am, 239Pu, 229Th, and 237Np need to be adsorbed by the clay (retention factor at least about 20) in order for the clay to be a sufficient barrier.

OPERA

Meer informatie:

Postadres
Postbus 202
4380 AE Vlissingen

T 0113-616 666
F 0113-616 650
E info@covra.nl

www.covra.nl