OPERA

ENGAGED Recommended reference values for the OPERA safety assessment

OPERA-PU-NRG1222

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.

OPERA-PU-NRG1222
Title: ENGAGED - Recommended reference values for the OPERA safety assessment
Authors: J. Hart & T.J. Schröder
Date of publication: 4 January 2017
Keywords: Reference values, safety assessment, safety indicator

Table of contents

Summary

As part of the OPERA Safety Case, safety assessments are performed. Some of the outcomes of these assessments are expressed as so-called ‘safety indicators’ that allow to judge the safety of the assessed disposal facility. Each safety indicator has to be accompanied by a reference value that can serve as ‘yardstick’ to judge whether a calculation outcome can be considered safe.

In this report reference values have been derived for the safety indicators *Effective dose rate*, *Radiotoxicity concentration in biosphere water*, and *Radiotoxicity flux from geosphere*, which will be analysed as part of the OPERA performance assessment:

Safety Indicator	
Effective dose rate	0.1 mSv/a
Radiotoxicity concentration in biosphere water	8 µSv/m^3
Radiotoxicity flux from geosphere	0.25 Sv/a

These reference values are based on legal limits as well as on considerations on radionuclide concentrations in biosphere water and estimates of water flows in the subsurface of the Netherlands.

Samenvatting

Als onderdeel van de OPERA Safety Case worden lange-termijn veiligheidsberekeningen uitgevoerd. De uitkomsten van deze berekeningen worden uitgedrukt in de vorm van zogenoemde veiligheidsindicatoren, waarmee de veiligheid van de eindbergingsfaciliteit kan worden beoordeeld. De berekende veiligheidsindicatoren worden getoetst aan bijbehorende referentiewaarden.

In dit rapport zijn referentiewaarden bepaald voor de veiligheidsindicatoren *Effectief dosistempo*, *Radiotoxiciteitsconcentratie in biosfeer water*, en *Radiotoxiciteitsflux vanuit de geosfeer*, die zullen worden bepaald als onderdeel van de veiligheidsberekeningen uitgevoerd in OPERA:

Veiligheidsindicator	
Effectief dosistempo	0,1 mSv/a
Radiotoxiciteitsconcentratie in biosfeer water	8 µSv/m^3
Radiotoxiciteitsflux vanuit de geosfeer	0,25 Sv/a

De referentiewaarden zijn gebaseerd op wettelijke limieten, als ook op beschouwingen over radionuclideconcentraties in biosfeer water en schattingen van de waterstromen in de Nederlandse ondergrond.

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]. This report (M1.2.2.2) provides input of the OPERA research project *ENGAGEDs*[1] work on reference values, as part of OPERA Task 1.2.2, *Legal requirements*.

1.2. Objectives

In the OPERA research programme [1], the long-term, post-closure safety of the proposed generic reference disposal concept for radioactive waste is being evaluated and assessed [2]. The OPERA programme follows in general terms the methodology known as '*Safety Case*' [3, 4, 5, 6, 7]. Central part of the Safety Case is the safety assessment which will be performed in OPERA WP7 in order to investigate potential risks of the OPERA disposal concept. The outcome of the assessments are expressed as co-called 'safety and performance indicators' [8, 9, 10, 11, 12, 13], which give an indication of the performance of system components, such as the engineered barriers and host rock, and related risks.

For the OPERA Safety Case, safety and performance indicators are elaborated in [12, 13]. For each of the three safety indicators recommended in [12; Section 5.1], a reference value has to be defined that serves as a 'yardstick' with which the assessment outcomes of the safety assessment calculations can be compared. The main objective of this report is to provide a list of reference values to be used in the OPERA Safety Case.

The definition of reference values is more than just a technical peculiarity: as noted in [14; p.1], the disposal of radioactive waste is a matter of public concern and comes with controversial views of different stakeholders. Stakeholders and the public are sensible to safety claims and can be easily reluctant, and even if reference values of safety and/or performance indicators are supported by a clear argumentation, there is a strong normative aspect that relates to the question what is considered as 'acceptable' by society.

Within the ENGAGED stakeholder workshop [15] it was generally agreed that the definition of reference values is an important issue in which public and stakeholders should be heard in [15 , Section 8.4.2]. On the other hand, the topic of safety and performance indicators itself is of too abstract and technical nature, and in the ENGAGED workshop no solid suggestions with respect to reference values for these properties were given: due to the early phase of the disposal process in the Netherlands, eventual positions on this matter have still to be established.

Although there are currently insufficient leads to establish reference values for the OPERA Safety Case which might be regard as 'acceptable' by the current (and future) Dutch society, it is assumed to be beneficial to have a societal agreement on the reference values to be applied for future safety cases. Therefore the second objective of this document is to provide some condensed background information on '*reference values*' that may serve as a first lead for future informed discussions on what is societal 'acceptable'.

The information provided here includes conceptual aspects related to '*safety indicators*' in more general; for more information we refer to [12, 13] and the literature cited therein.

[1] *End repository Network Geared towards Actor Groups involvement and Effective Decision making*

1.3. Realization

This document represents the ENGAGED report M1.2.2.2, *Recommended reference values for the OPERA safety assessment* and is prepared by NRG. It builds on the interim report M1.2.2.1, *Interim report on reference values*, and addresses the indicators proposed in [12]. The present report is mainly based on recommendations of the ICRP, NEA and IAEA and the outcomes of the European Framework projects *SPIN* [8] and *PAMINA* [9].

1.4. Explanation contents

Chapter 2 briefly summarizes the general concepts behind safety indicators and provides an overview of reference values for the indicators under consideration. In Chapter 3, reference values for safety indicators considered in OPERA Safety Case are provided. Chapter 4 gives a summary of the recommended reference values and outlines lessons learned. In Appendix A, some additional explanations on the derivation of the complementary reference values are given.

2. Safety indicators and reference values

2.1. The role of indicators in a Safety Case

Safety assessment calculations are an integral part of a Safety Case of the final disposal of radioactive waste [e.g. 6; p.1]. Safety assessment encompasses numerical evaluations of performance of the disposal system and of radionuclide migration from the waste to the biosphere and their potential effects on future populations. Such calculations are based on a combination of different sub-models representing all safety-relevant components of a repository, the host rock, the enclosing geosphere and the biosphere [16]. The calculations performed result in a huge numerical output for each scenario considered in the Safety Case. In order to analyse the system's safety and performance and to communicate calculation outcomes to a larger public, the calculation results are processed in order to derive meaningful entities or '*indicators*'.

In [17], *indicators* are defined as:

- 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

In radioactive waste management, so-called '*Safety and Performance Indicators*' are used to express the numerical outcomes of assessment calculations. *Performance indicators* provide measures of the performance of a disposal system or of particular aspects or components of a disposal system. *Safety indicators* are regarded as a special type of performance indicators used to assess the system's overall safety [17, p.7].

Safety and performance indicators are defined in a way that they can deliver meaningful information on a system's behaviour and overall safety. With respect to their role in the safety case, in [17, p.5] it is stated that safety indicators are used to construct arguments on "*the acceptability, in terms of safety, of the evaluated performance*". The most widely used safety indicator for assessing the (radiological) safety of radioactive waste disposal is the *effective dose rate*, implemented in several national regulations.

Safety indicators can also be linked to so-called '*safety statements*', in order to obtain clear statements on the safety of a disposal [9, p.69f], e.g.:

> "*Effective dose rate: Future generations living in the vicinity of the repository will not be exposed at any time to unacceptable concentrations of radionuclides released from the repository. By evaluating carefully different exposure paths and weighting all biological effects to a human individual, the impact on human health by the incorporation of radionuclides released from the repository is found to be insignificant*".

The development and use of safety and performance Indicators was discussed in more depth in several international projects [e.g. 17, 8, 9, 11; see for an overview also 12, 13]. In [12, 13] a set of safety and performance indicators for the OPERA Safety Case was proposed.

Of interest for the present report are the safety indicators, because they represent a measure for the safety of a disposal system. Consequently, a safety indicator has to be valued against a '*reference value*' which serves as 'yardstick' to assess whether a disposal facility can be considered 'safe'. This implies the evaluation whether the calculated values of considered safety indicators do not exceed their reference values at all time steps and for all scenarios of concern.

2.2. Safety indicators

2.2.1. General concepts

The safety against hazards provided by a geological disposal facility is a principal theme in radioactive waste management. An important principle with a broad support base is that a similar level of protection should be provided for future generations as that provided for the current generation (e.g. [18 , p.7]). It is recognized that safety assessments should be performed sufficiently far into the future to ensure that any peak in the potential radiological impact of the disposal facility has been taken into account. Thereby it is also recognized that the uncertainty of the calculated risk increases in time. When assessing the safety of a facility for the disposal of radioactive waste, one important question is what indicator(s) can be used to assess the safety on a long-term.

In early approaches it was argued that radioactive waste can be considered as safe when its radiotoxicity is comparable to the uranium ore from which the fuel was fabricated, resulting in periods of about 10.000 years for direct disposal to 500 years in case of reprocessing and reuse of the fuel (e.g. [19 , Fig. 8.2, p.261]). However, this argumentation is rather superficial since also natural uranium ore has to be considered toxic, with uranium mining tailings a relevant point of concern [e.g. 20; p.291]. Besides, it gives not much information about the actual risk (or dose rates) to humans since it involves no further analysis on the actual system selected for disposal.

Under natural conditions or in a geological disposal situation, the low mobility of uranium or other fractions of the waste will limit the exposure and thus realize an effective protection of mankind and the environment. Thus, risks related to natural situations and disposal situations are not directly comparable, making the overall radiotoxicity of the waste a less useful indicator for safety.

Requirements for safety indicators

As a consequence, other indicators have been established, also considering that such quantities would constitute a number of characteristics to serve as a basis for judging the quality of an indicator [18, 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.

Primary and complementary indicators

A “safety indicator” is a measure for assessing the long-term safety of a facility for the disposal of radioactive waste. The term safety indicator is defined in the IAEA Safety Glossary [21; p.176] as:

"*Safety Indicator: A quantity used in assessments as a measure of the radiological impact of a source or practice, or of the performance of protection and safety provisions, other than a prediction of dose or risk.*

Another definition of the term safety indicator comes from the EU-FP6 project PAMINA [22; p.6]:

"*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.*"

It was recognized in [18, p.10] that a single indicator cannot be expected to meet all of the desirable characteristics mentioned above. Indicators may also constitute various characteristics: a distinction can be made between *primary indicators*, which are related to reference values (or constraints) defined in regulations and which should not be exceeded, and *complementary indicators* that can be additionally used to support the safety case [18; p.10]. A widely used and generally accepted indicator is the '*effective dose rate*', and is often considered as the *basic* or *primary safety indicator*.

It was suggested in [18, p.8] that primary indicators (e.g. dose rate) should be supplemented by '*intermediate quantities*' which rely less on assumptions about future conditions, such as concentrations or fluxes (Figure 2-1; from [18, p.8]).

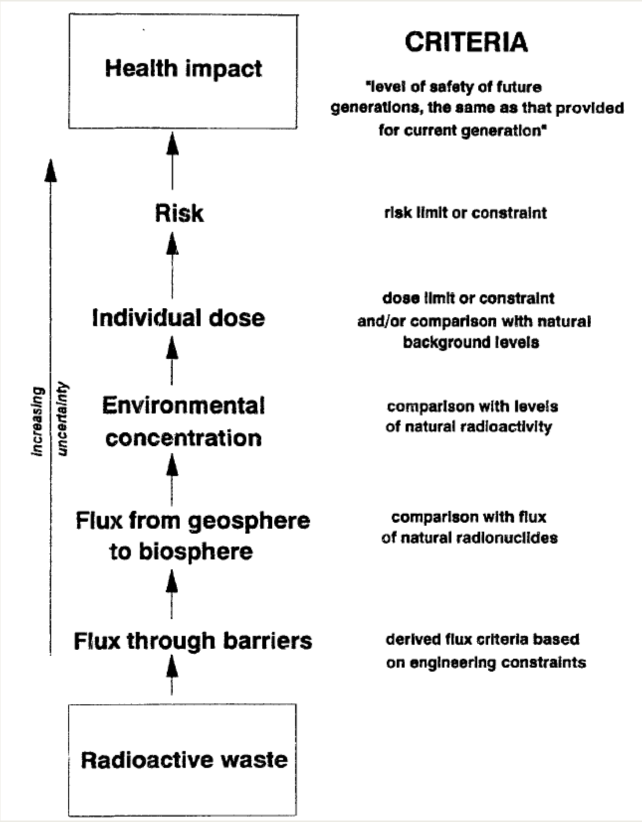

Figure 2-1:Hierarchy of safety indicators

These complementary indicators are considered useful if they can be compared to some known data based on natural processes. It was also argued that these complementary indicators may provide for flexibility, diversity and transparency for a wide range of stakeholders (technical and non-technical). Complementary indicators would allow comparisons with system features more easily understood, e.g. background radiation levels, fluxes and concentrations of naturally occurring radionuclides. However, a lack of international consensus about the application of complementary indicators needs to be mentioned, and some lack of understanding on how to apply complementary indicators to safety cases [17]. Other practical issues relate to the availability of information on radionuclide concentrations and fluxes present in the natural environment, and their variability, for use in the development of reference values.

Embedding of safety indicators in national regulations

The way safety indicators and their reference values as well as other indicators are addressed in national regulations differ from '*non-prescriptive*', over '*partially prescriptive*' to '*fully prescriptive*' [11, p.41*f*]. *Non-prescriptive regulation* does not mandate the use of complementary indicators and does not specify particular indicators or corresponding reference values to be used. However, regulations are often accompanied by non-statutory guidance documents that set-out advice how to meet regulations and thus might include recommendations on complementary indicators.

In *partially prescriptive regulation*, complementary indicators are found sufficiently important for demonstrating repository safety, and requirements are defined, i.e. one or few specific indicators have to be addressed in a safety assessment in addition to dose and/or risk. The legislation in the USA can be characterized as *fully prescriptive regulation*, here precise details are given what assessment calculations the repository developer must perform.

Consideration of timescales

The uncertainty of estimated values of indicators increases with time since future evolutions and/or events in the long term may change the development of the disposal facility foreseen at present. In ([18], p.18), it was therefore proposed to distinguish between three timescales:

- closure of the facility to 10'000 years (early timeframe)
- 10'000 to 1'000'000 years (intermediate timeframe)
- beyond 1'000'000 years (late timeframe).

Here it is important to note that the demarcation times of 10'000 and 1'000'000 years are indicative only.

For the early timeframe, it is recognized that information about the repository is expected to be maintained at least several hundreds of years after closure. In tectonically stable areas, significant natural changes in the geological environment are unlikely within the first 10'000 years. In addition, the biosphere can be assumed to be comparable to present day conditions, 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*" ([18], p.18). Although considerable uncertainty may exist during this time period, it is assumed to be reasonable to provide quantitative estimates for the indicators in this period. For example, the *effective dose rate* may be quantified by defining ranges of biosphere conditions and emphasizing that calculation results are general indications rather than accurate predictions of the repository's future performance.

In the intermediate timeframe of 10'000 to 1'000'000 years, long-term natural changes in the climate will occur with glacial or periglacial conditions present for substantial periods of time. The impacts of these natural phenomena, e.g. a sea level drop up to 140 m, can be evaluated by generic modelling of processes on a continental scale (e.g. [23]). In general, major tectonic changes are not expected during this time frame, thus no large impacts on the general transport routes of radionuclides from the deep geological repositories to the biosphere are expected. On the other hand, possible biosphere conditions and human behaviour might change considerably so that the modelling of biospheric transport, uptake and exposure would bear significant uncertainties. However, calculations can be performed assuming present conditions for illustration, resulting in indicative dose rates in the long term.

In the late time frame, beyond 1 million years, uncertainty increases, and beyond 10 million years, unpredictable large scale changes take place, e.g., the formation of mountains, large sea level changes, continental drift, massive erosion, etc. It is therefore concluded that little credibility can be obtained from safety assessments and calculated values of safety indicators beyond 1 million years.

2.2.2. Safety indicators considered in EU and NEA projects

In the *SPIN* project the following types of principal safety indicators [8, p.3*ff*] were identified:

- ***'Dose-rate'-type***, e.g. *Individual dose rate*, *Collective dose rate*, or *Dose rate to animals and plants*;
- '***Risk'-type***, e.g. *Individual risk* or, *Societal risk;*
- '***Concentration'-type***, e.g. Concentration in groundwater, biosphere water, soil or air
- '***Flux'-type***, e.g. *Radiotoxicity release*

In line with IAEA Tecdoc 767 [18], the *SPIN* project recognized that the '*effective dose rate*' has been applied widely in safety analyses and can be considered as the basic safety indicator. The *effective dose rate* is defined as "*the equivalent dose to an average member of the group of the most exposed individuals in a year*" [8, p.1].

A number of benefits of the use of complementary safety indicators is discussed in [17], among which the possibility to address uncertainties about the future validity of the assumed relationship between dose and detriment [ICRP 77, 1997]. Two additional, complementary safety indicators where identified and assessed in *SPIN* [8] and *PAMINA* [9]:

- *Radiotoxicity concentration in biosphere water*, a measure of the radiological consequences resulting from the ingestion of water from the biosphere, contaminated by radionuclides from the waste. This indicator is found to be preferential for the intermediate timeframe;

- *Radiotoxicity flux from geosphere*, a hypothetical measure of the annual radiological impact caused by ingestion of radionuclides originating from the waste as they are released from the geosphere to biosphere. This indicator is found to be preferential for the late timeframe.

With respect to the use of *radionuclide concentrations*, in [17] it was argued that concentrations in near-surface locations are likely to be of most use and can be compared to concentrations of naturally occurring radioactive elements, while for concentrations in the near-field e.g. inside a borehole, no meaningful reference value can be defined on basis of natural analogues. As complication was noted that with natural concentration based reference values, sites or host rocks with high natural concentrations would look more favourable. Consequently, it was suggested not to use such an indicator for site-comparisons. In case of radionuclides without natural counterparts, it was noted that reference values cannot be defined directly, but must be based on comparisons of related risks.

With respect to the use of *radionuclide fluxes*, the same arguments apply, leading to the conclusion that only fluxes outside the near-field are of relevance. Fluxes to the biosphere, or between biosphere compartments are seen as potential meaningful indicators.

PAMINA [9] also discusses the use of *risk* as safety indicator. Primary, risk is defined as a certain consequence multiplied by the occurrence of the situation that leads to it. The concept allows to cumulate risks from different scenarios in a single number, with the cumulated scenario probabilities of a complete set of scenarios adding up to 1. Furthermore, by multiplying dose or cumulated doses over all scenarios by a risk-per-dose coefficient, the more abstract dose rate can be translated into a risk (or change) to develop cancer. The advantage of such an approach it to be able to compare potential risks from the geological disposal of waste with risks from other activities or occurrences, e.g. the risk of having a fatal accident in road traffic ($6 \cdot 10^{-5}$ per year in Germany in the reference year 2007), or the risk of dying in a plane crash ($1 \cdot 10^{-7}$ per year) [9, p.26].

The NEA project *MeSA* (Methods for Safety Assessment) identified a

> "*growing international interest in the subject but also highlighted a clear lack of consistency in the terminology, characteristics and methods of application of the indicators used by different organisations*" [11, p.3].

Table 2-1 gives an overview of safety indicators identified by the MeSA Questionnaire, showing a large variety of safety indicators with some degree of overlap (adapted from [11, Table 2, p.34ff].

Table 2-1: Safety indicators identified by MeSA Questionnaire [11]

Indicator	Description	Source
Concentration in groundwater	Aquifer above host clay formation	SCK•CEN (Belgium)
Flux out of host formation	Aquifer above host clay formation	
Containment factor	Ratio of released radiotoxicity (up to 1 Ma) / initial radiotoxicity at time of disposal	
Source term	Water activity on the interface repository/host structure	RAWRA (Czech Republic)
Groundwater activity	Activity of groundwater on the interface host structure/biosphere	
Concentration of radionuclides in water	PA	NRI (Czech Republic)
Alternative indicator (no specific term)	Outer border of containment providing rock zone	GRS-K (Germany)
Radiotoxicity concentration in biosphere water	Near surface groundwater	GRS-B (Germany)
Power density in groundwater	Near surface groundwater	
Radiotoxicity flux from the geosphere	Interface host rock/overburden	
Radiotoxicity flux from geosphere	Near-surface groundwater	
Index of Radiological Insignificance (RGI)	Barrier system within and including the containment providing rock zone*	
Radionuclide concentrations in groundwater	Generic site in Japan	JAEA (Japan)
Effective dose rate	Biosphere	NRG (The Netherlands)
Radiotoxicity concentration in biosphere water	Biosphere water (rivers)	
Power density in groundwater	Groundwater	
Radiotoxicity flux from geosphere	Flux from geosphere to biosphere	
Relative activity concentration in biosphere water	Biosphere water	
Radionuclide concentration in the biosphere water	In the water course used by the receptor (well or river)	ENRESA (Spain)
Radiotoxicity flux from the geosphere	At the interface between the geosphere and biosphere	
Power density in biosphere water	In the water course used by the receptor (well or river)	
RTI of waste on ingestion	Throughout the system (once the waste starts to disperse)	Nagra (Switzerland)
RTI flux to biosphere	Geosphere/biosphere interface	
RTI concentration at top of host rock	Top of host rock	
RTI distribution	Within each of the main system compartments	
Diffusive transport time through host rock: half life	Outer boundary of host rock	

Indicator	Description	Source
Steady state transport distance	Across buffer and host rock	
Concentration of radiotoxic or chemically toxic elements in the biosphere over time	Biosphere	RWMD (UK)
Radiotoxicity flux from the geosphere to the biosphere over time	Geosphere	
Flux across defined accessible environment boundary	≤ 5 km from repository (accessible environment)	DOE/EPA/NRC (USA)
Radionuclide concentration in groundwater	≤ 5 km from repository (accessible environment)	
Radionuclide concentration in groundwater	≤ 18 km from repository (accessible environment)	

The MeSA project suggested [11, p.92*ff*]:

- to make a clear distinction between *primary* and *complementary indicators* with *primary indicator* the one that can be compared to a legal or regulatory defined radiological constraint (e.g. annual dose or risk);
- to use safety indicators only when appropriate reference values are available;
- to present safety indicators in a timescale context in order to address uncertainty in the far future. Complementary safety indicators are expected to have a great potential benefit when they do not rely on assumptions for future human behaviour.

2.2.3. Safety indicators considered in OPERA

In line with the recommendations from the *SPIN* project [9], three safety indicators are recommended to be applied within the OPERA programme for evaluating the results of the safety assessments. Table 2-2 summarizes the safety indicators addressed in this report.

Table 2-2: Safety indicators considered in OPERA

Safety Indicator
Effective dose rate
Radiotoxicity concentration in biosphere water
Radiotoxicity flux from geosphere

These safety indicators are defined as follows [13]:

- *Effective dose rate* [Sv/a]: This safety 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, various exposure pathways as well as living and nutrition habits.

  $$\textit{Effective dose rate} = \sum_{all\ nuclides} c_n DCF_n \qquad \textit{Equation 1}$$

  with

  DCF_n = *biosphere dose conversion factor [(Sv/a)/(Bq/m³)]* of radionuclide *n*

  c_n = *activity concentration* [Bq/m^3] of radionuclide n in the biosphere water

- *Radiotoxicity concentration in biosphere water* [Sv/m^3]: This safety 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 1 m^3 of biosphere water.

$$\textit{Radiotoxicity concentration in biosphere water} = \sum_{all\ nuclides} c_n e(50)_n \qquad \textit{Equation 2}$$

with $e(50)_n$ the *ingestion dose coefficient* [Sv/Bq].

- Radiotoxicity flux from geosphere [Sv/a]: This indicator 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.

$$\textit{Radiotoxicity flux from geosphere} = \sum_{all\ nuclides} s_n e(50)_n \qquad \textit{Equation 3}$$

with s_n the *activity flux* [Bq/a] of radionuclide n from the geosphere to the biosphere.

In addition, OPERA document M7.3.1.1 [12] discussed the *Power density in groundwater* as newly proposed in [9] as an auxiliary candidate parameter. The calculation of the power density is carried out with a simple weighting scheme, and no correction for the - relative to its decay energy - stronger biological effects of ingested α-sources is made. Instead, the activity is directly multiplied by the radionuclides' decay energy to obtain the power density indicator (see also [13]). That candidate indicator is not addressed in OPERA, because it was judged to provide no additional, meaningful information on long-term safety.

2.3. Reference values

Calculated values of safety indicators in themselves have restricted significance unless they are valued against appropriate reference values. These reference values serve as '*yardsticks*' to assess whether a disposal facility can be considered 'safe'.

The following sections introduce general concepts for obtaining reference values of safety indicators and summarize reference values applied in other countries or waste disposal programmes.

2.3.1. General concepts

As outlined in the previous section, it is common practice to compare calculated values of safety indicators to appropriate yardsticks to help judge whether those safety relevant aspects have been met, e.g. to judge the effectiveness of barrier performance or the acceptability of calculated safety levels. Examples of yardsticks are guidelines, criteria, reference values or other parameters that can be used to judge the acceptability of calculated safety levels.

Yardsticks may be derived from a number of sources, including legislation or regulation, which typically provides guidelines or limits on dose or risk, as illustrated in Figure 2-2 [11; Fig. 15, p.79]. These sources include:

- Safety recommendations from international organisations that may relate to radiological safety (e.g. ICRP) or broader health and environmental safety (e.g. drinking water standards);
- The principle that the repository should not significantly perturb the radiological or chemical conditions naturally present in the environment. Corresponding yardsticks can be derived from natural radionuclide concentrations and fluxes;
- Societal values or expectations;

- The results of performance assessments (e.g. a critical minimum container lifetime);
- System understanding, considering the physical processes by which the safety functions of the disposal system are provided.

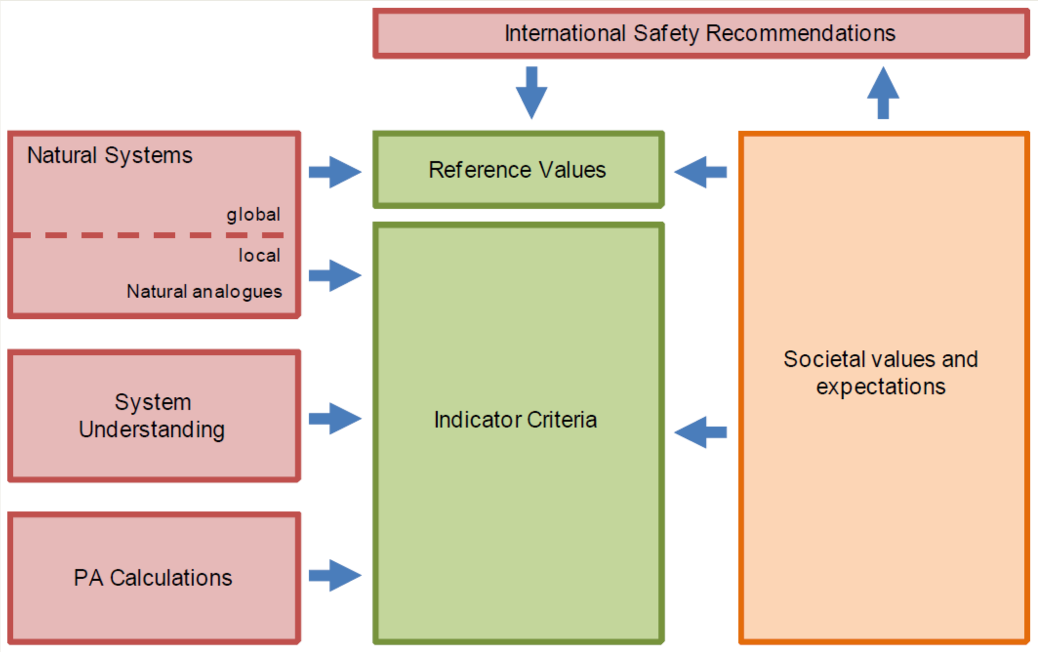

Figure 2-2: Sources of references values and indicator criteria

In [18, p.10*ff*] it is noted that in order to constitute a meaningful measure of safety, a safety indicator must be compared to a yardstick that conveys information with respect to the impacts on humans and the environment. It also emphasizes that reference values should be defined in a way that is generally considered to be acceptable.

In principle, reference values for safety indicators can be based on three lines of reasoning:

- dose constraints, that can be related to actual calculated risks;
- natural processes or features, e.g. radiotoxicity fluxes or concentration in groundwater;
- reference values used for other purposes.

While the first type of argument is based on legally or regulatory defined radiological constraints, the second type is related to natural features of a site, e.g. concentrations of naturally occurring uranium in groundwater. In MeSA [11, p.79*f*], it is stated that a repository system can be considered safe if possible radionuclide releases remain low in comparison with the natural radionuclide content of the environment. It is however noted that this is a "*somewhat problematic principle*" because the concentrations and fluxes in natural systems vary widely, and no guarantee exists that the natural environment is safe. This is of interest especially where high local natural concentrations of uranium or other radionuclides are present, while no epidemiological evidence exists suggesting that people have any increased risk of cancers. On the other hand, [11, p.80] noted that in areas with extremely low radionuclide concentrations unduly low reference values may be derived.

Reference values can also be based on limits used for other purposes. E.g. in [9, p.30], a reference value for a flux-related indicator was derived from an existing national regulation on the application of phosphate fertilizer. In such cases one needs to carefully investigate what the rationale behind the ‘adapted’ reference values or guidelines is: reference values can represent practical attempts to implement a certain policy, e.g. based on feasibility aspects or the desire to steer a certain process, rather than that the values are directly linked to assessed radiological risk limits.

Although there is a small number of universally applicable reference values that may be used in all safety cases, such as internationally agreed drinking water standards, it was acknowledged in *MeSA* that the derivation of appropriate reference values can be difficult. A number of recommendations with respect to the use of safety indicators were provided [11, p.92*ff*], under which:

- Reference values for comparison with safety indicators should have a generally accepted safety significance and, ideally, local context. Good examples of reference values provided where:
    - maximum permissible concentrations defined in drinking water standards such as those provided by the World Health Organisation
    - measured concentrations in local rivers and ground waters
    - measured fluxes in the accessible environment (e.g. due to groundwater discharge or surface erosion)
- It was noted that when using locally derived reference values, care should be given to evaluate spatial and temporal variations, and to express this appropriately.
- Reference values derived from local conditions should be treated with care to incorporate spatial and temporal variations, and to express this appropriately.

2.3.2. ‘*Acceptability*’ of risks

Additional to the scientific-technical discussion on reference values, it is also important to acquire what a society in general assumes to be an ‘acceptable’ risk. The concept of defining an ‘acceptable’ risk evolved from the fact that absolute safety can never be achieved in any everyday activity or industrial practice, including radioactive waste disposal [11, p.83*f*]. In the current understanding, exposure of people and other biota to even very low radiological or chemotoxic substances involves some risk. In the UK, for example, the Health and Safety Executive (HSE) defines’ acceptable risks as [24, p.31]:

> *“a level of risk which, provided there is a benefit to be gained, and proper precautions are taken, does not worry us or cause us to alter our ordinary behaviour in any way”.*

The general concept of ‘benefit’ (or ‘justification’, see [25]) is rather difficult to apply in case of the disposal of radioactive waste due to the long timescales until peak exposures are expected in performance assessment (ten thousand to hundred thousands of years). In [36, p.3], it is stated that the

> “*judgement of safety - or what is an acceptable level of risk in particular circumstances - is a matter in which society as a whole has a role to play. The final judgement as to whether the benefit resulting from the adoption of any of the Guidelines or guideline values as national or local standards justifies the cost is for each country to decide.*”

In [24, p.30*f*], a set of definitions with respect to risk perception was elaborated, covering qualification ranging from ‘*just about tolerable*’ to ‘*acceptable*’ risks:

- 1 in 1000 as the ‘*just about tolerable risk*’ for any substantial category of workers for any large part of a working life.

- 1 in 10,000 as the '*maximum tolerable risk*' for members of the public from any single non-nuclear plant.
- 1 in 100,000 as the '*maximum tolerable risk*' for members of the public from any new nuclear power station.
- 1 in 1,000,000 as the level of '*acceptable risk*' at which no further improvements in safety need to be made.

What a society considers 'acceptable' depends on the complex national context and may differ between stakeholders and members of the public. Risks (and their benefits) are quite differently distributed across societies, and the societal factors and processes that determine whether a risk is acceptable will change with time and may affect the public perception of risk, eventually causing discrepancies in subjectivity judgment and statistically based measures of risks. In [26, p.208], a list of standpoints has been elaborated that could be used as a basis for determining whether a risk is considered 'acceptable' (or, perhaps, 'tolerable'). A risk is 'acceptable' when:

- it falls below an arbitrary defined probability;
- it falls below some level that is already tolerated;
- it falls below an arbitrary defined attributable fraction of total disease burden in the community;
- the cost of reducing the risk would exceed the costs saved;
- the cost of reducing the risk would exceed the costs saved when the '*costs of suffering*' are also factored in;
- the opportunity costs would be better spent on other, more pressing, public health problems;
- public health professionals say it is acceptable;
- the general public say it is acceptable (or more likely, do not say it is not);
- politicians say it is acceptable.

In the PAMINA project the term acceptable risk was described as the level of loss a society considers acceptable given existing social, economic, political, cultural, technical and environmental conditions [9; p. 26]. In environmental and especially in nuclear sciences there is the general agreement, that a risk of $1 \cdot 10^{-6}$ per year of suffering a serious health effect is an appropriate level as a regulatory constraint or target (e.g. [27]; p.72).

Reference values for risk-related safety indicators cannot be derived technically, when it is not known what level of risk a society considers acceptable. In the current phase of the Dutch disposal programme, no societal discussion could be identified that allows to link what is considered as 'societally accepted' with respect to risks for future generations.

Although discussions in ENGAGED with stakeholders pointed out that the use of reference values is very relevant and stakeholders liked to be engaged [15], no suggestions were given that can be used for the derivation of reference values in this report. However, a 'golden standard' [26, p.208] used in many risks-related field is a risk of $1 \cdot 10^{-6}$ per year (incidence or mortality), e.g. as regulatory constraint or target for a citizen living nearby a nuclear power plant under normal operation [24]. In many other international guidance documents and national regulations, an individual risk of 10^{-6} per year of suffering a serious health effect is often applied as a 'target level' for an acceptable risk [11, p.83*f*]. A value of 10^{-6} per year is discussed and applied also in the Netherlands with respect to risk attributed to nuclear power generation [28, 29].

2.3.3. Treatment of altered, unlikely scenarios

Within the safety assessments performed as part of a safety case, besides the most likely, '*normal evolution scenario*', also altered scenarios are considered, e.g. early container failure, abandonment of the facility without proper closure, human intrusion, or glaciation.

Altered evolution scenarios, especially scenarios with low probabilities of occurrence, are often more difficult to assess quantitatively than the normal/expected evolution of the disposal system. In addition, altered evolution scenarios may result in increased risks.

A point of discussion is how to weigh the low probability of altered evolution scenarios against reference values of safety indicators. It makes sense to attribute higher reference values for very unlikely scenarios, e.g. magmatic eruptions in geological rather stable environments. E.g. in probabilistic safety assessment (PSA), a particular health effect is multiplied by the frequency of occurrence [30].

In [27], it is proposed to distinguish between '*likely scenarios*', '*less likely scenarios*', '*scenarios not to be considered in assessment calculations*' and '*scenarios assuming direct human intrusion into the repository*'. For the likely scenarios, a dose constraint of 0.1 mSv/a was suggested, while for less likely scenarios a ten times higher dose constraint of 1 mSv/a was proposed.

2.3.4. Overview of reference values discussed in EU projects

In several studies, the usefulness of safety indicators and their reference values has been evaluated, or reference values were derived, e.g. in the *SPIN* project [8, Ch. 6] and *PAMINA* [9; Ch. 5]. The present section provides an overview of reference values for the safety indicators considered in OPERA (see Section 2.2.3) which have been reported in literature. In addition, means to derive reference values for these indicators from e.g. drinking water standards have been included.

Reference values have been established for the following safety indicators:

- Effective dose rate
- Radiotoxicity concentration in biosphere water
- Radiotoxicity flux from geosphere

Effective dose rate

The *effective dose rate* of a member of the public is a widely accepted measure and is based on ICRP recommendations: *ICRP 60* recommends for dose limits from *all* external source for the public an annual exposure of < 1 mSv/a [31, p.45], representing an appropriately small level of risk to human health. The European Union follows the ICRP-103 recommendations [32;L 13/2].

The IRCP recommendations formed the basis for the IAEA recommendation of 0.3 mSv/a, assuming that member of the public can be exposed by more than one single source [33, p.15]. On that basis further constraints are recommend by ICRP for the exposure from a single radiation source such as a waste disposal facility: *ICRP 103* recommends a limit of 0.3 mSv/a [34, Table 8][2].

The reference values reported for the effective dose to a member of the public applied in *PAMINA* ranged from 0.1 mSv/a to 0.3 mSv/a [9, Table 5.8], reflecting minor differences in national regulation or guidelines, e.g. due to the application of a 'safety factor'.

[2] For potential exposures of the public, the ICRP recommends a risk constraint of 10-5/a [34; p.107]

The Dutch guideline on radiation protection prescribes a reference value of < 0.1 mSv/a on the general public for any commercial activity[3] ([35], §48, p.21).

The above-mentioned reference values for the safety indicator effective dose rate are summarized in the following table.

Table 2-3: Reference values for the safety indicator "effective dose rate", applicable to members of the public

Reference value	Source
1.0 mSv/a	ICRP 60 [31]
1.0 mSv/a	EU Directive 2013/59 [32]
0.3 mSv/a	IAEA SSR-5 [33]
0.3 mSv/a	ICRP 103 [34]
0.1 - 0.3 mSv	PAMINA D3.4.2 [9]
0.1 mSv/a	Besluit Stralingsbescherming (NL) [35]

Radiotoxicity concentrations in biosphere water

Reference values for *radiotoxicity concentrations in biosphere water* have been proposed in literature, e.g. based on drinking water regulations and as part of the EU Framework projects *SPIN* and *PAMINA*.

The World Health Organization (WHO) recommends <0.1 mSv/a for drinking water [36, p.203], or <0.14 mSv/m^3, based on the ingestion of 730 l of drinking water per person per year [36, p.208*ff*]. The WHO emphasises that, except in extreme circumstances, the radiation dose resulting from the ingestion of drinking-water is much lower than that received from other sources of radiation, i.e. weight in their recommendation the contribution of drinking water compared to other natural radiation sources.

Reference values for radiotoxicity concentrations were determined in *SPIN* for biosphere water because this is assumed to be the main exposure path. Based on source information from Finland, Switzerland and Czech Republic, in *SPIN* measured average concentrations of the most relevant radionuclides were aggregated. The resulting indicative reference value for the radiotoxicity concentration in biosphere water derived was 20 μSv/m^3 [8, p.44].

Additional analyses performed in *PAMINA* established a range of natural groundwater concentrations in different geological formations around the world ranging from 10^{-8} to 10^{-3} Sv/m^3, leading to a reference value of 10 μSv/m^3 [9, p.27*f*].

Calculations based on measurements of minimal natural radiotoxicity fluxes from the geosphere in Czech Republic resulted in a reference value of 4 μSv/m^3, [9, p.34]. Based on measurements in drinking water, Wolf et. al. suggests a reference value of 2 μSv/m^3 for the German situation [37, p.9].

Table 2-4 gives a summary overview on reference values for the safety indicator *radiotoxicity concentrations in groundwater and biosphere water* (adapted from [11, Table 13, p.86ff]. It is seen that, although the approaches may differ, the outcomes are generally in line.

[3] *"De ondernemer zorgt ervoor dat voor een lid van de bevolking als gevolg van handelingen, die onder zijn verantwoordelijkheid worden verricht, op enig punt buiten de locatie ten gevolge van die handelingen een effectieve dosis van 0,1 mSv in een kalenderjaar niet wordt overschreden."*

Table 2-4: Reference values for the safety indicator radiotoxicity concentration in groundwater and biosphere water

Indicator	Reference value	Source
Radiotoxicity concentration in groundwater	20 µSv/m^3	SCK•CEN (*SPIN*)
	$^{226}Ra + ^{228}Ra$ <5 pCi/L [<0.19 Bq/L] [4] Gross alpha <15 pCi/L [<0.56 Bq/L][5]	USA
Radiotoxicity concentration in biosphere water	20 µSv/m^3	NRG
	4 µSv/m^3	NRI (*PAMINA*)
	2 µSv/m^3 11 µSv/m^3	GRS
	20 µSv/m^3	ENRESA (*SPIN*)
Radiotoxicity concentration in surface waters	20 µSv/m^3	NWMO

Radiotoxicity flux from geosphere

Reference values for the indicator *radiotoxicity flux from geosphere* were determined in *SPIN* on basis of measured concentrations, and information on groundwater fluxes. It was noted that insufficient data were available. Based on two cases, inland pluton and crystalline basement environment under sedimentary cover, an indicative reference value was determined of 60 Sv/a for a surface area of 200 km^2 [8, p.45], equivalent to 0.3 Sv/a·km^2.

Reference values for the *radiotoxicity flux from geosphere* collected in PAMINA appeared to vary more than two orders of magnitude, indicating not only local variability, but also a lack of agreement on the overall concept of the indicator. A reference value for the Belgian disposal concept was derived on basis of the application of phosphate fertilisers in Flanders, resulting in a reference value of 10 Sv/a. That value was based on a footprint of the Belgian disposal site of 1 km^2 [9, p.30], equivalent to 10 Sv/a·km^2.

Calculations based on measurements of minimal natural radiotoxicities from the geosphere in Czech Republic resulted in a reference value of 8 Sv/a, for an surface area of the repository of 10 km^2 [9, p.32] , equivalent to 0.8 Sv/a·km^2.

For the local situation around Gorleben, Wolf et. al. suggests a reference value of 0.1 Sv/a [37, p.16]. No surface area is given, but the reference values is related to measurements in the location-specific migration path considered in PA [37, p.9*ff*].

A summary of values for the indicator *radiotoxicity flux from geosphere* is provided in Table 2-5. The calculated values for this indicator differ considerably which is partially due to local differences and the surface area considered, and partially due to different calculation approaches.

[4] Corresponds to about 50 µSv/m^3
[5] Corresponds to about 400 µSv/m^3

Table 2-5: Reference values for the safety indicator radiotoxicity flux from the geosphere

Indicator	Reference value	Source
Radiotoxicity flux from the geosphere	60 Sv/a	ENRESA (*SPIN*)
Radiotoxicity flux from the geosphere	10 Sv/a	SCK·CEN (*PAMINA*)
Radiotoxicity flux from the geosphere	60 Sv/a	NRI (*PAMINA*)
Radiotoxicity flux from the geosphere	0.1 Sv/a	GRS

Summary of reference values for safety indicators

Table 2-6 gives an overview of the safety indicators considered for OPERA [12, 13] and their reference values as applied in the EU projects *SPIN* [8, Table 7-1, p.43] and *PAMINA* project [9, Table 5-8, p.34]).

Table 2-6: Summary overview of reference values for safety indicators developed in the projects *SPIN* and *PAMINA*

Safety indicator	Reference values	
	SPIN	PAMINA
Effective dose rate	0.1 – 0.3 mSv/a	0.1 – 0.3 mSv/a
Radiotoxicity concentration in biosphere water	20 µSv/m^3	2 - 20 µSv/m^3
Radiotoxicity flux from geosphere	60 Sv/a	0.1 - 60 Sv/a

3. Reference values for the OPERA Safety Case

3.1. Synthesis: Safety indicators and reference values

Based on the discussions in the previous chapter, some general statements with respect to the use of safety indicators can be summarized as follows:

- to express safety, more than one single indicator should be used;
- the use of several safety indicators allows to address uncertainty on very long, geological timescales by defining indicators based on fewer assumptions;
- no generally accepted approach exists on how to derive reference values in case of indicators not related to dose or risk: often, natural concentrations or fluxes are used, implicitly stating that background concentration can be assumed 'safe'. However, additional complications arise when localized conditions results in either very large or very small radionuclide concentrations or fluxes;
- no consistent concept exists on whether localized values should be used, an how spatial and temporal variations are addressed. This results in a variety of reference values, covering a large range.

There is international agreement on the use of the *effective dose rate* as basic safety indicator, with a reference value based on ICRP recommendations. The *effective dose rate* can also be expressed as risk, allowing to compare it more directly to everydays' risk. Currently, no recommendation exists for a collective dose rate, i.e. the size of the potentially exposed population is not considered, and neither a recommendation exists for a cumulated dose rate over time in relation to geological disposal.

The summarized arguments in the previous chapter indicate that currently, although the general benefit is recognized, no general agreement exists on the application of complementary safety indicators and the method to derive their reference values. A number of reason for this has been given in [38, p.2]:

- a lack of appropriate data on measured concentrations and fluxes of naturally occurring radionuclides;
- a lack of internationally agreed forms of comparisons between repository and natural radionuclide abundances;
- an absence of internationally agreed hazard indices against which to evaluate the comparisons.

In [27, p.5], two principally different approaches to deriving reference values for complementary indicators from measured data set on natural concentrations or fluxes were discussed:

- At the simplest level, calculated repository releases may be compared with the equivalent abundances of naturally occurring radionuclides measured in the rocks and groundwater at the repository site, based on the assumption that the natural environment is generally considered to be safe. This simple approach to using safety indicators is consistent with suggestions that the impact of a repository should not lead to a significant increase in radiation exposure in the environment.
- The approach can be refined by making more specific comparisons between particular transport pathways (e.g. groundwater discharge), and abundances can be defined for either concentrations or fluxes of all radionuclides or just for specific nuclides of interest.

3.2. Proposed reference values for OPERA

The following paragraphs summarize the argumentation of establishing the proposed reference values for the three safety indicators which will be assessed in the OPERA performance assessment.

Effective dose rate

As discussed in the previous chapter, a general dose constraint of 0.3 mSv/a was recommended in [34, Table 8], and a risk constraint of 10^{-5}/a [34, p.105]. The range of reference values for the effective dose rate to a member of the public applied in *PAMINA* spans from 0.1 mSv/a to 0.3 mSv/a [9, p.34], reflecting minor differences in national regulation or guidelines, e.g. due to application of a 'safety factor'. The Dutch guideline on radiation protection prescribes a reference value of < 0.1 mSv/a on the general public for any commercial activity ([35], §48, p.21). The latter value can be seen as an upper constraint for a reference value, and is therefore the recommended value for the OPERA safety assessments.

Radiotoxicity concentration in biosphere water

Reference values provided in PAMINA for the safety indicator *Radiotoxicity concentration in biosphere water* range from 2 - 20 μSv/m^3 [9].

Reference values for the radiotoxicity concentration in biosphere water are derived from (1) Dutch legislation concerning drinking water and surface waters [39; p.3], and (2) measured values of uranium and thorium concentrations in Dutch subsoils [40; p.242; p.256]. Hereby it has been assumed that measured and/or reported values of the concentrations in surface waters of natural uranium and thorium and their decay products are in equilibrium. A large dataset of $CaCl_2$-extractable uranium and thorium concentrations from a wide variety of Dutch soils was used as input to estimate natural background concentrations for the radiotoxicity concentration in biosphere water, when converted to μSv/m^3.

The procedure for obtaining a reference value for the radiotoxicity concentration in biosphere water is described in Appendix A. The resulting reference value equals 8 μSv/m^3 which compares well with values reported elsewhere (cf. Table 2-4).

Radiotoxicity flux from geosphere

Reference values for radiotoxicity fluxes were determined in *SPIN* and PAMINA on basis of measured concentrations and information on groundwater fluxes. For the OPERA disposal concept, a reference value for the *radiotoxicity flux from geosphere* can be obtained from multiplying the reference value derived for the indicator *radiotoxicity concentration in biosphere waters* (see previous section) with estimates for the water flow rate entering the biosphere. This last parameter has been calculated from model calculations performed within OPERA Task 6.2.1 "*Modelling approach for hydraulic transport processes*" [41; Section 3.3]. Based on the quantitative results in that report, for the OPERA disposal concept a reference value of 0.25 Sv/a has been derived, which is comparable with the reference value derived for the Gorleben site in Germany (cf. Table 2-5).

It must be noted that the variabilities of the parameter values required to derive reference values for this indicator are significant. The procedure for deriving the reference value for the *radiotoxicity flux from geosphere* is described in Appendix A.

4. Concluding remarks

Table 4-1 gives an overview of the reference values for the three safety indicators considered in OPERA. The values given in Table 4-1 have been implemented in the tool utilized for the OPERA safety assessment.

Table 4-1: Reference values recommended for the safety indicators assessed in OPERA

Safety Indicator	
Effective dose rate	0.1 mSv/a
Radiotoxicity concentration in biosphere water	8 $\mu Sv/m^3$
Radiotoxicity flux from geosphere	0.25 Sv/a

In establishing the reference values for the safety indicators the following ‘lessons-learned’ were acquired:

- To express safety, more than a single indicator should be used.
- The use of several safety indicators allows to address uncertainty on very long, geological timescales.
- A distinction can be made between *primary indicators*, which are related to reference values (or constraints) defined in regulations, and *complementary indicators* that can be additionally used to support the safety case. In the latter case it should be made clear, what the status of such an indicator is.
- The most common used and generally accepted safety indicator is the *effective dose rate* for an exposed individual.
- The *effective dose rate* can also be expressed as risk, allowing to compare it more directly to everydays’ risk.
- Currently, no recommendation exists for a collective dose rate in relation to geological disposal, i.e. the size of the potentially exposed population has not been considered relevant.
- No recommendation exists either for a cumulated dose rate, i.e. the time interval of exposure does not matter.
- No well-established agreements exist on the nature of reference values in case of indicators not related to dose or risk: often, natural concentrations or fluxes are used, implicitly stating that background concentration can be assumed ‘safe’.
- No consistent internationally agreed ideas exist on whether localized values should be used, an how spatial and temporal variations are addressed. This results in reference values covering a large range and uncertainty.
- The reference values derived here should be seen as a first set, particularly meant for the OPERA Safety Case. Stakeholder interactions provided no input that could be used in the derivation of the reference values, but nevertheless a general interest of stakeholder in defining what is an “acceptable’ risk was noted.

References

[1] Verhoef, E, TJ Schröder, *OPERA Research plan*, OPERA-PG-COV004, 2011, 1-48.

[2] Verhoef, E, E Neeft, JB Grupa, A Poley, *OPERA. Outline of a disposal concept in clay*, OPERA report OPERA-PG-COV008, First update 13 november 2014, 1-18.

[3] Nuclear Energy Agency (NEA), *Confidence in the Long-term Safety of Deep Geological Repositories. Its Development and Communication,* OECD, Paris, 1999, 1-80.

[4] Nuclear Energy Agency (NEA), *Stepwise Approach to Decision Making for Long-term Radioactive Waste Management. Experience, Issues and Guiding Principles*, NEA report No. 4429 - ISBN 92-64-02077-2OECD, Paris, 2004, 1-72.

[5] Hart, J, P Davis, D-A Becker, U Noseck, L Hendriksen, AFB Wildenborg, TNO, M Winegram, *OSCAR. Evaluation of current state-of-the art on Safety Case methodologies,* OPERA Deliverable M2.1.1.a. OPERA Report OPERA-CF-NRG211A/NRG-report NRG-23194/12.117766/P, December 2012, 1-209.

[6] International Atomic Energy Agency (IAEA), *The Safety Case and Safety Assessment for the Disposal of Radioactive Waste*, Specific Safety Guide No. SSG-23, STI/PUB/1553, Vienna, September 2012.

[7] Grupa, JB, P Davis, *Report on the OPERA Safety Case structure,* OPERA report OPERA-PU-NRG008, October 2013, 1-24.

[8] Becker, D-A, D Buhmann, R Storck, J Alonso, J-L Cormenzana, M Hugi, F van Gemert, PO'Sullivan, A Laciok, J Marivoet, X Sillen, H Nordman, T Vieno and M Niemeyer, *Testing of Safety and Performance Indicators (SPIN) – Final Report*, EC report EUR 19965 EN, European Commission, 2002), 1-94.

[9] Becker D-A, JL Cormenzana, A Delos, L Duro, J Grupa, J Hart, J Landa, J Marivoet, J Orzechowski, TJ Schröder, A Vokal, J Weber, E Weetjens, J Wolf, *Safety Indicators and Performance Indicators, Performance Assessment Methodologies in Application to Guide the Development of the Safety Case (PAMINA)*,EC , Deliverable D-N:3.4.2, 2009, 1-75.

[10] Nuclear Energy Agency (NEA), *The Nature and Purpose of the Post-closure Safety Cases for Geological Repositories*, OECD Publication NEA No. 78121, 2013, 1-53.

[11] Nuclear Energy Agency (NEA), Indicators in the Safety Case, *A report of the Integrated Group on the Safety Case (IGSC), NEA/RWM/R(2012)7*, 2012, 1-143.

[12] Rosca-Bocancea E, TJ Schröder, *Development of Safety and Performance Indicators*, OPERA-PU-NRG7311, 29 October 2013, 1-32.

[13] Schröder TJ, Rosca-Bocancea E, *Safety and performance indicator calculation methodology*, OPERA-PU-NRG7312, 23 December 2013, 1-29.

[14] Jelgersma, E, TJ Schröder, Interim report on communicating Safety Case results, OPERA report OPERA-IR-NRG131A, May 2014, 1-79.

[15] Mozaffarian H (ed.), S Brunsting, E Luken, M Uyterlinde (ECN); A Slob, T Geerdink (TNO); T Schröder, B Haverkate (NRG); S Breukers (DuneWorks), *Stakeholder Engagement in the Implementation of a Geological Disposal for Radioactive Waste (Main Report)*, OPERA-PU-ECN121 November 2015.

[16] Meeussen JCL, E Rosca-Bocancea, *The OPAP Baseline Model for Performance Assessment*, OPERA-IR-NRG7241B, 24 October 2014, 1-26.

[17] International Atomic Energy Agency (IAEA), *Safety indicators for the safety assessment of radioactive waste disposal. Sixth report of the Working Group on Principles and Criteria for Radioactive Waste Disposal*. IAEA-TECDOC-1372, Vienna, 2003, 1-36.

[18] International Atomic Energy Agency (IAEA), *Safety indicators in different time frames for the safety assessment of underground radioactive waste repositories. First report of the INWAC Subgroup on Principles and Criteria for Radioactive Waste Disposal*, IAEA-TECDOC-767, Vienna, 1994, 1-35.

[19] Hewitt, GF, JG Collier, *Introduction into nuclear power*, 2nd edition, Taylor & Francis, New York, 1997, 1-304.

[20] UNSCEAR, United Nations Scientific Committee on the Effects of Atomic Radiation, *Sources and Effects of Ionizing Radiation: 2008 Report*, Volume I, Annex B (Exposures of the public and workers from various sources of radiation), ISBN 978-92-1-142274-0, New York, 2010.

[21] International Atomic Energy Agency (IAEA), *IAEA Safety Glossary: Terminology Used in Nuclear Safety and Radiation Protection (2007 Edition)*. IAEA, Vienna, Publication STI/PUB/1290, June 2007.

[22] Becker, D-A, J Wolf, *PAMINA. General concepts of supporting the safety case by means of safety and performance indicators*, PAMINA Deliverable Report M3.4.1, July 2008, 1-22.

[23] Wildenborg, AFB, B Orlic, G de Lange, CS de Leeuw, W Zijl, F van Weert, EJM Veling, S de Cock, JF Thimus, C Lehnen-de Rooij, EJ den Haan, *Transport of RAdionuclides disposed of in Clay of Tertiary ORigin (TRACTOR). Final report*, TNO-report NITG 00-223-B, October 2000, 1-221.

[24] Health & Safety Executive (HSE), *The tolerability of risk from nuclear power stations*. Reviesed version, HSE, London, 1992, 1-61.

[25] International Atomic Energy Agency (IAEA), *Fundamental Safety Principles*, IAEA Safety Standards Series No. SF-1, IAEA, Vienna, 2006, 1-21.

[26] Hunter, PR, L Fewtrell, *Acceptable risk*, In: Fewtrell, L, J Bartram (ed). *World Health Organization (WHO)*. Water Quality: Guidelines, Standards and Health, IWA Publishing, London, UK. ISBN: 1900222280, 2001, p.207-227.

[27] Nuclear Energy Agency (NEA), *Management of Uncertainty in Safety Case and the Role of Risk*, Workshop Proceedings, Stockholm, Sweden, 2-4 February 2004. NEA report No. 5302, NEA, Paris, 2005, 1-234.

[28] Kew, 1963, Dutch Government, *Nuclear Energy Act*, "Kernenergiewet", Kew, Stb. 1963, No. 82.

[29] *Dossier Kernenergie*, Minstry of Economic Affairs, The Hague, 1993, 1-75.

[30] International Atomic Energy Agency (IAEA), *Development and application of Level 1 probabilistic safety assessment for nuclear power plants*, IAEA Specific Safety Guide SSG-3, Vienna, 2010, 1-192.

[31] International Commission on Radiological Protection (ICRP), *1990 Recommendations of the International Commission on Radiological Protection*, ICRP Publication 60, Ann. ICRP 21 (1-3), 1991, 1-201.

[32] European Council, *European Union Council Directive 96/29/Euratom*, Council Directive 2013/59/EURATOM of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom. https://ec.europa.eu/energy/sites/ener/files/documents/CELEX-32013L0059-EN-TXT.pdf (last accessed: 31 October 2016).

[33] International Atomic Energy Agency (IAEA), *Disposal of Radioactive Waste. Specific Safety Requirements*, IAEA Safety Standards Series No. SSR-5, Vienna, 2011, 1-62.

[34] International Commission on Radiological Protection (ICRP), *The 2007 Recommendations of the International Commission on Radiological Protection,* ICRP Publication 103. Ann. ICRP 37 (2-4), 2007, 1-332.

[35] *Besluit stralingsbescherming*, Staatscourant 397, 16 July 2001.

[36] World Health Organisation (WHO), *Guidelines for drinking-water quality*, 4th ed., ISBN 978 92 4 154815 1, World Health Organization, Geneva, 2011, 1-541.

[37] Wolf, J, D-A Becker, A Rübel, U Noseck, *Safety and performance indicators for repositories in salt and clay formations*, GRS report GRS-240, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Braunschweig, Germany, 2008, 1-98.

[38] International Atomic Energy Agency (IAEA*), Natural activity concentrations and fluxes as indicators for the safety assessment of radioactive waste disposal. Results of a coordinated research project,* IAEA-TECDOC-1464, IAEA, Vienna, October 2005, 1-181.

[39] van Herwijnen R,Verbruggen EMJ, *Water quality standards for uranium - Proposal for new standards according to the Water Framework Directive*, RIVM Letter report 270006003, National Institute for Public Health and the Environment, Bilthoven, The Netherlands 2014.

[40] Mol G, Spijker J, Pauline van Gaans P, Römkens P, *Geochemische bodematlas van Nederland*, Wageningen Academic Publishers ISBN: 978-90-8686-186-6, 2012; http://www.geochemischebodematlas.nl.

[41] Valstar JR, Goorden N, *Hydrological transport in the rock formations surrounding the host rock*, OPERA report OPERA-PU-DLT621, 2016, 1-79.

Appendix A: Derivation of reference values for the OPERA safety assessment

Reference value for radiotoxicity concentration in biosphere water

Reference values for the radiotoxicity concentration in biosphere water can be derived from (1) Dutch legislation concerning drinking water and surface waters, and (2) measured values of uranium (thorium) concentrations in Dutch surface waters. Hereby it has been assumed that measured and/or reported values of the concentrations in surface waters of natural uranium and thorium and their decay products can serve as input to estimate reference values for the radiotoxicity concentration in biosphere water, when converted to $\mu Sv/m^3$.

Uranium

Under the Dutch Water Framework Directive two types of ecotoxicological quality standards for surface waters are considered: the Annual Average Environmental Quality Standard (AA-EQS) and the Maximum Acceptable Concentration EQS (MAC-EQS) [1; p.3]. The AA-EQS is an average concentration which should protect the ecosystem against adverse effects resulting from long-term exposure. The proposed AA-EQS for uranium is 0.5 µg/l. The MAC-EQS protects aquatic ecosystems from effects due to short-term exposure or concentration peaks, and is proposed at 8.9 µg/l. Both standards are expressed as dissolved uranium, including background levels. The proposed values are based on the chemotoxicity of uranium, i.e. are related to the effects of uranium only.

The reference value for natural uranium of AA-EQS of 0.5 µg/l [1; p.3], converted to radiotoxicity including the presence of daughter nuclides, results in a total radiotoxicity concentration of 8.2 $\mu Sv/m^3$.

With respect to natural background values, measured values of selected metal concentrations in the top 1.2 m of different soil types as reported in the “Geochemische Bodematlas van Nederland” [2] have been analysed. Assuming that the $CaCl_2$-extractable natural uranium (in µg/l; p. 256) provides a useable estimator for the pore water concentration of uranium, the natural background radiotoxicity level has been calculated accordingly. Because of the lack of data on natural concentrations of other radionuclides, the contribution of the daughter nuclides of uranium to the overall radiotoxicity is accounted for by assuming equilibrium of all daughter nuclides of both U-235 and U-238. For conversion of the mass concentrations of natural uranium to radiotoxicity concentrations, the contributions of ^{235}U (0.7% by mass; relevant decay products: ^{238}Pu, ^{234}U, ^{230}Th, ^{226}Ra, and ^{210}Pb) and ^{238}U (content 99.3% by mass; relevant decay products: ^{231}Pa and ^{227}Ac) have been considered. Hereby the mass concentrations of the respective nuclides are converted to activity concentrations and multiplied with the dose conversion factor for ingestion, $e(50)_{ing}$ [35; Table 4.1].

The average uranium concentration in all measured soils in [2] is about 0.1 µg/l (corresponding to 1.6 $\mu Sv/m^3$), with the highest measured values at about 3.5 µg/l (corresponding to 57.7 $\mu Sv/m^3$). The 95-percentile, averaged over the “top” and “lower” surface layers, equals 0.56 µg/l (corresponding to 9.3 $\mu Sv/m^3$), which is close to the AA-EQS mentioned above.

This report follows the recommended AA-EQS value for surface waters, extrapolated to the combined radiotoxicity of natural uranium and its daughter nuclides. The resulting, rounded *reference values for radiotoxicity in biosphere water* is **8 $\mu Sv/m^3$**. Although this value is lower than in regulations on drinking water [3, 4], it is close to actual measured concentrations of uranium in Dutch top soils.

Reference value for radiotoxicity flux from geosphere

As discussed in the previous chapters, is it difficult to establish the natural radiotoxicity flux from the geosphere. Due to lack of data, a simplified, conservative approach is applied. For calculating the radiotoxicity flux from the geosphere the following quantities are used:

- The reference value for natural uranium of AA-EQS of 0.5 µg/l, extrapolated to the total radiotoxicity concentration of natural uranium and its decay products (8.2 µSv/m^3, cf previous paragraph);
- The average vertical flow velocity, established by recalculating the path lengths and residence times provided in ([41, Table 3-1]; see also Table A1 below). This vertical component can be obtained by multiplying the total advective flow velocity in the aquifer with the quotient of the distance between the top of the Boom Clay (450 m) and the total travel distances for the three "streamlines" given in Table A1.
- The footprint area of the OPERA disposal facility. An estimate of the footprint area of the OPERA disposal concept can be obtained from the following considerations:
  - The dimensions of the OPERA disposal concept as provided in the Appendix of [2; Table A-4] apply;
  - It is assumed that the curvature of the disposal section *Vitrified HLW+SF* is represented by ¾ of a circle's curvature with a diameter of 1300 m.
  - In addition to the rectangular areas of the disposal sections *LILW+DU* and *non-heat-generating HLW*, and the curved area of the disposal section *Vitrified HLW+SF*, an additional surrounding area of 50 m width is considered in order to take into account for diffusion and dispersion in the horizontal directions. The resulting footprint obtained in this way equals $1.86 \cdot 10^6$ m^2 (*LILW+DU+non-heat-generating HLW*: $1.43 \cdot 10^6$ m^2; *Vitrified HLW+SF*: $0.43 \cdot 10^6$ m^2).

The radiotoxicity flux from the geosphere can then be obtained by multiplication of (Radiotoxicity concentration in biosphere water) * (vertical flow velocity) * (footprint area). The results are provided in Table A1.

Table A1: Estimates for parameter values for the indicator radiotoxicity flux from geosphere for the three subcases of fast, medium and slow streamlines, for a moderate climate

Streamline	Travel distance [m]	Residence time [a]	Flow velocity [m/a]	Vertical flow velocity [m/a]	Radiotoxicity flux from geosphere [Sv/a]
Fast (**FS**)	23'300	30'700	0.76	1.47E-02	0.23
Medium (**DV**)	14'000	164'000	0.09	2.74E-03	0.04
Slow (**SS**)	28'200	853'000	0.033	5.28E-04	0.01

Following the recommendation to establish general applicable reference values rather than local or regional values, it is proposed for the OPERA safety assessment to utilize the highest value of Table A1, i.e. the value calculated for the *fast streamline,* as the reference value (0.23 Sv/a). That value is in line with the value proposed for Germany (cf. Table 2-5). The resulting, rounded *reference value for radiotoxicity flux from geosphere* is **0.25 µSv/m^3**.

References in Appendix A

[1] van Herwijnen R,Verbruggen EMJ, *Water quality standards for uranium - Proposal for new standards according to the Water Framework Directive*, RIVM Letter report 270006003, National Institute for Public Health and the Environment, Bilthoven, The Netherlands 2014.

[2] Mol G, Spijker J, Pauline van Gaans P, Römkens P, *Geochemische bodematlas van Nederland*, Wageningen Academic Publishers ISBN: 978-90-8686-186-6, 2012; http://www.geochemischebodematlas.nl.

[3] World Health Organisation (WHO), *Guidelines for drinking-water quality*, 4th ed., ISBN 978 92 4 154815 1, World Health Organization, Geneva, 2011, 1-541.

[4] World Health Organisation (WHO), Uranium in Drinking-water, *Background document for development of WHO Guidelines for Drinking-water Quality*, WHO/SDE/WSH/03.04/118/Rev/1, World Health Organization, 2012, 1-21.

Disclaimer

This report has been prepared at the request and for the sole use of the Client and for the intended purposes as stated in the agreement between the Client and Contractors under which this work was completed.

Contractors have exercised due and customary care in preparing this report, but have not, save as specifically stated, independently verified all information provided by the Client and others. No warranty, expressed or implied is made in relation to the preparation of the report or the contents of this report. Therefore, Contractors are not liable for any damages and/or losses resulting from errors, omissions or misrepresentations of the report.

Any recommendations, opinions and/or findings stated in this report are based on circumstances and facts as received from the Client before the performance of the work by Contractors and/or as they existed at the time Contractors performed the work. Any changes in such circumstances and facts upon which this report is based may adversely affect any recommendations, opinions or findings contained in this report. Contractors have not sought to update the information contained in this report from the time Contractors performed the work.

The Client can only rely on or rights can be derived from the final version of the report; a draft of the report does not bind or obligate Contractors in any way. A third party cannot derive rights from this report and Contractors shall in no event be liable for any use of (the information stated in) this report by third parties.

OPERA

Meer informatie:

Postadres
Postbus 202
4380 AE Vlissingen

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

www.covra.nl