Safety and Performance Indicator calculation methodology

OPERA-PU-NRG7312

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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Summary

This report presents a detailed elaboration of safety and performance indicators to be used in communicating the outcome of safety assessments on the long-term safety of radioactive waste disposal that will be part of the OPERA Safety Case. The report is the successor of the OPERA Milestone report M7.3.1.1, *Development of Safety and Performance Indicators*, which proposed a set of safety and performance indicator to be applied for the OPERA Safety Case. The current report M7.3.1.2, *Safety and Performance Indicator calculation methodology*, provides a more detailed description of the selected list of indicators proposed in M7.3.1.1 in terms of mathematical definitions, compartment selection, and aspects related to their tabular and graphical representation.

Samenvatting

Dit rapport geeft een gedetailleerd overzicht van zgn. 'safety and performance indicators', die gebruikt kunnen worden in de communicatie van de resultaten van lange termijn veiligheid evaluaties van een berging voor radioactief afval in de diepe ondergrond. Dit rapport volgt het OPERA Milestone rapport M7.3.1.1, *Development of Safety and Performance Indicators*, op, waarin een voorstel uitgewerkt is, welke 'safety and performance indicators' binnen het OPERA programma toegepast kunnen worden. Het voorliggend rapport M7.3.1.2, *Safety and Performance Indicator calculation methodology*, geeft een gedetailleerde omschrijving van de indicatoren zoals voorgesteld in M7.3.1.1, in termen van wiskundige afleiding, selectie van de compartimenten waar de indicatoren op toegepast worden, en aspecten gerelateerd aan de tabellarische en grafische weergave van de indicatoren.

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 [Verhoef & Schröder 2011]. In this report, the execution and results of the research proposed for OPERA Task 7.3.1, '*Safety and Performance Indicators calculation methodology*' of the OPAP-I project is described. 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 set will enable a statement on the long-term safety of a future disposal of radioactive waste in Boom Clay.

This report is the successor of the OPERA Milestone report M7.3.1.1, *Development of Safety and Performance Indicators*, which presented an overview of safety and performance indicators and their use in the assessment of long-term safety of radioactive waste disposal, and proposed a set of safety and performance indicators for the OPERA Safety Case. The current report M7.3.1.2, *Safety and Performance Indicator calculation methodology* provides a more detailed description of the list of indicators proposed in M7.3.1.1 in terms of mathematical expressions, compartment selection, and aspects related to their graphical and tabular representation.

1.2. Objectives

A preliminary list of safety and performance indicators suitable for the OPERA Safety Case is proposed and documented in the preceding Milestone report M7.3.1.1. The main objectives of the present report M7.3.1.2 is to give support for the application of the selected indicators by providing mathematical descriptions of the indicators, by describing and discussing the compartments to which the indicators will be applied, and by discussing several aspects related to their tabular and graphical presentation. These aspects will be worked out in a detailed way to serve as input for the integrated modelling environment developed in OPERA Task 7.2.4 and other OPERA tasks involved in the definition of modelling approaches.

1.3. Realization

The study presented in this report is performed by NRG. It is based on the selection of safety and performance indicators presented in M7.3.1.1 and general considerations from the EC-funded projects *Testing of Safety and Performance Indicators* (*SPIN)* [Becker et al. 2002] and *Performance Assessment Methodologies in Application to Guide the Development of the Safety Case* (*PAMINA*) [Becker et al. 2009], the recent Nuclear Energy Agency's (NEA) project *Methods for Safety Assessment* (*MeSA*) [NEA 2012], and international guidelines and recommendations provided by IAEA en NEA [IAEA 1994; IAEA 2003; IAEA 2006; NEA 2013] as discussed in the previous Milestone M7.3.1.1 [Rosca-Bocancea & Schröder 2013]. Additional information on the current Belgian approach provided by SCK·CEN was considered, too.

The report also intended to include input provided by OPERA WP1.2 (ENGAGED) to gain a coherent list of indicators that fit consistently in the communication strategy. Besides, as part of WP1.2, reference values for the safety indicators discussed in this report have to be provided. However, due to different timings of the projects, input from WP1.2 is not expected before 2014, and is therefore not considered in this report, and no reference values are provided[1]. With respect to interactions on communication aspects with the OPERA Task 1.3.1 (CIP), in Chapter 3 several examples of tabular and graphical indicator representations are provided that are meant as input for the CIP project. The communication of complex information on a topic with controversial public views and perceptions [Jelgersma & Schröder, 2014], as will be the case of the presentation of the OPERA Safety Case outcome to a broader (lay) target audience, is too much off-topic for this report. Any conclusion on this topic will therefore be integrated in the CIP report but not repeated here. It should also be noted that the definition of what exactly belongs to the geosphere and what is part of the biosphere need to be elaborated in more detail by the OPERA Tasks 6.2 and 6.3: currently the interface between both projects is not defined sufficiently well to provide a detailed technical description in this report[1]. Although the representation of uncertainty is discussed briefly in this report, the selection of suitable uncertainty measures for the OPERA Safety Case is part of Task 7.3.2 and is not discussed further in the present report.

1.4. Explanation contents

In chapter 2, the methodological aspects are discussed: in Section 2.1, the selection of compartments for the OPERA Safety Case and mapping of the indicators to the selected compartments is carried out. Section 2.2 contains the calculation methodology of the indicators proposed in M7.3.1.1, including a description of the used nomenclature. Chapter 3 discusses briefly several aspects related to the presentation of the indicators. Section 3.1 provides some examples of graphical and tabular representation of safety and performance indicators. Section 3.2 discusses shortly the presentation of safety and performance indicators either as individual radionuclides or as sum of all radionuclides. Section 3.3 addresses the representation of uncertainty, and in section 3.4, a first outlook of the potential graphical and tabular output for the OPERA Safety Case is given, in order to provide input for discussion in later stages of the OPAP-I and -II projects.

[1] an update may be provided in a later stage

2. Methodology

2.1. Compartment selection and definition

In the OPERA Research plan, the system of multiple barriers (MBS) is subdivided into the following compartments [Verhoef & Schröder 2011, p.8]:

- The *near-field* - including
  - i) waste packages (waste matrix, container, overpack if used);
  - ii) further engineered barriers (buffer materials if used, seals, cap or cover); and
  - iii) zone disturbed by the presence of any excavations (excavation disturbed zone, EDZ);
- The *far-field* –the host rock and surrounding geological formations (or overburden);
- The *biosphere* - the physical media (atmosphere, soil, sediments, and surface waters) and the living organisms (including humans) that interact with them.

In the generic OPERA reference concept, the following compartments are distinguished [Verhoef et al., 2011, p.2*f*]:

- *Waste form*
- *Waste package* (canister, overpack, concrete buffer, steel envelope)
- *Repository building & affected materials* (backfill, concrete support, EDZ)
- *Host rock* (unaffected by the presence of excavations)
- *Surrounding rock formations* (aquifer)
- *Biosphere* (soil, atmosphere, climate, water bodies etc., humans, animals, bacteria)

In the application studies performed during the SPIN and PAMINA projects [Becker et al. 2002, p. 13], [Becker et al. 2009, p.51], [Rosca-Bocancea and Schröder 2013] a slightly different set of the compartments was used for analysis:

- *Waste matrix* or *Waste form*
- *Precipitate* (all radionuclides in the waste package which are neither in the waste form, nor dissolved in the water)
- *Waste package* (container together with its content)
- *Borehole* or *Near field* (the buffer and the waste package)
- *Buffer* (the buffer surrounding the waste package)
- *Repository structure*
- *Host formation*
- *Geosphere* or *Overlying rock*[2]
- *Biosphere*

From the definitions above it is evident that some clarification of the precise content of the different compartments is necessary, because for the purpose of the OPERA project, clear definitions are needed. International guidelines were found not useful in this case, because these are of a more generic nature, e.g. according to the IAEA Radioactive Waste Management Glossary [IAEA, 2003], the biosphere is defined as *"part of the environment normally inhabited by living organisms"* and the geosphere as *"parts of the lithosphere not considered to be part of the biosphere"*, but it was also recognized by the IAEA that *"in practice, the biosphere is not usually defined with great precision"*. Likewise, the term '*near-field*' is used differently in different disposal concepts and host rocks, and some confusion may appear from the use of terms as '*biosphere water*', '*groundwater*' and

[2] The *overlying rock* is an *aquifer* in case of the Belgian geological disposal concept in Boom Clay [Marivoet et al., 2010, p. 13].

‘*aquifer*’ in countries with a high groundwater table as the Netherlands, where exact boundaries are difficult to define and overlap of the compartments are likely. Furthermore, some compartments are defined by properties that may change in time or are difficult to establish (e.g. in case of a disposal in Boom Clay, the EDZ may disappear rather quickly due to the plastic properties of the host rock).

The definition of compartments should reflect besides existing safety functions also the systems model representation used for safety assessment calculations, in order to avoid the definition of compartment boundaries that are difficult to assess or define (e.g. boundary of EDZ - undisturbed host rock). It can also be noted that none of the lists of compartments above is complete: for specific analyses or scenarios, one may consider splitting the mentioned compartments into smaller subcompartments, e.g. define the disposal shaft as separate subcompartment to analyse flooding scenarios, or define a disposal cell as separate subcompartment to analyse which part of the waste is safely contained during operational phase. Because at the current moment the analyses that will be part of the safety assessment calculations are not known to the last detail, the list of necessary compartments[3] presented in this report should not be envisaged as ‘final’ or ‘complete’.

Based on the selection discussed in the previous report M7.3.1.1 [Rosca-Bocancea and Schröder 2013, Appendix 1, Table 1] we propose the use of a set of *primary compartments*. These compartments are arranged in a sequential, non-overlapping manner, and may be subdivided further into *subcompartments*, dependent on the analyses to be performed, the scenarios considered, the model representation of the disposal concept and the expected results. Table 2-1 gives an overview and definition of the primary compartments, and examples of potential subcompartments to be considered.

The definitions of compartments *engineered barrier system (EBS)* and *host rock* are slightly different from [Verhoef & Schröder 2011, p.8] and [Verhoef et al. 2011, p.2f]: here, the *host rock* is regarded as one compartment, based on the expected representation of the disposal system as performance assessment model. It can also be noted that the definition of what exactly belongs to the geosphere and what is part of the biosphere need to be elaborated in more detail by the OPERA Tasks 6.2 and 6.3. Currently the interface between both projects is not defined sufficiently well to provide a detailed technical description in this report.[4]

For the analysis of certain performance indicators, it might be beneficial to analyse combinations of compartments and/or subcompartments, e.g.:

- *repository structure*: the overall facility including the disposed waste and all man-made structures in the host rock;
- *host formation*: the host rock, including the *repository structure*.

[3] the number of indicators and compartments should be limited to an essential set
[4] an update of this report can be provided in a later stage in order to have a complete reference document for the OPERA project

Table 2-1: Compartments and subcompartments to be considered in the OPERA Safety Case

primary compartment	description	examples of subcompartments
waste package	the waste container including waste	*waste form*: disposed radionuclides including the waste matrix *concrete buffer* and *overpack:* parts of the OPERA supercontainer concept*
engineered barrier system (EBS)	all man-made structures of the disposal facility, excluding the *waste packages*	*disposal cell*: sealed space in which the waste is disposed of, including the *sealing plug*, the surrounding *gallery support*, the *backfill* and the *waste package* *sealing plug:* seal of a disposal cell *gallery support:* mechanical support in all parts of the disposal facility *backfill*: buffer that fills the open space between *waste package* and *disposal cell* *shaft*: shaft that gives access to the disposal facility, including mechanical support structure
host rock	Boom Clay formation, excluding the *EBS* and *waste packages*	*EDZ:* part of the host rock affected by disposal operations and emplaced waste *unaffected host rock:* part of the host rock not affected by disposal operations and emplaced waste
geosphere	part of environment enclosing the *host rock*, and that is not part of the *biosphere;*	*groundwater**:* water that is held in rocks and soil beneath the surface of the earth
biosphere	part of the environment normally inhabited by living organisms	*biosphere water**:* the water which is used by man for drinking, feeding livestock or for irrigation, and naturally taken up by plants or animals. *deep wells* *arable land* *grassland*

* see [Verhoef et al. 2011, p.14]

** a more technical description needs to be provided by WP6.2/WP6.3

Matrix of compartments and indicators

Safety indicators and *performance indicators based on safety functions* are related to a compartment by definition. A summary of these indicators selected in M7.3.1.1 for the OPERA Safety Case, and the compartments they apply to, is given in Table 2-2 and Table 2-3. A short description of all indicators is provided in Section 2.2.

Table 2-2: Safety indicators[5] for the OPERA Safety Case and the related compartments

Safety indicator	compartments
Effective dose rate	biosphere
Radiotoxicity concentration in biosphere water	biosphere water
Radiotoxicity flux from geosphere	geosphere
Power density in the groundwater	groundwater

[5] note that the accompanying reference values are part of WP1.2 (ENGAGED)

Table 2-3: Performance indicators based on safety functions for the OPERA Safety Case and the related compartments

Performance indicator based on safety functions	compartments
Containment (C-RT)	waste package
Limitation of release (R1-RT)	waste package
Retardation due to migration through host formation (R3 - RT)	waste package, host rock
Retardation due to migration through geosphere (R4 - RT)	host rock, biosphere
Performance of the integrated repository system (IRS-RT)	waste package, biosphere
Activity based indicators (C, R1, R3, R4, IRS)	waste package, host rock, biosphere

For performance indicators, two kinds of indicators can be distinguished: indicators directly related to compartments by definition, and indicators that can be applied to various compartments. Table 2-4 gives an overview of the first kind of indicators selected in M7.3.1.1 for the OPERA Safety Case. These indicators need no further refinement here, because these are explicitly related to a certain compartment. Table 2-5 provides an overview of the indicators that can be applied to different compartment.

Table 2-4: Performance indicators for the OPERA Safety Case, directly related to compartments

Performance indicator	compartments
Host rock confinement factor	host rock, waste package
Transport time through compartments	waste package - geosphere, waste package - biosphere*
Contribution of each safety function	waste package, host rock, biosphere

* dependent on reference value/safety indicator chosen

Table 2-5: Performance indicators for the OPERA Safety Case, applicable to different compartments

Performance indicator
Radiotoxicity in compartments
Radiotoxicity flux from compartments
Time-integrated radiotoxicity flux from compartments
Radiotoxicity concentration in compartment water

For each of the indicators in Table 2-5, different compartments where evaluated by NRG and/or SCK·CEN in the PAMINA project [Marivoet et al. 2009; Schröder et al. 2010], but no clear recommendations were given with respect to the usefulness of the application of a specific combination. Based on the general consideration and criteria for the selection of indicators as described in [Rosca & Schröder 2013, Section 2.1 and 4.1], potential combinations of the indicators in Table 2-5 and the primary compartments defined in Section 2.1 were evaluated with respect to the applicability for the OPERA reference concept in Boom Clay [Verhoef et al. 2011]. Some general guidelines for primary compartments can be given, but as discussed above, a selection of subcompartments can not be made in the current report:

- for the indicators *Radiotoxicity in compartments* and *Time-integrated radiotoxicity flux from compartments* a full sequential set of primary compartments should be used: *waste package* > *EBS* > *host rock* > *geosphere* > *biosphere*. Additional subcompartments can be used to indicate specific relevant pathways for radionuclide migration (e.g. *shaft* in flooding scenarios). Likewise, additional indicators can be used to evaluate the performance of specific parts of the EBS (e.g. the inner overpack of the OPERA supercontainer;
- for the indicator *Radiotoxicity flux from compartments*, the same set of primary compartments as discussed in the previous bullet should be used. Whether fluxes from the *biosphere* provide useful information depends on the biosphere model and underlying assumptions (part of WP6.3);
- for the *Radiotoxicity concentration in compartment water* a full sequential set of primary compartments should be used, without considering the *waste form* as independent compartment: *waste package* > *EBS* > *host rock* > *geosphere* > *biosphere*. The considerations on the use of additional subcompartments as discussed above are applying here, too.

2.2. Indicators calculation methodology

In this section, the calculation methods for the safety and performance indicators are summarized. An overview on the indicators proposed for the OPERA Safety Case, based on [Rosca-Bocancea & Schröder 2013, p.26], is given in Table 2-6.

For the definition of the indicators, the following nomenclature is used:

- *Radionuclides* are numbered by *n*
- The *ingestion dose coefficient* $e(50)_n$ is the dose caused by ingestion of radionuclide *n* [Sv per Bq intake]. The ingestion dose coefficients for adults, which correspond to the committed effective dose integrated over 50 years, are used [VROM 2001, Appendix 4, Table 4.1]. The effects of radioactive daughter nuclides produced in vivo are accounted for.
- The *biosphere dose conversion factor* DCF_n is the annual dose to the most exposed members of the public (so-called critical group) caused by a unit concentration of radionuclide *n* in the biosphere water. It is measured in [(Sv/a)/(Bq/m^3)]. It takes into account different exposure pathways as well as living and nutrition habits. Biosphere dose conversion factors are provided by the biosphere analyses, following the guidance given in national regulations where available. The generic dose conversion factors for OPERA will be deduced within OPERA Task 6.3.1 '*Modelling approach for transport & uptake processes*'.
- c_n is the *activity concentration* [Bq/m^3] of radionuclide *n* in the biosphere water
- s_n is the *activity flux*[6] [Bq/a] of radionuclide *n* from the geosphere to the biosphere
- $a_{n,i}$ is the *activity* [Bq] of radionuclide *n* in compartment *i*
- $c_{n,i}$ is the average *activity concentration* [Bq/m^3 of water] of radionuclide *n* in the water of compartment *i*
- $s_{n,i}$ is the *activity flux*[6] [Bq/a] of radionuclide *n* released from compartment *i*

[6] note that although strictly speaking *flux* is defined as the rate of *flow* of a property per unit area, we follow here the definitions as used in the literature on safety and performance indicator

- $(a_{n,i})_t$ is the *activity* [Bq] of radionuclide n in compartment i on time step t
- E_n is the decay energy of a radionuclide n

Table 2-6: 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*
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 confinement 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 host formation (R3 - RT)
Retardation due to migration through geosphere (R4 - RT)
Performance of the integrated repository system (IRS-RT)
Activity based indicators (C, R1, R3, R4, IRS)

* potential additional candidate parameter

Safety indicators

Effective dose rate

The *Effective dose rate* represents the annual individual 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.

Calculations can be performed either for individual radionuclides

$$\textit{Effective dose rate for radionuclide } n \ [Sv/a] = c_n DCF_n \qquad \textit{Equation 1}$$

or for the sum of all radionuclides:

$$\textit{Effective dose rate } [Sv/a] = \sum_{all\ nuclides} c_n DCF_n \qquad \textit{Equation 2}$$

For better readability of this document, in the remainder of this section, we only depict the equations for the sum of all radionuclides.

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. Calculation:

$$\text{Radiotoxicity concentration in biosphere water } [Sv/m^3] = \sum_{all\ nuclides} c_n e(50)_n \qquad \text{Equation 3}$$

Radiotoxicity flux[7] 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. Calculation:

$$\text{Radiotoxicity flux from geosphere } [Sv/a] = \sum_{all\ nuclides} s_n e(50)_n \qquad \text{Equation 4}$$

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. The calculation of the power density is carried out with a simple weighting scheme by multiplying the activity concentration of every radionuclide [Bq/m^3] with its decay energy:

$$\text{Power density in ground water } [MeV/s\cdot m^3] = \sum_{all\ nuclides} c_n E_n \qquad \text{Equation 5}$$

Performance indicators

Radiotoxicity in compartments
The indicator represents the total radiotoxicity in the compartment *i* at different points in time for single radionuclides *n* or summed over all radionuclides:

$$\text{Radiotoxicity in compartments } [Sv] = \sum_{all\ nuclides} a_{n,i} e(50)_n \qquad \text{Equation 6}$$

See section 2.1 for considered compartments.

Radiotoxicity flux from compartments
This indicator represents the radiotoxicity flux from compartment *i* for single radionuclides *n* or summed over all radionuclides:

$$\text{Radiotoxicity flux from compartments } [Sv/a] = \sum_{all\ nuclides} s_{n,i} e(50)_n \qquad \text{Equation 7}$$

[7] note that although strictly speaking *flux* is defined as the rate of *flow* of a property per unit area, we follow here the definitions as used in the literature on safety and performance indicator

See considered compartments in section 2.1.

Time-integrated radiotoxicity flux from compartments
The indicator presents the cumulated radiotoxicity flux from a compartment *i* for single radionuclides *n* 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 confinement 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.

Calculation:

$$\text{Time-integrated radiotoxicity flux from compartments [Sv]} = \sum_{all\ nuclides} \left(\int_0^t \boldsymbol{e(50)_n\, s_{n,i}(\tau) d\tau} \right) \qquad \textit{Equation 8}$$

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

$$\text{Radiotoxicity concentration in compartment water [Sv/m}^3\text{]} = \sum_{all\ nuclides} \boldsymbol{e(50)_n c_{n,i}} \qquad \textit{Equation 9}$$

Transport time through compartments
This indicator combines in a single graph the outcome of migration calculations in terms of a safety indicators evolution in time, and a representation of the radionuclide inventory considered. No generic equation can therefore be given here, but it will depend on the outcome of safety assessment calculations. Dependent on the safety indicator used, its reference values will be divided by either normalized fluxes or concentrations, resulting in a risk value with the unit [Sv]. To cover the presence of nuclide chains, the inventory is expressed as '*effective inventory*' (in [Sv]), following the procedure:

- if a mother nuclide has a longer half-life, equilibrium with the daughter nuclide is assumed and the activity of the mother is added up by the daughter;
- in case the mother nuclide has a shorter half-life, the mother is added up by the daughter (in molar amount).

These additions are performed cumulative for all relevant consecutive nuclides of the four nuclide chains. Likewise, the half-life is presented as '*adjusted half-life*', i.e. for daughters of longer living mother, the half-life of the mother is attributed to.

Figure 2-1 shows an example of the indicator. This indicator will be elaborated in more detail and will be - if necessary - refined as part of OPERA Task 1.1.2 (OPCHAR). For a more detailed description we refer to OPERA Milestone M1.1.2.1.

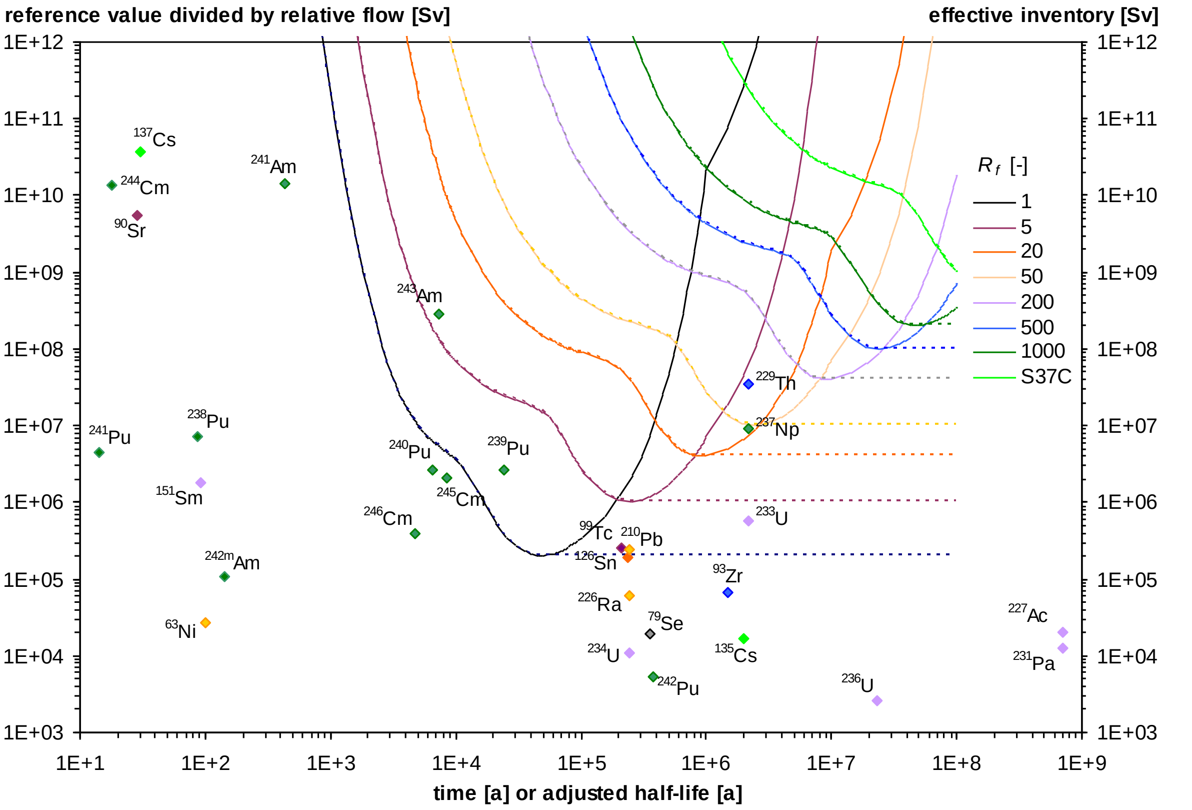

Figure 2-1 Example of transport time related indicator

Host rock confinement factor

This indicator quantifies the effectiveness of the confinement provided by the host formation (i.e. host rock, EBS and waste package together) and is calculated as the (time-dependent) radiotoxicity released from host rock divided by the (time-dependent) inventory radiotoxicity present in the host formation. Calculation:

Host rock confinement factor [-] = $$\sum_{all\ nuclides} a_{n,i} e(50)_n \ / \sum_{all\ nuclides} a_{n,host\ rock} e(50)_n$$ *Equation 10*

with *i* = *geosphere* + *biosphere*

Contribution of each safety function

The *indicator Contribution of each safety function* shows the contribution of each of the performance indicators based on safety functions (C-RT, R1-RT, R3-RT, R4-RT) to the overall performance of the integrated repository system (IRS-RT) in terms of percentage.

Calculation:

Contribution of each safety function [%] = $$100 \times \frac{1}{PI_m} \ / \sum_{safety\ functions} \frac{1}{PI_m}$$ *Equation 11*

with PI_m = the values of the performance indicators based on safety function C-RT, R1-RT, R3-RT, and R4-RT as described in the following subsection.

Performance indicators based on safety function

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 (see [Verhoef & Schröder 2011; Rosca-Bocancea & Schröder 2013, p.25, 28] for more information on safety functions and performance indicators based on safety function). The last indicator can be derived by multiplication of the other four. Like the previous indicators, these can be expressed for individual radionuclides and summed up over all radionuclides (only the latter is shown).

<u>*Containment (C-RT)*</u>

The *Containment* represents the radiotoxicity in waste package at time of overpack failure (t_1) divided by the initial radiotoxicity in waste package (t_0 = time of disposal). Calculation:

$$PI_{C\text{-}RT}\ [-] = \sum_{all\ nuclides} (a_{n,i})_{t_1}\, e(50)_n \Big/ \sum_{all\ nuclides} (a_{n,i})_{t_0}\, e(50)_n \qquad \text{Equation 12}$$

with i = waste package

<u>*Limitation of release (R1-RT)*</u>

The *Limitation of release* represents the time-integrated (up to time t) radiotoxicity flux released from waste package divided by the radiotoxicity in waste package at time of overpack failure (t_1). Calculation:

$$PI_{R1\text{-}RT}\ [-] = \sum_{all\ nuclides} \left(\int_0^t e(50)_n\, s_{n,i}(\tau) d\tau \right) \Big/ \sum_{all\ nuclides} (a_{n,i})_{t_1} e(50)_n \qquad \text{Equation 13}$$

with i = waste package

<u>*Retardation due to migration through buffer and host formation (R3 - RT)*</u>

The *Retardation due to migration through buffer and host formation* represents the time integrated radiotoxicity flux released from host formation divided by the time-integrated (up to time t) radiotoxicity flux released from waste package. Calculation:

$$PI_{R3\text{ - }RT}\ [-] = \sum_{all\ nuclides} \left(\int_0^t e(50)_n\, s_{n,j}(\tau) d\tau \right) \Big/ \sum_{all\ nuclides} \left(\int_0^t e(50)_n\, s_{n,i}(\tau) d\tau \right) \qquad \text{Equation 14}$$

with j = host rock and i = waste package.

<u>*Retardation due to migration through geosphere (R4 - RT)*</u>

The *Retardation due to migration through geosphere* represents the time integrated radiotoxicity flux released to biosphere divided by the time integrated radiotoxicity flux released from host formation. Calculation:

$$PI_{R4\text{ - }RT}\ [-] = \sum_{all\ nuclides} \left(\int_0^t e(50)_n\, s_{n,k}(\tau) d\tau \right) \Big/ \sum_{all\ nuclides} \left(\int_0^t e(50)_n\, s_{n,j}(\tau) d\tau \right) \qquad \text{Equation 15}$$

with j = host rock and k = geosphere.

Performance of the integrated repository system (IRS-RT)

The *Performance of the integrated repository system* represents the time integrated radiotoxicity flux released from geosphere divided by the initial radiotoxicity in waste package (t_0= time of disposal). Calculation:

$$PI_{IRS\text{-}RT}\ [\text{-}] = \sum_{all\ nuclides}\left(\int_0^t e(50)_n\, s_{n,k}(\tau)d\tau\right) / \sum_{all\ nuclides}(a_{n,i})_{t_o} e(50)_n \qquad \text{Equation 16}$$

with i = waste package and k = geosphere.

For purpose of internal consistency checks as part of QA and comparison reasons, the use of activity-based indicator as defined by SCK·CEN [Marivoet et al. 2010] was proposed to be calculated as well in the OPERA safety assessments[8].

Containment (C)

The indicator *Containment* describes the activity in waste package at time of overpack failure (t_1)divided by the initial activity in waste package (t_0 = time of disposal):

$$PI_C\ [\text{-}] = \sum_{all\ nuclides}(a_{n,i})_{t_1} / \sum_{all\ nuclides}(a_{n,i})_{t_o} \qquad \text{Equation 17}$$

with i = *waste package*

Limitation of release (R1)

The *Limitation of release* describes the time-integrated (up to time t) activity flux released from waste package divided by the activity in waste package at time of overpack failure (t_1):

$$PI_{R1}\ [\text{-}] = \sum_{all\ nuclides}\left(\int_0^t s_{n,i}(\tau)d\tau\right) / \sum_{all\ nuclides}(a_{n,i})_{t_1} \qquad \text{Equation 18}$$

with i = waste package

Retardation due to migration through buffer and host formation (R3)

The indicator *Retardation due to migration through buffer and host formation* describes the time integrated activity flux released from host formation divided by the time-integrated (up to time t) activity flux released from waste package

$$PI_{R3}\ [\text{-}] = \sum_{all\ nuclides}\left(\int_0^t s_{n,j}(\tau)d\tau\right) / \sum_{all\ nuclides}\left(\int_0^t s_{n,i}(\tau)d\tau\right) \qquad \text{Equation 19}$$

with j = host rock and i = waste package.

[8] note that SCK•CEN does not attribute a safety function to the geosphere, i.e. indicator R4 equals 1

Retardation due to migration through geosphere (R4)
The indicator *Retardation due to migration through geosphere* describes the time integrated activity flux released to biosphere divided by the time integrated activity flux released from host formation

$$PI_{R4}\ [-] = \sum_{all\ nuclides}\left(\int_0^t s_{n,k}(\tau)d\tau\right) / \sum_{all\ nuclides}\left(\int_0^t s_{n,j}(\tau)d\tau\right) \qquad \text{Equation 20}$$

with j = host rock and k = geosphere.

Performance of the integrated repository system (IRS)
The indicator *Performance of the integrated repository system* describes the time integrated activity flux released from geosphere divided by the initial activity in waste package (t_0= time of disposal).

$$PI_{IRS}\ [-] = \sum_{all\ nuclides}\left(\int_0^t s_{n,k}(\tau)d\tau\right) / \sum_{all\ nuclides}(a_{n,i})_{t_o} \qquad \text{Equation 21}$$

with i = waste package and k = geosphere.

3. Presentation of results

3.1. Graphical and tabular representation

By selection of suitable indicators as performed in M7.3.1.1, the massive amount of output data can already be transformed into a limited number of relevant and convincing safety and performance indicators. However, the set of chosen safety and performance indicators can be calculated for either individual radionuclides or the sum of all radionuclides, can be applied for different compartments, and the calculation will be performed for a large number of combinations of parameter values to address the numerical uncertainty of the used parameter. Presenting all this content for each scenario considered in the safety assessment of the OPERA Safety Case will result in a large amount of figures. In this section, it is established how the information can be represented in tabular and graphical form in the most compact and comprehensive way.

The use of tables

Tables can give in a compact way precise numerical values of a large number of safety and performance indicators. However, because the representation in tables is reduced to a small number of significant features or time steps - typically the maximum value or time-integrated value at a chosen point in time, information on the evolution of a parameter in time is largely lost when the results are only presented in tables. Table 3-1 to Table 3-3 gives examples of tabulated safety and performance indicators.

Table 3-1 Example of a table with maximum *Effective dose rate* values [Schröder et al. 2009, p.40]

scenario	maximum effective dose rate [Sv/a]		time step of maximum effective dose rate [a]
	single Supercontainer	total repository	
"average"	$5.4 \cdot 10^{-10}$	$1.5 \cdot 10^{-6}$	47'000
"minimum"	$8.8 \cdot 10^{-10}$	$2.6 \cdot 10^{-6}$	37'000
"maximum"	$7.7 \cdot 10^{-10}$	$2.3 \cdot 10^{-6}$	27'000

Table 3-2 Example of a table of performance indicators of the *Contribution to each safety function* calculated for actinides for a 10 million years period [Marivoet et al. 2010, p.61]

	PI_C	PI_{R1}	PI_{R3}	PI_{IRS}
4N	8.75E-01	2.92E-06	3.95E-02	1.01E-07
4N+1	7.73E-04	1.71E-01	1.99E-04	2.62E-08
4N+2	5.02E-01	6.72E-03	1.21E-07	4.07E-10
4N+3	8.57E-01	6.24E-02	6.75E-06	3.61E-07

Table 3-3 Example of a table of *Relative time integrated activity fluxes* for individual radionuclides for a 10 million years period [Marivoet et al. 2010, p.53]

Radionuclides	Waste package	Buffer	Clay
C14	6.38E-02	5.58E-02	1.09E-05
Cl36	4.98E-01	4.96E-01	3.44E-01
Ni59	8.76E-01	8.70E-01	4.04E-05
Se79 (VI)	3.98E-01	3.96E-01	1.14E-01
Se79 (0,-II)	2.24E-01	2.24E-01	1.71E-01
Zr93	8.14E-01	8.12E-01	1.62E-03
Nb94	6.82E-01	6.74E-01	1.84E-09
Tc99	2.96E-02	2.92E-02	2.04E-02
Pd107	3.64E-01	3.62E-01	2.24E-01
Sn126	3.04E-01	3.04E-01	1.02E-02
I129	9.78E-01	9.78E-01	9.72E-01
Cs135	8.68E-01	8.66E-01	5.78E-08

The use of figures

Unlike tables, figures are well-suited to present the evolution of an indicator in time. In this section, a number of examples for the graphical presentation of safety and performance indicators are provided. The presentation can take place as actual or normalized values, calculated for one or more compartments and may include information on numerical uncertainties. In most cases, the graphical representation of indicators is on *log-log* scale, with a time scale on the *x*-axis.

In order to reduce the number of graphs, it is recommended to combine several features in a graph (see also Section 3.2 to 3.4), e.g.

- indicator values for all relevant radionuclides, and the sum of all radionuclides
- indicator values for a single radionuclide in different compartments
- several normalized indicator evolutions in one graph
- mean indicator value and two or more uncertainty measures

In the remainder of this section, a number of practical examples of indicator graphs are given to visualize some of their typical features. This is intended as input for the CIP project and may serve for later discussion in the OPERA project.

The first graph (Figure 3-1) is an example on how several complementary safety indicators can be combined in a beneficial way in one graph. The use of several complementary safety indicators is recommended, as discussed in [Rosca-Bocancea & Schröder 2013], because it addresses future uncertainties. A normalized representation of safety indicators (normalized by their reference values) allows all indicators to be summarized in one single graph (Figure 3-1) [Schröder et al. 2009, p.46] and facilitate an easy comparison of the different calculation outcomes. As pointed out in [Rosca-Bocancea & Schröder 2013], if the main message of all indicators is comparable, it will underline the robustness of the different approaches to quantify risks and may help to increase confidence in the safety of a geological repository.

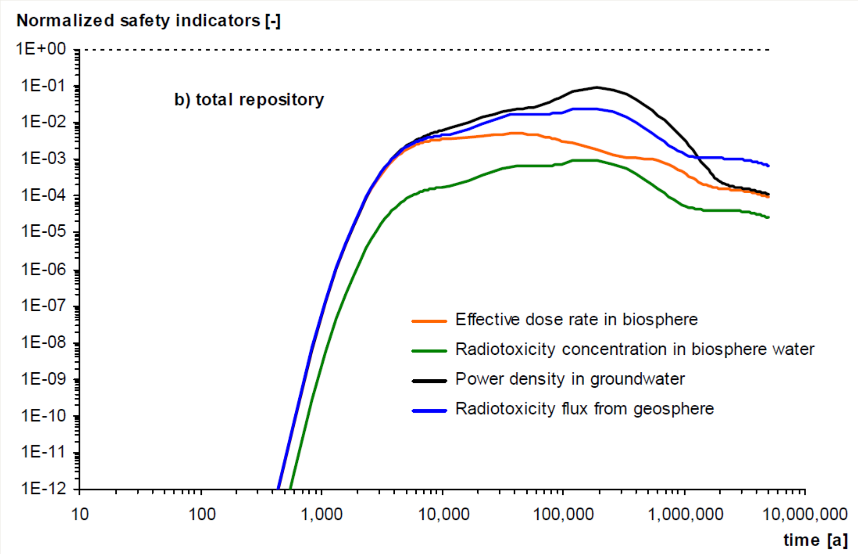

Figure 3-1 Example of normalized safety indicators [Schröder et al. 2009, p.47]

Figures 3-2 and 3-3 are examples that show two different ways to present the contribution of the most relevant individual radionuclides to the total value of an indicator. To keep the graphs easy to read, the number of curves in a graph should be limited, and the use of coloured lines is recommended. It should also be considered to add the combined contribution of the less relevant part of the radionuclides, represented as e.g. '*other radionuclides*', in order to make clear that no information is omitted. However, even for the most relevant radionuclides only, the y-axis range of indicators often stretches large intervals (six and nine orders of magnitude in Figures 3-2 and 3-3, respectively), and considerations should also be given to the range of values that will be presented.

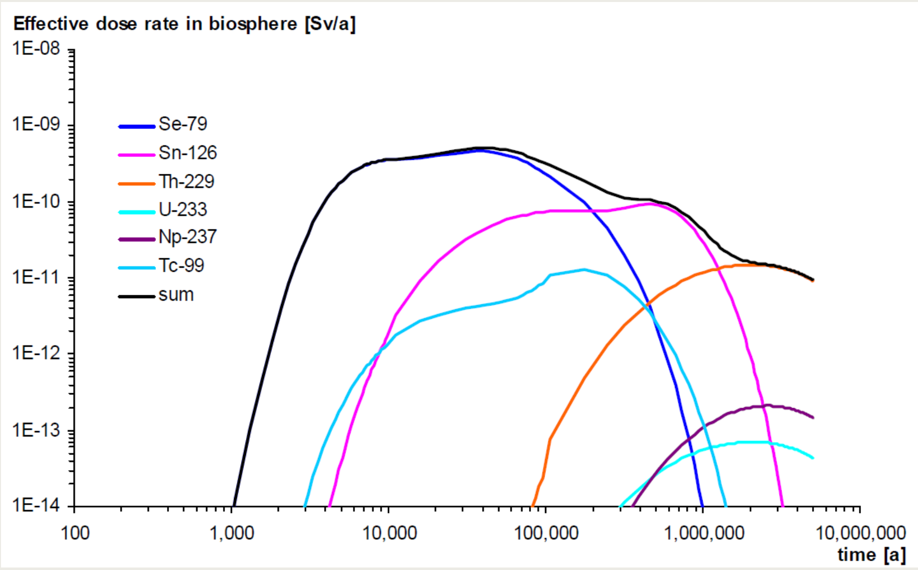

Figure 3-2 Example of safety indicator *Effective dose rate in the biosphere* including the contribution of the most relevant nuclides [Schröder et al. 2009, p.41]

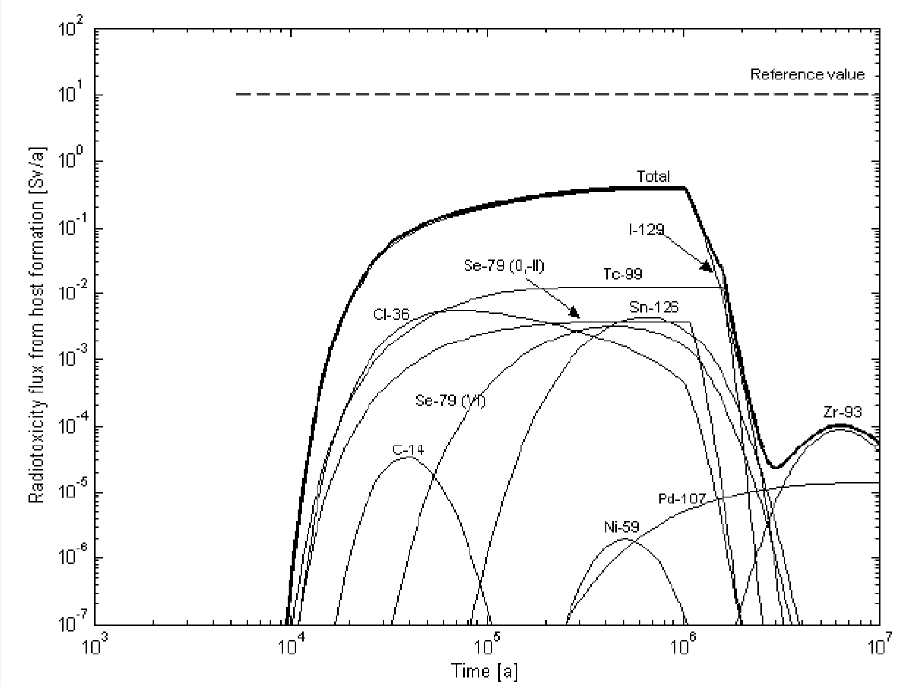

Figure 3-3 Example of indicator *Radiotoxicity flux from host formation* including the contribution of the most relevant nuclides [Marivoet et al. 2009, p.24]

Figure 3-4 shows an example of the combined presentation of indicators values in different compartments in one graph, that can give a clear overview on the distribution of single radionuclides (^{79}Se in this case) or the sum of radionuclides over the different compartments in a single graph.

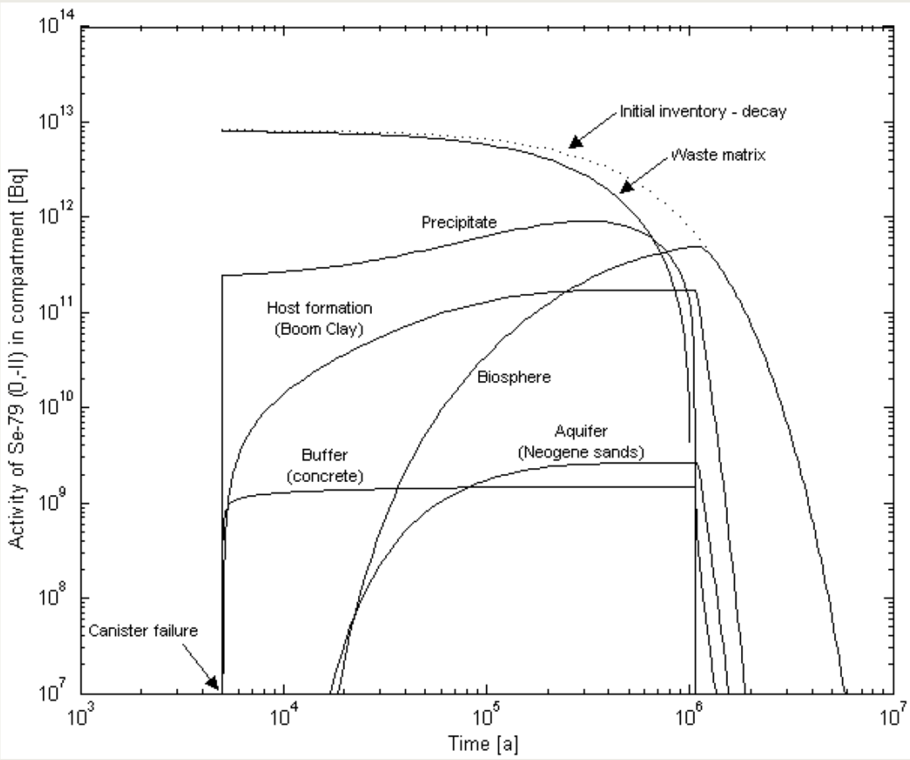

Figure 3-4 Example of indicator *Activity in compartments* for ^{79}Se [Marivoet et al. 2009, p.38]

An example of the presentation of uncertainty measures is given in Figure 3-5. The evolution of an indicator is plotted for different calculated parameter realizations (indicated as '*minimum*', '*maximum*', and '*average*'). It can also be considered to present individually all calculations outcomes of the uncertainty analyses, overlaid by uncertainty indicators (e.g. Figure 3-6). Such a representation allows making use of percentile values (rather than maximum and minimum values) without omitting any information. Which representation should be preferred in OPERA, depends on the uncertainty measures chosen and the calculation outcomes.

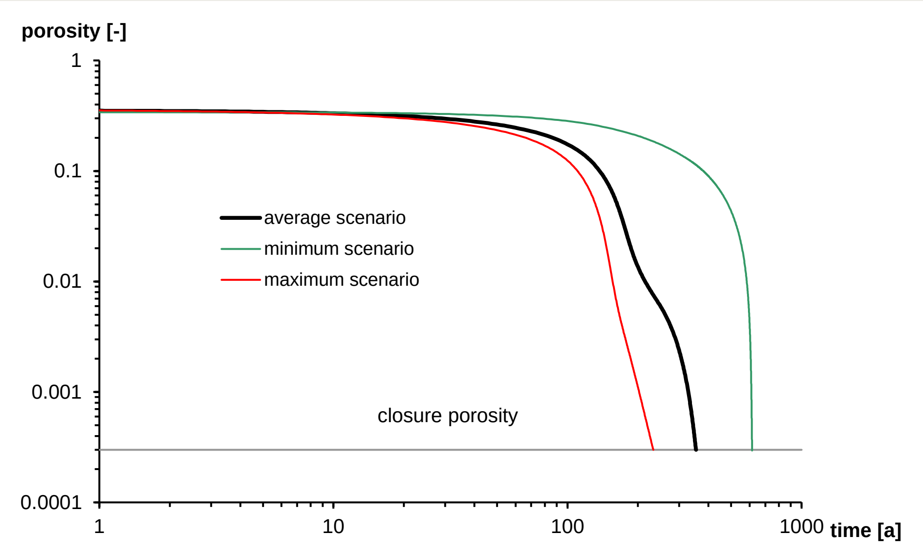

Figure 3-5 Example of indicator *Porosity of sealing plug* including uncertainty measure [Becker et al. 2009, p.63]

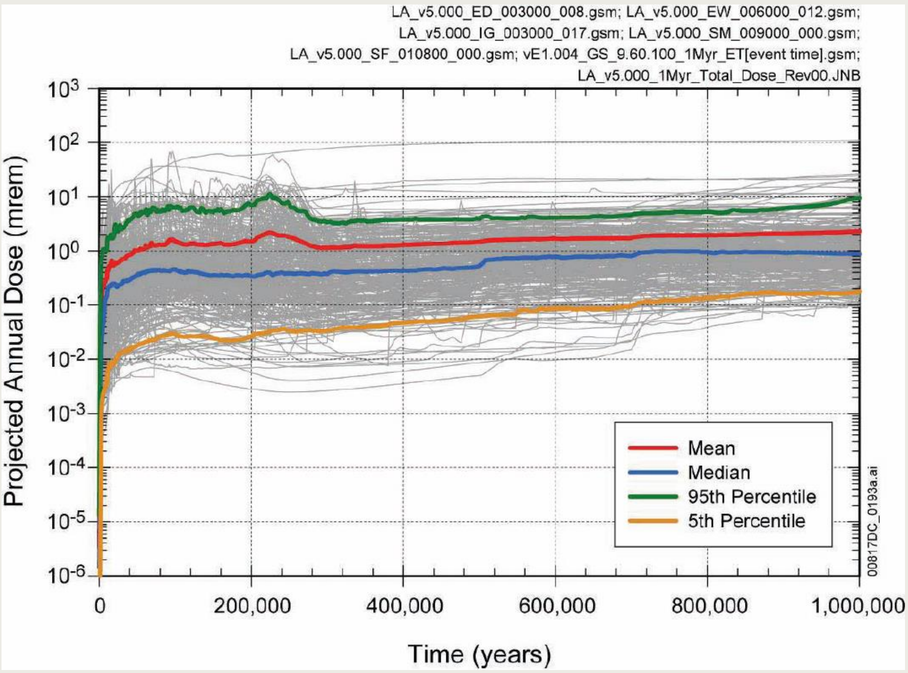

Figure 3-6 Example of safety Indicator *Projected Annual Dose*, including uncertainty measure [DOE 2007, p.S-41]

The radiotoxicity fluxes from different compartments represented in one plot show the impact of different barriers on the outflow of radionuclides and give a realistic picture of the barrier performance (Figure 3-7). Problems may occur with the representation of fluxes on logarithmic scale in case of a negative flux (i.e. influx instead of outflux). In the example of Figure 3-6, information on the flux out of the disposal cell in 850 and 4.800 year is invisible (i.e. can anything between insignificant small positive fluxes up to large negative fluxes). However, due to the large range of the *y*-axis (12 orders of magnitude), the application of a linear scale is not helpful. In such a case, it is advisable to use separate plots that represent positive and negative flux (or influx and outflux to a compartment) on *log*-scale instead.

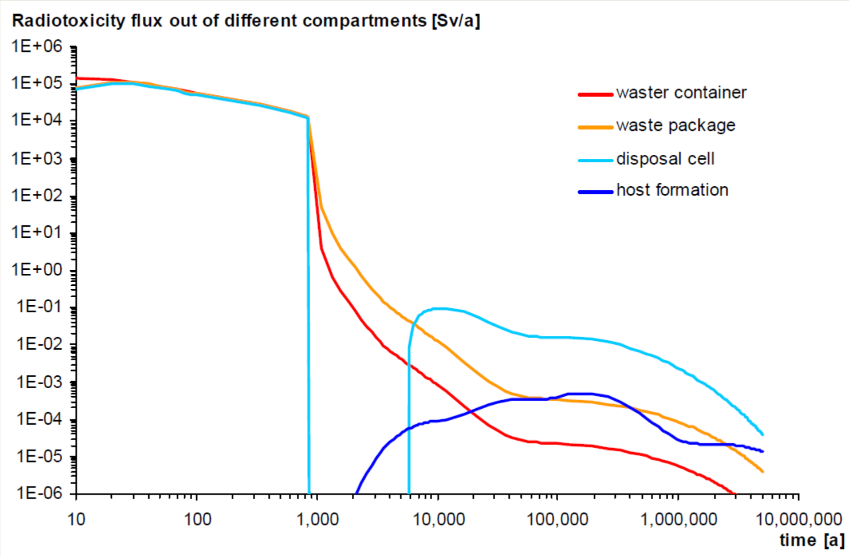

Figure 3-7 Example of indicator *Radiotoxicity flux out of different compartments* [Schröder et al. 2009, p.62]

Figure 3-8 gives an example of a graphical representation with strongly overlapping curves (i.e. values of different curves are largely the same). This should be avoided, because it can result in difficulties to read the graph. In such a case, considerations should be given whether the combined presentation is more beneficial or the presentation of an outcome over several graphs.

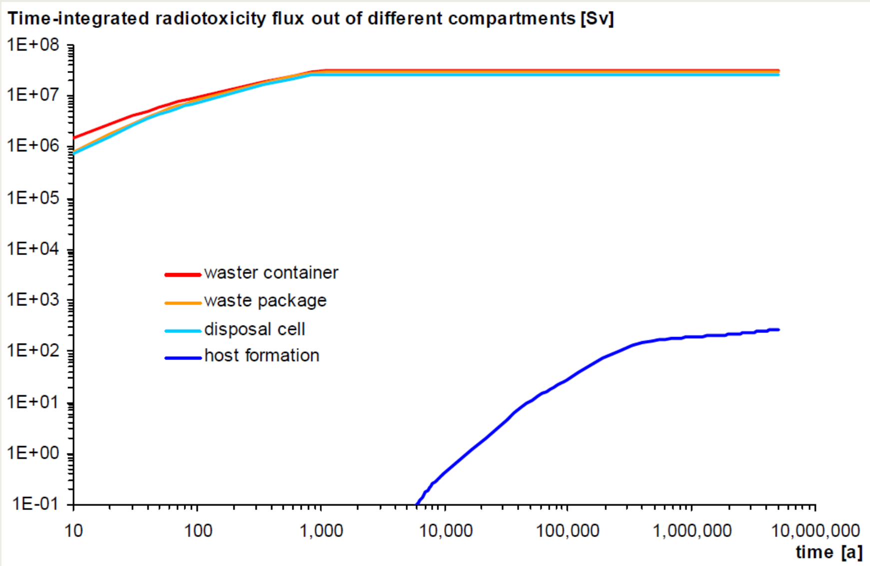

Figure 3-8 Example of indicator *time-integrated radiotoxicity flux out of different compartments* [Schröder et al. 2009, p.63]

Figure 3-9 gives an example of a graphical representation of safety indicators, where - unlike in the other examples presented - the risk increases at the right end of the depicted timescale. In case risks are not clearly decreasing at the end of the calculation interval, it needs to be carefully explained, which evolution of the risk indicator is expected for time periods after the depicted period, and what the relevance of such an increase is.

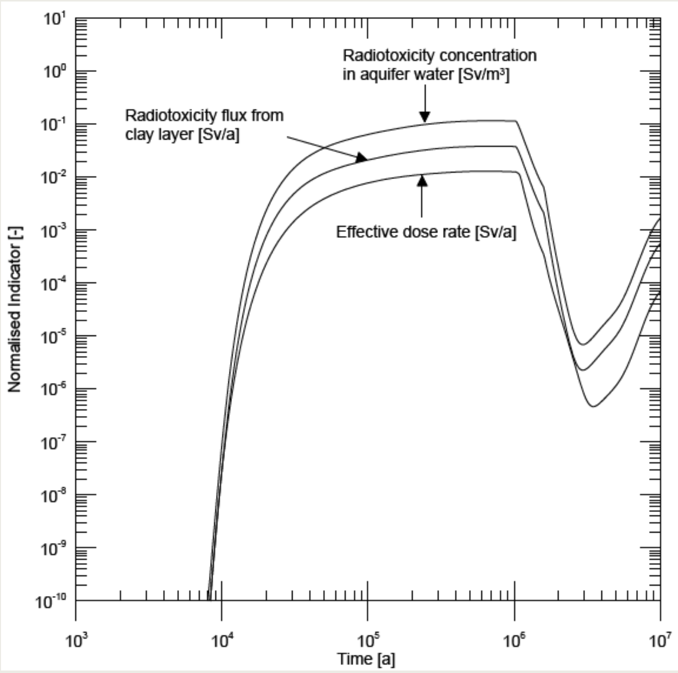

Figure 3-9 Example of normalized safety indicators, with increasing risk at the end of the depicted timescale [Becker et al. 2009, p.40]

3.2. Radionuclides

Safety and performance indicators may be based on the total radionuclides spectrum as well as on individual radionuclides. Indicators based on individual nuclides can improve the understanding of and communication about the safety a system and its individual barriers provides, for each radionuclide or decay chain of interest [Becker et al. 2009, p. 71]. They may be especially interesting in case that only a few radionuclides are dominating the larger part of the total dose rate.

The performance indicators evaluated in [Schröder et al. 2009] and [Marivoet et al. 2009] - except for the *transport time through compartments* - include a presentation of the sum of radionuclides, which gives a clear illustration in terms of the overall risk. Although no radionuclide-specific analyses were given in [Schröder et al. 2009], it was found useful to check the consistency of some output parameters by analysing the main contributing radionuclides. The number of individual radionuclides that are responsible for more than 90% of the total dose rate was rather limited (^{79}Se, ^{126}Sn, ^{229}Th, ^{233}U, ^{237}Np and ^{99}Tc), and in the first 100’000 years, the dose rate is mainly determined by ^{79}Se, followed by ^{126}Sn in the interval until 1’000’000 years and ^{229}Th for later times. All other radionuclides contribute less than 10% to the total dose rate at any time. However, it needs to be understood that the set of relevant radionuclides can differ per indicator, compartment and scenario considered and therefore a selection of relevant radionuclides must be performed specifically for each indicator and compartment (e.g. ^{241}Am can be relevant in EBS compartments).

With respect to the representation of decay chains of actinides, here usually only the longer living radionuclides are explicitly modelled, with the number of moles of a daughter nuclide increased by the number of moles of the non-considered parent nuclides. Simulations of the migration of actinides must take account of the decay chains. The main isotopes in the four decay chains to be considered are:

- 4*N*: $^{248}Cm \rightarrow {}^{244}Pu \rightarrow {}^{240}Pu \rightarrow {}^{236}U \rightarrow {}^{232}Th$
- 4*N*+1: $^{245}Cm \rightarrow {}^{241}Pu \rightarrow {}^{241}Am \rightarrow {}^{237}Np \rightarrow {}^{233}U \rightarrow {}^{229}Th$
- 4*N*+2: $^{242}Pu \rightarrow {}^{238}U \rightarrow {}^{234}U \rightarrow {}^{230}Th \rightarrow {}^{226}Ra$
- 4*N*+3: $^{247}Cm \rightarrow {}^{243}Am \rightarrow {}^{239}Pu \rightarrow {}^{235}U \rightarrow {}^{231}Pa$

For OPERA safety assessment calculations we recommend the computation and graphical representation of all safety and performance indicators based on the sum of all radionuclides considered in OPERA. Additionally, relevant individual radionuclides should be presented in order to:

- visualize the contribution of the individual radionuclides to the overall radiotoxicity (flux);
- to visualize the different distribution and behaviour of the individual radionuclides;
- allow external reviewers to reproduce and understand the assessment outcomes and final conclusions.

Consideration should be given to present radionuclides of minor importance that contribute only insignificantly to the indicators outcome, e.g. < 0.1%, as '*sum of other radionuclides*'. However, dependent on the outcome, in few cases one may choose to present individual radionuclides with only a minor relevance in a certain compartment, e.g. when it helps to understand the overall migration behaviour of the radionuclide. Also, the number of radionuclides or lines in a graph should be limited to keep the figures readable and clear, by presenting only the most important radionuclides. The final selection of the numbers of radionuclides will depend on the model representation used for the safety assessment calculations and its calculation outcomes.

3.3. Uncertainty representation

OPERA intends to analyse the role of uncertainty on the calculation outcomes, and therefore, additionally to central or mean values, uncertainty measures need to be added to the graphical outputs of the indicators. Uncertainty methods for the OPERA Safety Case are part of Task 7.3.2, *Uncertainty analysis* [Becker et al. 2013] and will not be discussed here in further detail.

A frequently used uncertainty measure is the confidence interval, based on e.g. the 90-, 95- or 99-percentile values (see Figure 3-6). Also the maximum and minimum values can be represented (Figure 3-5). One may also consider to (additionally) represent all sample realizations (Figure 3-6), but an overload of such a figure should be avoided (i.e. in practice, only one feature can be presented in each figure). The selection of suitable central value and uncertainty measures for the OPERA Safety Case is part of Task 7.3.2, *Uncertainty analysis*

3.4. Overview of proposed graphical and tabular representation

While in the main OPERA Safety Case report it is recommended to graphically present only a small number of representative data, the results of the performance assessment calculations will be documented in all relevant details in an underlying report (M7.3.3.1 and/or M7.3.3.2; [Verhoef & Schröder 2011]), for the convenience of both reviewers and end users. However, in view of very large amounts of potential combinations of indicators, compartments, radionuclides and uncertainty measures for each calculation scenario, some selections need to be done, in order to avoid the presentation of hundreds of graphs that does not contain relevant information on the performance of disposal components, the principal migration behaviour of relevant radionuclides or on the overall safety of the disposal concept assessed. As discussed in the previous section, combination of several features in one graph (e.g. several radionuclides or several compartments) is recommended, but it can only partially be defined in advance what information will be relevant once the performance assessments calculations for OPERA will be conducted. The experts who carry out performance assessment calculation therefore have to decide which data are presented graphically as well as on the specific format to be used. Nevertheless, in the sections below, a concise overview is given on what can be envisaged from current point of view as recommended minimum number of presentations for the three groups of indicators identified.

Safety indicators

Safety indicators are very valuable in external communications. Therefore, we recommend a detailed reporting of the safety indicators results, both in graphical and in tabular form. Table 3-4 show an estimation of the minimum number of graphical representations for each scenario.

Table 3-4 Expected minimum graphical output for the safety indicators in the OPERA Safety Case

Safety Indicator	compartments	number of graphs
Effective dose rate	biosphere	1xΣU, 1xI
Radiotoxicity concentration in biosphere water	biosphere water	1xΣU, 1xI
Radiotoxicity flux from geosphere	geosphere	1xΣU, 1xI
Power density in the groundwater	groundwater	1xΣU, 1xI
	overall number of graphs	8

ΣU = graph for the **sum** of radionuclides, including **uncertainty measure**

I = graph with **relevant individual radionuclides**

Furthermore, one may consider presenting graphs of individual, relevant radionuclides, including uncertainty measures, in case this is envisaged as relevant in order to clarify the outcome depicted in the graphs summarized in Table 3-4.

The peak values of each safety indicator, time step of the peak values, and the reference values should be summarized in one table (see example
Table 3-5). Optionally, the peak values can be accompanied by an uncertainty indicator or range.

Table 3-5 Example of a table template for the peak value of the safety indicators

Safety indicator	peak value	time step of peak value	reference value
Effective dose rate			
Radiotoxicity concentration in biosphere water			
Radiotoxicity flux from biosphere			
Power density in the groundwater			

Additionally, tables may be used to represent the contribution of individual (relevant) radionuclides to the peak value of each indicator, or the peak value for the most relevant radionuclides for each indicator. However, such tables only have additional value if the contribution of individual radionuclides to the peak values is not already obvious from one of the graphs summarized in
Table 3-5 (i.e. in case one radionuclide clearly dominates the overall value in a certain time interval).

Performance indicators

The graphical representation of all performance indicators may lead to a large number of figures. Table 3-6 and 3-7 show an estimation of the minimum number of graphical representations resulting for each scenario. Table 3-7 is limited to the primary compartments defined in Table 2-1. If calculated for all subcompartments defined in Table 2-1, then the number of figures can go much higher. Not all figures are interesting though. For reporting, an evaluation and selection of those figures that contain valuable information should be made. However, as discussed above, such a selection is beyond the scope of this report.

Table 3-6 gives an overview of the number of graphs for the performance indicators directly related to a certain compartment (see also Table 2-3).

Table 3-6 Expected minimum graphical output for performance indicators related to pre-defined compartments

Performance Indicator	compartments	number of graphs
Host rock confinement factor	host rock, waste package	1xΣU, 1xI
Transport time through compartments	waste package - biosphere, waste package - geosphere*	3
Contribution of each safety function	waste package, host rock, biosphere	1xΣ, ≥5xI
	overall number of graphs	≥11

* dependent on reference value/safety indicator chosen
Σ = graph for the **sum** of radionuclides
ΣU = graph for the **sum** of radionuclides, including **uncertainty measure**
I = graph with **relevant individual radionuclides**

Table 3-7 gives an overview of the number of graphs for the performance indicators that can be applied to several compartments, only considering primary compartments (see also Table 2-5). For both groups of performance indicators one may consider to present graphs of individual, relevant radionuclides, including uncertainty measures. As discussed already for the safety indicators, this should only be envisaged when found relevant in order to clarify the outcome depicted in the graphs summarized in Table 3-6 and Table 3-7.

Table 3-7 Expected minimum graphical output for generally-applicable performance indicators

Performance Indicator	compartments	number of graphs
Radiotoxicity in compartments	waste package, EBS, host rock, geosphere, biosphere	1xΣ, 5xU, ≥5xI
Radiotoxicity flux from compartments		1xΣ, 5xU, ≥5xI
Time-integrated radiotoxicity flux from compartments		1xΣ, 5xU, ≥5xI
Radiotoxicity concentration in compartment water		1xΣ, 5xU, ≥5xI
	overall number of graphs	≥44

Σ = graph for the **sum** of radionuclides
U =graph with **uncertainty measure** for each compartment
I = graph with **relevant individual radionuclides**

Because for performance indicators often the evolution in time is more important than the peak values, a tabular format might be of less relevance for most of the indicators of this group. One exception to be considered is the *Time-integrated radiotoxicity flux* indicator, which develops to rather constant values in time (see Table 3-2 and Figure 3-8). In this case, the values of the indicator for each primary compartment at the end of the calculation interval can be listed in a Table, either for the sum of all radionuclides or for the most relevant radionuclides (see example Table 3-8).

Table 3-8 Example of a table for the performance indicator *Time integrated radiotoxicity flux* for individual radionuclides

Radionuclide	Time-integrated radiotoxicity flux [Sv/a]				
	Waste package	EBS	Host rock	Geosphere	Biosphere

Another exception is the performance indicator *Contribution of each safety function*, which can easily be used to present the outcomes for the last calculation time step for selected radionuclides and/or the sum of all radionuclides (Table 3-9).

Table 3-9 Example of a table for the performance indicators *Contribution of each safety function*

Radionuclide	Contribution of each safety function [%]			
	C-RT	R1-RT	R3-RT	R4-RT

Performance indicators based on safety function

Likewise as discussed for the performance indicators, for the performance indicators based on safety function, a minimum number of graphs for each scenario can be defined (Table 3-10).

Table 3-10 Expected minimum graphical output for performance indicators based on safety functions

Performance indicators based on safety functions	compartments	number of graphs
Containment (C-RT)	waste package	1xΣU, ≥5xI
Limitation of release (R1-RT)	waste package	1xΣU, ≥5xI
Retardation due to migration through buffer and host formation (R3 - RT)	waste package, host rock	1xΣU, ≥5xI
Retardation due to migration through geosphere (R4 - RT)	host rock, biosphere	1xΣU, ≥5xI
Performance of the integrated repository system (IRS-RT)	waste package, biosphere	1xΣU, ≥5xI
Activity based indicators (C, R1, R3, R4, IRS)	waste package, host rock, biosphere	5x(1xΣU, ≥5xI)
	overall number of graphs	≥60

Σ = graph for the **sum** of radionuclides
ΣU = graph for the **sum** of radionuclides, including **uncertainty measure**
U =graph with **uncertainty measure** for each compartment
I = graph with **relevant individual radionuclides**

4. References

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