Effects of parameter uncertainty on the long-term safety

OPERA-PU-NRG732/746

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 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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Table of content

Table of content 1
Summary 1
Samenvatting 1
1. Introduction 3
 1.1. Background 3
 1.2. Objectives 3
 1.3. Realization 3
 1.4. Explanation contents 4
2. Uncertainties in the OPERA Safety Case 5
 2.1. Calculation cases 6
3. Deterministic Uncertainty calculations results 7
 3.1. 'Best estimate' case (DV) 7
 3.2. Variation of Waste-EBS parameters 9
 3.3. Variation of Host Rock parameters 10
 3.4. Variation of Overburden parameters 12
 3.5. Variation of Biosphere parameters 14
 3.6. 'Worst case' analysis 15
 3.7. Overall system behaviour 16
4. Conclusions, recommendation 17
References 20
Appendix A: Case overview 22

Summary

This report describes the set-up and the results of deterministic uncertainty analyses carried out in the context of OPERA Task 7.4.6: *Addressing effects of parameter uncertainty*. The calculations presented in this report have been performed by NRG. The results of the simulations are presented as graphs, containing calculated dose rates for outer envelopes of parameter variations (i.e. minimum- and maximum-values) as documented in the OPERA report OPERA-PU-NRG7251-NES. The graphs are complemented by some general observations. Since the envelop of all bounding NES calculation cases remains below the reference dose rate value,this observation is valid for *all* NES subcases, too.

Since a probabilistic uncertainty analysis of the Normal Evolution Scenario would only yield a testable 95-percentile curve within the present established envelop – and therefore below the given reference dose rate value – it is recommended to focus further safety assessment work for support of the OPERA Safety Case on the alternative scenarios.

Samenvatting

Dit rapport beschrijft de opzet en de resultaten van deterministische onzekerheidsanalysen die uitgevoerd zijn in het kader van OPERA Taak 7.4.6: *Aanpak voor de effecten van parameter onzekerheden*. De berekeningen in dit rapport zijn door NRG uitgevoerd. De resultaten zijn grafische weergaven van de berekende radiologische blootstellingen voor de extreemwaarden van de parametervariaties (minimum en maximum waarden) zoals deze in het OPERA rapport OPERA-PU-NRG7251-NES vastgelegd zijn. Tevens zijn enkele algemene observaties over de resultaten gerapporteerd. Omdat de omhullende van alle extreme NES ontwikkelingen onder de dosistempo-referentiewaarde blijft, geldt dat ook voor *alle* mogelijke NES ontwikkelingen.

Omdat een probabilistische onzekerheidsanalyse van het Normale Evolutie Scenario alleen een te testen 95-percentiel curve kan opleveren binnen de in dit rapport bepaalde omhullende – en daarmee lager dan de vastgestelde referentiewaarde – wordt aanbevolen verder veiligheidsanalyse-werk ter ondersteuning van de OPERA Safety Case te concentreren op onderzoek van de alternatieve scenario’s.

1. Introduction

1.1. Background

In the OPERA research programme [1], all safety relevant aspects of a given generic reference disposal concept for radioactive waste [2] are evaluated and assessed in order to evaluate the long-term safety of such a facility [1]. The programme follows in general terms the methodology known as '*Safety Case*' [3, 4, 5]. A central part of the Safety Case are safety assessment calculations that are performed in order to investigate potential risks of a disposal concept. In this report, additional performance assessment (PA) calculations are performed with parameter variations as derived for the *Normal Evolution Scenario* (NES) and documented in [6]. These calculations complement the PA outcomes of the so-called 'Central Assessment Case' as reported in [7].

1.2. Objectives

The purpose of this additional contribution to OPERA is to provide input for addressing uncertainties in the Opera Safety Case (OSC). It was noted that in the draft OSC-report uncertainties are discussed in detail, while on the basis of existing computational analyses performed in the OPAP-projects, little information can be given on how these uncertainties affect the overall outcome of the PA. The objective of this report is to provide information on the latter in order to support confidence in the robustness of the OSC.

1.3.Realization

The work presented in this report was carried out by NRG. The overall set-up of OPERA [1] and the PA-model implementation and parameterization [8, 9,10, 6] allow to perform uncertainty and sensitivity analyses in principle; however, because of the limited time available for this study, a very condensed approach is followed: rather than analysing a larger set of parameter variations, only a limited set of deterministic uncertainty analyses is performed, aiming to compute the outer envelopes of parameter variations (i.e. *min*- and *max*-values). This decreases relevantly the computational efforts and time for pre- and post-processing, while providing sufficient information on the system behaviour to support the communication of key messages with respect to the impact of relevant uncertainties on parameter values used in the performance assessment. To be able to fit the work in the critical time schedule, the results of these calculations are presented only for the primary safety indicator '*dose rate in the biosphere*'.

The activities were divided in two stages:

- In *Stage 1*, a limited number of PA-calculations was performed in order to investigate the most efficient way of presenting the outcomes of the deterministic uncertainty analysis, and to verify assumptions on the principal system behaviour. The necessary calculations were performed on basis of a preliminary set of parameter values. A first set of figures was generated to judge whether the chosen presentation is useful in order to communicate the effect of parameter variations documented in [6]. However, because of several updates of the parameter set, this stage is not documented in this report.

- In *Stage 2*, a limited number of PA-calculations were performed, according to the grouping established in the previous stage. The calculations are performed with the full PA-model as documented in [6] and are discussed in the remainder of this document. The results complement the outcomes presented in [7].

1.4. Explanation contents

Chapter 2 shortly summarizes the parameter uncertainties established in the OPERA research programme and used as input for the OPERA PA calculations, and gives an overview on the calculation cases performed. The results of the deterministic uncertainty analyses are presented in Chapter 3. Chapter 4 provides general conclusions. In Appendix A, an overview of the used parameter sets is given.

2. Uncertainties in the OPERA Safety Case

A safety case for a deep geological repository of radioactive waste has to provide evidence that the facility will be safe in every respect, in both the near and far future. The uncertainties regarding the future evolution should therefore be assessed carefully. Numerical uncertainties with respect to the parameter values used in the PA, or other uncertainties relevant for the long-term safety should be identified and quantified as well.

The incorporation of probabilities in PA calculation is an important challenge for the OPERA Safety Case. A well-founded safety statement needs to be formulated. Uncertainty and variability attached to the many parameters used as input for the PA calculations need to be thoroughly accounted for.

The inclusion of parameter uncertainties in PA as performed in [6] is assumed to be an important technological step forward in analysing, presenting and understanding the overall behaviour of a repository concept. Generally, all experimentally derived parameter values are uncertainty-ridden due to inaccuracy and natural variability. Moreover, conservative, simplified representation of complex processes introduces additional inaccuracies resulting in numerical uncertainties as well. The application of uncertainty analysis in PA enables to estimate the overall numerical uncertainty for a given indicator as result of all combined processes.

The PA-model implementation and documented ranges of parameter values in [6] support the performance of deterministic uncertainty analyses. Within the scope of this study, a limited set of parameter variations was analysed, aiming to compute the outer envelopes of the expected variations (i.e. minimum- and maximum-values) of the primary safety indicator, the *dose rate in the biosphere*. The parameter variations were grouped in order to reduce the number of necessary computations, and to allow a more straightforward communication of the outcome. The grouping is performed on basis of understanding of the main features of the disposal system, understanding of the effect of parameter variations on the overall system performance, and on previous analyses.

For the following input parameter, defined parameter variations (e.g. minimum- and maximum-values) are given in [6]:

- *Waste-EBS* compartment:
  - Time of container failure $t_{failure}$
  - Release rate λ_{rel}
  - Solubility limit S
- *Host Rock* compartment:
  - Retardation factors R_{aq} and R_{DOC}
  - Diffusion parameters η_i, $D_{pore,i}$, η_{DOC}, and D_{pore}
- *Overburden* compartment:
  - Residence time T_{res}
  - Retardation factor R
  - Dilution by dispersion F_{disp} (and related flow rates)
- *Biosphere* compartment:
  - Dilution factor F_d
  - Dose conversion factor DCC

2.1. Calculation cases

The parameter variations summarized in the previous section where arranged into four principal groups, each related to one of the model compartments distinguished in the OPERA PA-model. For each group, the least and the most conservative set of parameter values is established, resulting in 13 calculation cases. The outcomes are compared with the 'base case', denoted as '**DV**' (default values). An additional subcase ('Worst case') was calculated combining the most conservative subcases for each compartment: *EBS-1*, *HR-1*, *OV-1*, and *BIO-1*. Table 2-1 summarizes the calculation cases considered.

Table 2-1: Subcases identified as part of preparatory deterministic calculations

Case ID	Waste-EBS	Host Rock	Overburden	Biosphere
DV	Base Case values (DV)	Base Case values (DV)	Base Case values (DV)	Base Case values (DV)
EBS-1	**Early Failure, Fast release**	Base Case values (DV)	Base Case values (DV))	Base Case values (DV)
EBS-2	**Late Failure, Slow release**	Base Case values (DV)	Base Case values (DV)	Base Case values (DV)
EBS-3	**Low solubility (LS)**	Base Case values (DV)	Base Case values (DV)	Base Case values (DV)
HR-1	Base Case values (DV)	**Lower Value R, Max. porosity, Max. diffusion rate**	Base Case values (DV)	Base Case values (DV)
HR-2	Base Case values (DV)	**Upper value R, Min. porosity, Min. diffusion rate**	Base Case values (DV)	Base Case values (DV)
OV-1	Base Case values (DV)	Base Case values (DV)	**Cold climate without ice cover (CB)**	Base Case values (DV)
OV-2	Base Case values (DV)	Base Case values (DV)	**Slow Streamline (SS)**	Base Case values (DV)
OV-3	Base Case values (DV)	Base Case values (DV)	**Moderate sorption (Rov)**	Base Case values (DV)
OV-4	Base Case values (DV)	Base Case values (DV)	**Large dilution (LaD)**	Base Case values (DV)
BIO-1	Base Case values (DV)	Base Case values (DV)	Base Case values (DV)	**Mediterranean Climate (MC)**
BIO-2	Base Case values (DV)	Base Case values (DV)	Base Case values (DV)	**Boreal Climate (BC)**
BIO-3	Base Case values (DV)	Base Case values (DV)	Base Case values (DV)	**Local drinking water-well (DW-LW), Mediterranean climate (MC)**
BIO-4	Base Case values (DV)	Base Case values (DV)	Base Case values (DV)	**Large River (RL-L), Boreal climate (BC)**
'Worst case'	**Early Failure, Fast release**	**Lower Value R, Max. porosity, Max. diffusion rate**	**Cold climate without ice cover (CB)**	**Mediterranean Climate (MC)**

For the deterministic uncertainty calculations reported here, the same PA-model was used as for the *Central Assessment Case* (model version 9.3; [7]). The calculations were carried out using the parameter set as established in [6].

3. Deterministic Uncertainty calculations results

The purpose of this chapter is to give general insight in the relevance of various parameter variations summarized in [6], and to provide some understanding of the general system behaviour. Therefore, in the remainder of this chapter, different aspects with respect to system understanding and parameter sensitivity are presented per compartment.

The results are based on a set of safety assessment calculations, applying either default values (DV), or parameter variations (min- & max-values) as reported in M7251 [6]. The calculations are organized in 14 subcases (see Table 2-1), and were compared with the outcomes of the DV case reported in [7]. The results are presented in terms of the safety indicator '*Effective dose rate in the biosphere*' [11, 12, 13], representing the annual individual effective dose to an average member of the group of the most exposed individuals. The indicator accounts for dilution and accumulation in the biosphere, various exposure pathways as well as living and nutrition habits [10, 6] and is generally seen as the most important, *primary safety indicator* [11].

3.1.'Best estimate' case (DV)

The results of the calculated DV case were presented in detail in [7]. Figure 3-1 and Table **3-1** summarize the main results in terms of *Effective dose rate in biosphere*. The case is based on 'best estimate' parameter values for the Host Rock and *Waste-EBS* compartment, and conservative values for the overburden and biosphere.

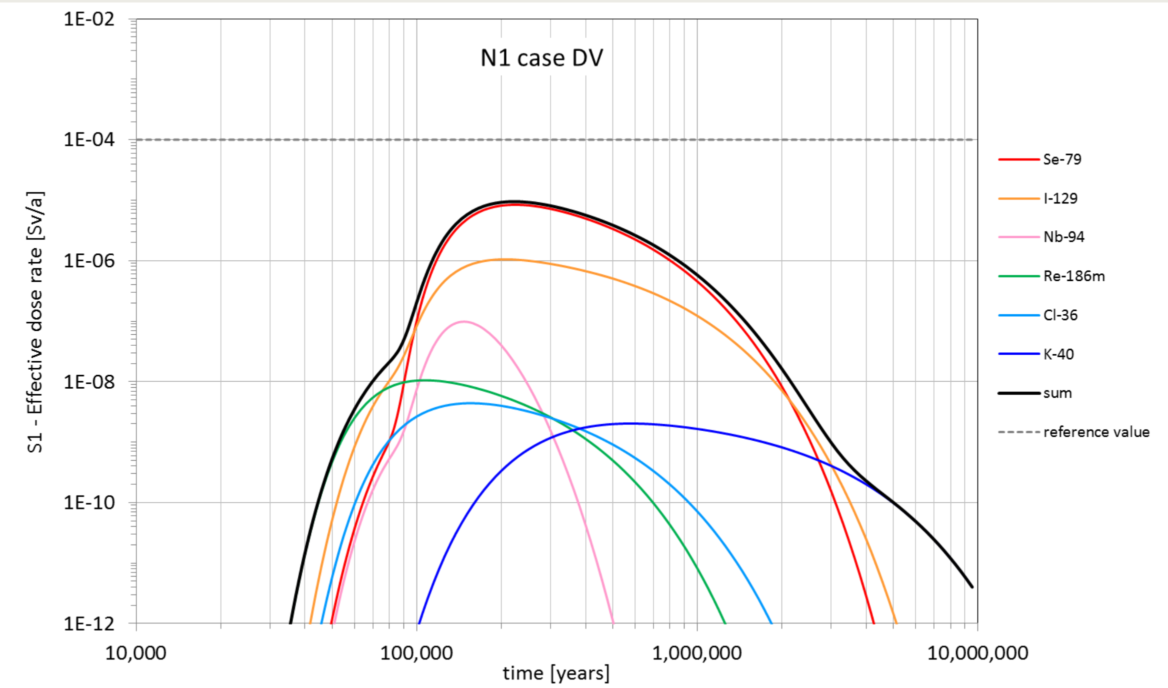

Figure 3-1: Effective dose rate. Calculation case *DV*. PA-model version 9.3.

Three aspects are highlighted here, because they are important to understand the general system behaviour of the base case, and the other cases discussed below:

- The calculated peak dose rate at 220.000 years is dominated by the contribution of ^{79}*Se* and ^{129}*I*. Both radionuclides are long-living, and are not retarded by sorption. All other nuclides contribute little to the overall dose rate: they have maximum values of less than 1.2% of the maximum dose rate (Table 3-1).

- *U* and other members of the natural nuclide chains are strongly retarded in the *DV* case and do not reach the biosphere within the calculation period of 10 million years. The peak caused by *U* and its daughter nuclides is therefore not visible in the graph. From calculations over longer periods (not shown here) it is expected that these nuclide chains would dominate the dose rate on the very long term (>40 million years), at a time far beyond the period in which comparison with a dose rate reference limit is meaningfull.

- Due to the immediate failure of the LILW container, radionuclides from this waste section dominate in early times (until about 80'000 years in the *DV* case). However, the peak dose rate from this waste section is two orders of magnitude smaller than from the HLW sections (Figure 3-2), where supercontainer failure is assumed to occur after 35'000 years.

Table 3-1: Maximum values of the *Effective dose rate* (S1). Calculation case *N1-DV*. PA-model version 9.3.

Nuclide	Time [a]	Dose Rate [Sv/a]
Se-79	2.29E+05	8.43E-06
I-129	2.09E+05	1.06E-06
Nb-94	1.45E+05	9.79E-08
Re-186m	1.05E+05	1.06E-08
Cl-36	1.58E+05	4.40E-09
K-40	5.75E+05	2.03E-09
Sum	**2.19E+05**	**9.51E-06**

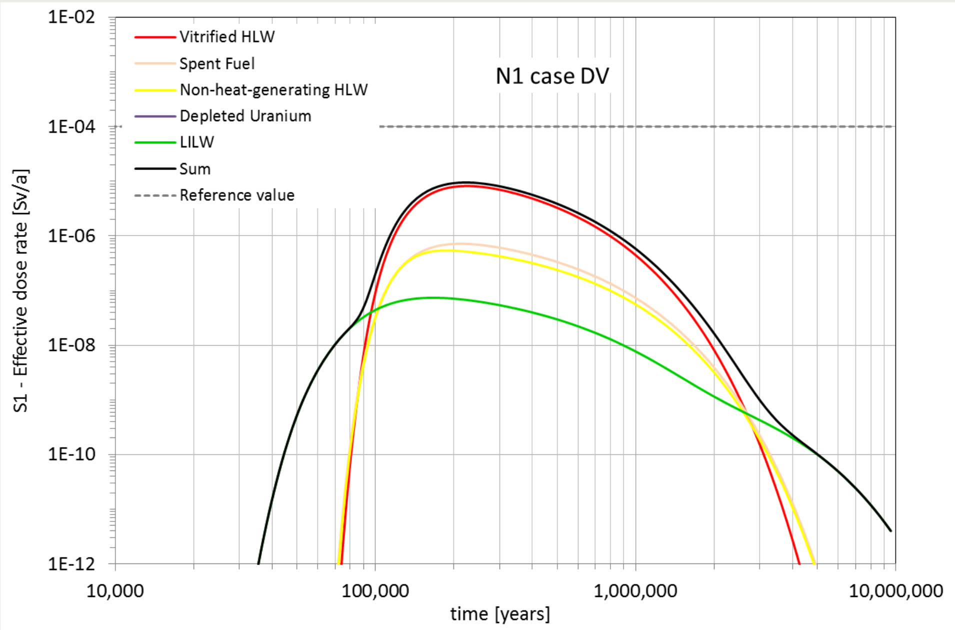

Figure 3-2 Effective dose rate. Calculation case *DV*. PA-model version 9.3.

3.2. Variation of Waste-EBS parameters

Figure 3-3 shows the effects of parameter variations for the failure times of containers and release rates of vitrified HLW. Here, a larger range of values is applied than the subcase reported in [7]:

- the failure time of the supercontainers varies from 1000 to 700’000 years
- the failure time of the Konrad container varies from 150 to 200’000 years
- the release rate of vitrified HLW varies from $3.8 \cdot 10^{-3}$ to $1.6 \cdot 10^{-7}$ yrs^{-1}.

The failure times and release rates have limited effect on the peak dose rates: for the *EBS-1* case, the dose rate is 7% higher than the *DV* case, and for the *EBS-2* case the maximum is about one third of the *DV* case due to decay of ^{79}*Se* (half-live: 377’000 years). The time of the peak value shifts more or less linear with the chosen assumed time of supercontainer failure.

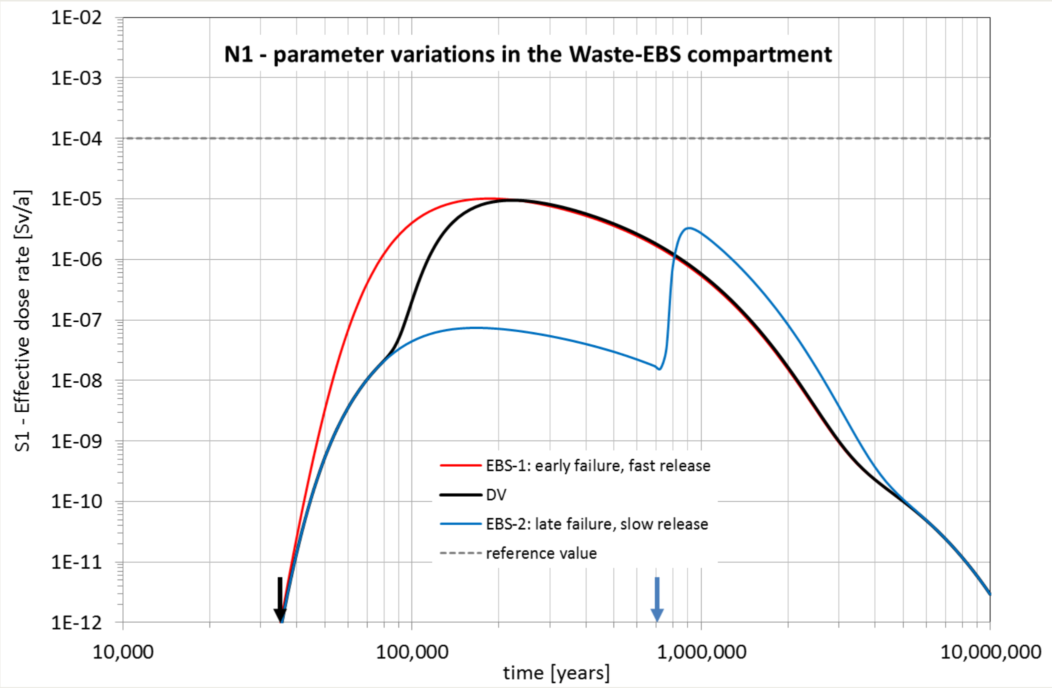

Figure 3-3 Effective dose rate. Calculation cases *EBS-1*, *DV*, and *EBS-2*. PA-model version 9.3. The arrows indicate the assumed time of the supercontainer failure for the *DV* case (black) and the *EBS-2* case (blue).

In the *EBS-3* case, a lower solubility for Uranium is assumed. Due to the long retardation of *U*, no effect is visible within the calculation period (data not shown).

3.3. Variation of Host Rock parameters

The results of the Host Rock parameters variation are presented in Figure 3-4. *HR-1* represents the fastest migration case, with the lowest retardation values and the highest pore diffusion coefficients and diffusion accessible porosities. *HR-2* represents the slowest migration case, applying the opposite side of the parameter distribution in [6], Table 4-4 and 4-5.

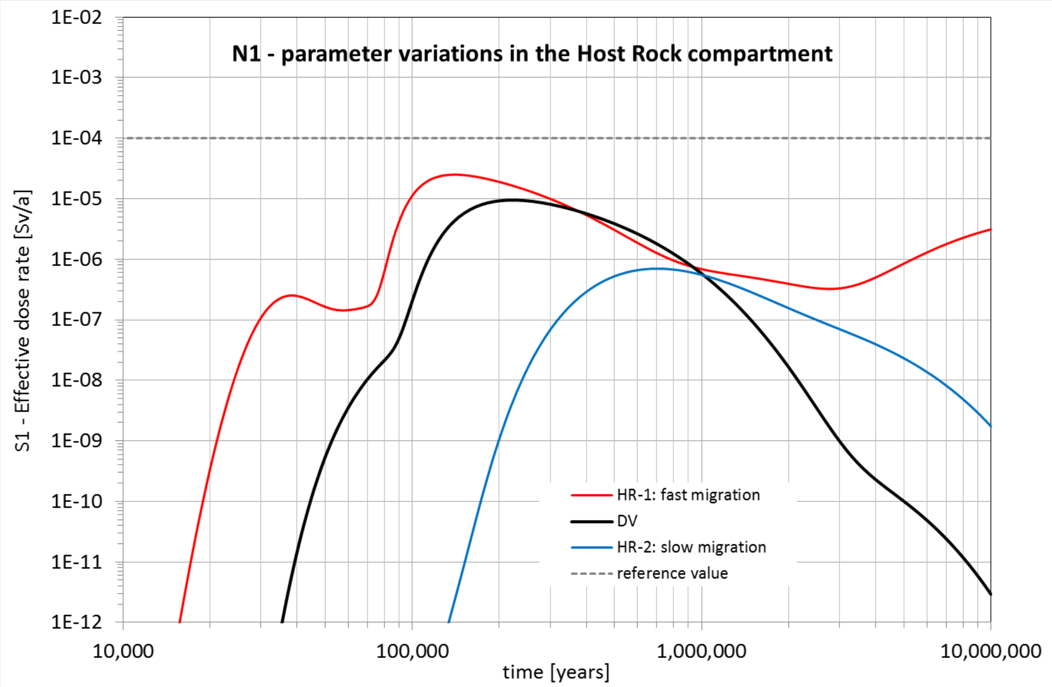

Figure 3-4: Effective dose rate. Calculation cases *HR-1*, *DV*, and *HR-2*. PA-model version 9.3.

The maximum dose rate in the *HR-1* case is almost three times higher than in the *DV* case, partially due to the higher diffusion accessible porosities and diffusion rates, and partially due to the decay of ^{79}Se. The maximum dose rate in the *HR-2* case is less than 10% of the *DV* case, due to slower diffusion and decay of ^{79}Se. The times of the maximum dose rate values ranges from about 140'000 years to 700'000 years.

In the *HR-1* case, other radionuclides are of relevance than in most other calculation cases (Figure 3-5):

- The first peak in the *HR-1* case is due to ^{186m}Re from the LILW section, for which a conservative approach was followed in the derivation of the retardation factor [14]. The maximum dose rate of ^{186m}Re is about 1% of the maximum dose rate of the overall system.
- Between 700'000 and 4'000'000 years, ^{135}Cs dominates the dose rate. In [14] it was recognized that the model underestimates sorption of *Cs*. The maximum dose rate from ^{135}Cs is about 2.5% of the maximum dose rate of the sum of all nuclides.
- After 4 million years, Uranium and its daughter nuclides dominate the dose rate. The maximum dose rate is not reached within the calculation period of 10 million years.

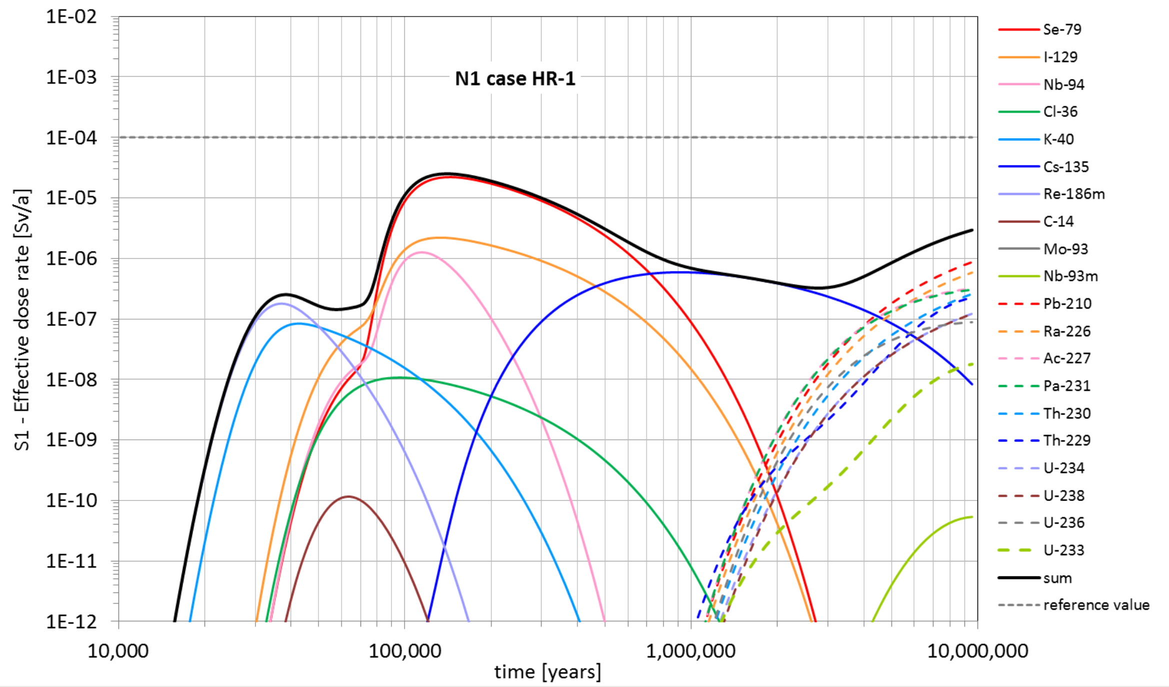

Figure 3-5: Effective dose rate. Calculation case *HR-1*. PA-model version 9.3.

3.4. Variation of Overburden parameters

The results of the variation of residence times in the overburden are presented in Figure 3-6. The fastest streamline (*OV-1*) from all climatic scenarios considered in [6], Table 5-3, leads to a 5% higher dose rate than the *DV* case. The slowest streamline (*OV-2*) results in a dose rate about 5 times smaller than the *DV* case, mainly due to decay of ^{79}*Se*. Moderate sorption of radionuclides in the overburden (*OV-3*), using the minimum values in [6], Table 5-5, causes a slight delayed onset of the breakthrough curve by retardation of ^{94}*Nb*.

For the fastest streamline, the maximum value occurs at 190'000 years, and in case of the slowest streamline, the peak value occurs at 1.1 million years, consistent with the longer travel time through the overburden.

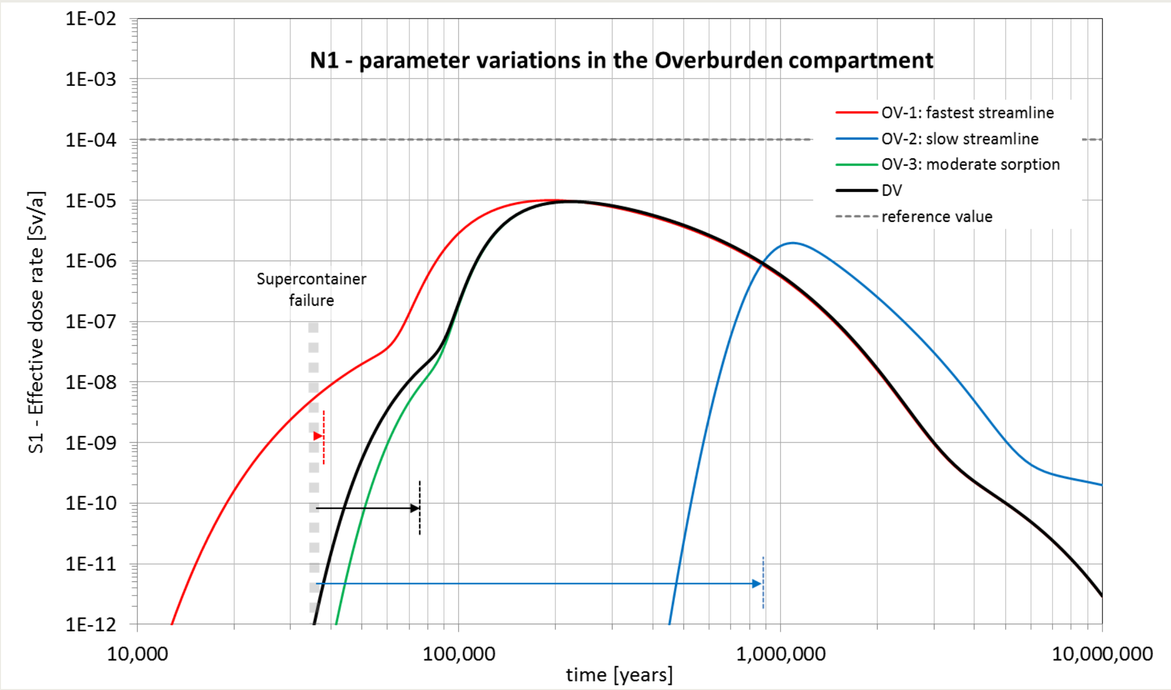

Figure 3-6: Effective dose rate. Calculation cases *OV-1*, *OV-2*, *OV-3*, and *DV*. PA-model version 9.3. The arrows indicate the overburden residence times for the cases, starting at the moment of assumed supercontainer failure.

Larger dilution by dispersion (*OV-4*) results in a lower overall dose rate, as is depicted in Figure 3-7.

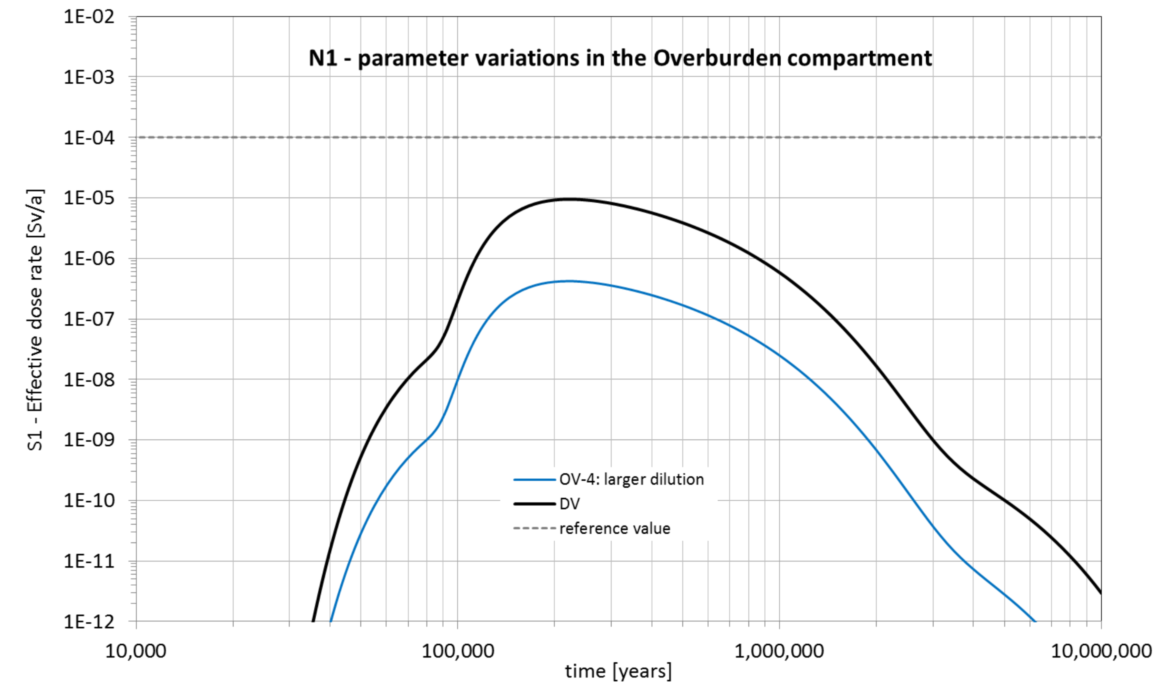

Figure 3-7: Effective dose rate. Calculation cases *OV-4* and *DV*. PA-model version 9.3.

3.5. Variation of Biosphere parameters

Figure 3-8 shows the effect of different climates on the maximum dose rates: in case of a Mediterranean climate (*BIO-1*), the dose rate is almost three times higher than for the base case (*DV*). For a boreal climate (*BIO-2*), the maximum dose rate is about 60% of the dose rate in the base case.

In case of a local drinking water well (*BIO-3*), the maximum dose rate is about a factor of 8 lower than in case of the irrigation well, as assumed in the base case. Unlike in the drinking water well case, where water is used for human consumption only, in the irrigation well case water is also used for agriculture and other purposes, explaining the larger risk of this pathway.

The large river case (*BIO-4*) with a boreal climate represents the most favourable case of all pathways defined in [6]. The dose rates are almost a million times smaller than in case of a local irrigation well.

As depicted in Figure 3-8, the time of the peak value and the overall shape of the five cases are almost identical, since these five cases only differ in the value of the applied dose conversion factors (DCCs) or in the dilution by mixing in the biosphere. All other possible combinations of biosphere pathways and climates will result in dose rate curves situated between the cases *BIO-1* and *BIO-4*.

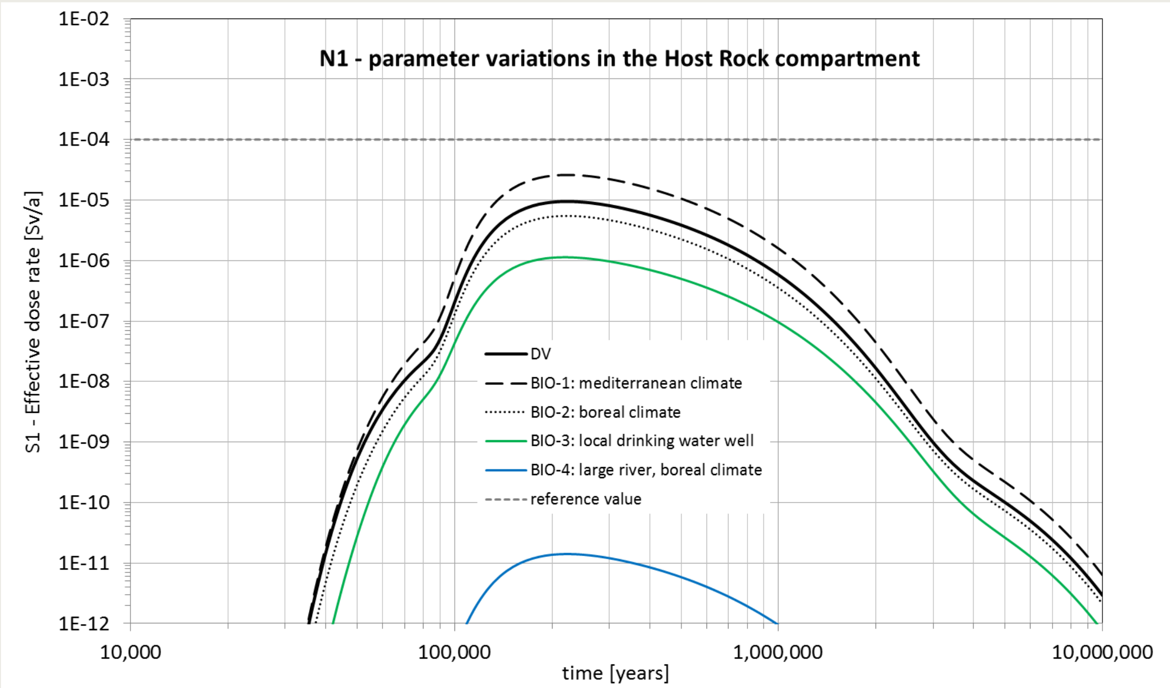

Figure 3-8: Effective dose rate. Calculation cases *DV*, *BIO-1*, *BIO-2*, *BIO-3*, and *BIO-4*. PA-model version 9.3.

3.6. 'Worst case' analysis

Figure 3-9 shows the calculated dose rate for the least favourable conditions in each compartment (*EBS-1*, *HR-1*, *OV-1*, and *BIO-1*), and for the 'worst case', a combination of these cases (*EBS-1HR-1OV-1BIO-1*). In this hypothetical, very conservative case, a maximum dose rate of 0.08 mSv/a is calculated, about 8 times higher than in the base case (*DV*). The peak value of the dose rate in the *EBS-1HR-1OV-1BIO-1* case is reached after 76'000 years. An early peak of about 0.5% of the maximum dose rate appears at 8700 year, due to very conservative assumption on the diffusion rate of ^{186m}*Re* [6].

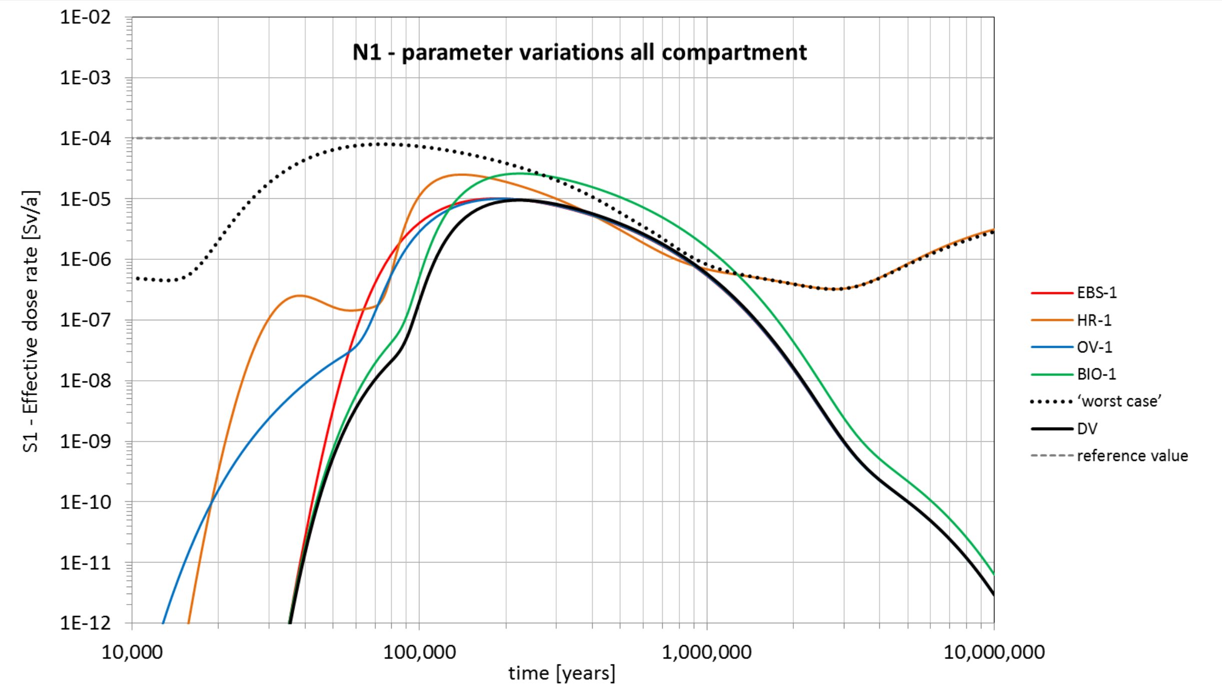

Figure 3-9: Effective dose rate. Calculation cases *EBS-1*, *HR-1*, *OV-1*, *BIO-1*, 'worst case' (*EBS-1HR-1OV-1BIO-1*), and *DV*. PA-model version 9.3.

3.7. Overall system behaviour

An overview of all analysed cases is presented in Figure 3-10. Due to overlap with the *DV* case, the case *EBS-3* is not visible.

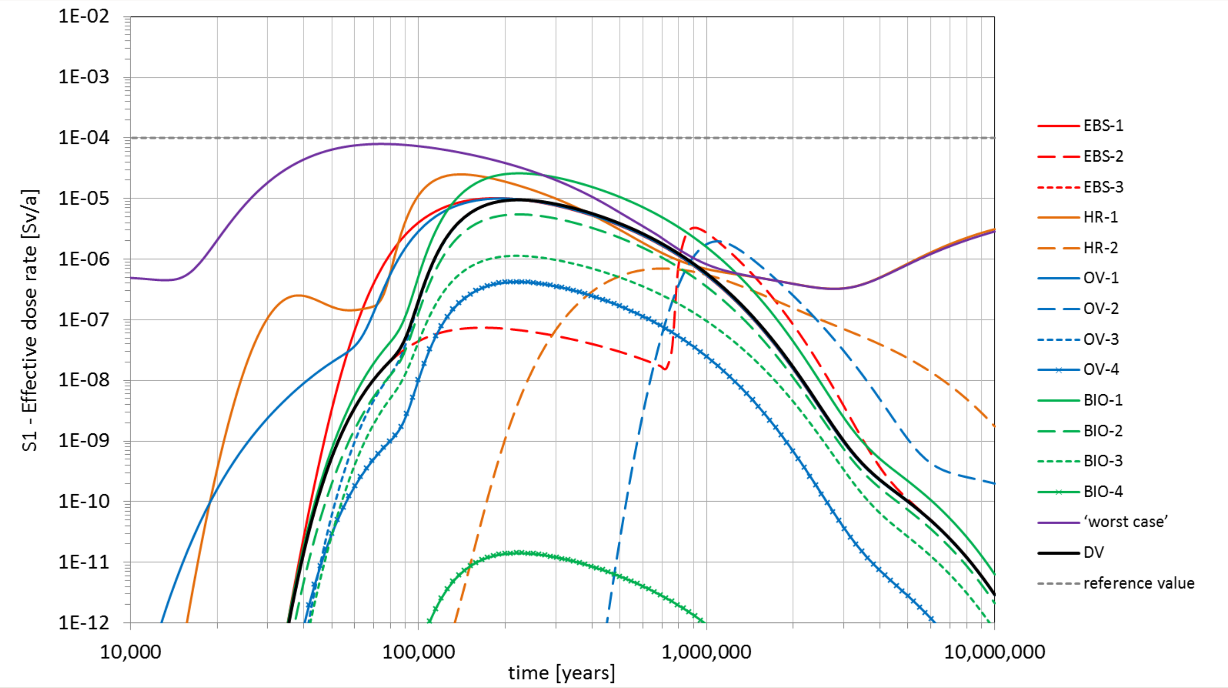

Figure 3-10: Effective dose rate. Overview of all analysed cases. PA-model version 9.3. Note that the *EBS-3* is not visible due to overlap with the *DV* case.

Table 3-2 summarizes all times of maximum dose rates and maximum dose rate values for the parameter variations analysed in this report.

Table 3-2: Time of maximum dose rate and maximum dose rates for all calculated parameter variations of the *Central Assessment Case* (N1) of the *Normal Evolution Scenario*

Case	time of maximum dose rate [yrs]	maximum dose rate [Sv/a]	maximum dose rate, relative to the DV case [%]
DV	219'000	$9.5 \cdot 10^{-6}$	100
EBS-1	182'000	$1.0 \cdot 10^{-5}$	107
EBS-2	912'000	$3.3 \cdot 10^{-6}$	35
EBS-3	219'000	$9.5 \cdot 10^{-6}$	100
HR-1	138'000	$2.5 \cdot 10^{-5}$	263
HR-2	692'000	$7.0 \cdot 10^{-7}$	7.4
OV-1	190'600	$1.0 \cdot 10^{-5}$	105
OV-2	1'100'000	$2.0 \cdot 10^{-6}$	21
OV-3	219'000	$9.5 \cdot 10^{-6}$	100
OV-4	219'000	$4.2 \cdot 10^{-7}$	4.4
BIO-1	219'000	$2.6 \cdot 10^{-5}$	274
BIO-2	219'000	$5.5 \cdot 10^{-6}$	58
BIO-3	219'000	$1.1 \cdot 10^{-6}$	12
BIO-4	219'000	$1.4 \cdot 10^{-11}$	0.00015
EBS-1HR-1OV-1BIO-1	76'000	$7.9 \cdot 10^{-5}$	836

4. Conclusions, recommendation

As part of the deterministic uncertainty assessment performed in this study, 14 parameter variations of the PA-model representation of the *Central Assessment Case N1* of the *Normal Evolution Scenario* were calculated and analysed. The results complement the primary PA analyses as reported in [7].

The deterministic uncertainty analysis provides a good overview on the overall system behaviour and shows the impact of all parameter variations documented in [6]. The results show that for all cases, the dose rate remains below the reference value. Although only a limited set of combined min-max values was used, from the general system understanding it can be assumed that these calculations cover sufficiently the parameter space defined in [6], although incidentally other parameter combinations may lead to maximum dose rates slightly above the 'worst case' calculation case (*EBS-1HR-1OV-1BIO-1*), mainly in case of a later release (*EBS-2*) or longer travel times (*OV-2*). However, it is expected that the peak values will not be higher than the maximum dose rates of the 'worst case' presented here.

The PA calculations were limited to a period of 10 million years, in accordance with the assessment strategy defined by the OPERA Safety Case Group (OSCG) [15]. Therefore, no conclusions on the effect of the parameter uncertainty on the dose rate by Uranium and its daughter nuclides can be given: the peak in the dose rate caused by these nuclides is beyond the calculation period. However, from understanding of the involved processes it is expected that:

- parameter variations in the *Waste-EBS* compartment related to container failure and waste release rates (*EBS-1*, *EBS-2*) will have a comparable influence as on the first peak discussed in Section 3.2, although due to the long time scales the effect will be less visible on a (log-scaled) graph;
- a lower solubility of Uranium in the *Waste-EBS* compartment (*EBS-3*) will result in a lower dose rate of Uranium and its daughter nuclides. This effect is however not visible in the calculated time frame of 10 million years;
- parameter variations in the *Host Rock* compartment will result either in an earlier appearance of Uranium and its daughter nuclides (*HR-1*, see Figure 3-4 in Section 3.3) or a further delay of the peak dose rate (*HR-2*), eventually exceeding the expected life-time of the Earth (~5 billion years, [16]). Due to the long-half live of ^{238}U and the solubility limitation in the *Waste-EBS*, the parameter variation will have little effect on the peak dose rate within this period;
- parameter variations in the *Overburden* compartment related to residence times (*OV-1*, *OV-2*) will have a comparable influence as on the first peak shown in Section 3.4, although due to the long time scales, the effect will be less visible on a (log-scaled) graph;
- parameter variations in the *Overburden* compartment related to sorption (*OV-3*) will have a comparable influence as discussed for *HR-2*;
- parameter variations in the *Overburden* compartment related to dilution by dispersion (*OV-4*) and parameter variation in the Biosphere (*BIO1 - BIO4*) will have a very comparable influence on the dose rate curves as shown in Section 3.4 and 3.5.

Since a probabilistic uncertainty analysis of the Normal Evolution Scenario would only yield a testable 95-percentile curve within the present established envelop – and therefore below the given reference dose rate value – it is recommended to focus further safety assessment work for support of the safety case on the alternative scenarios.

References

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

[2] Verhoef, E, E Neeft, JB Grupa, A Poley, *OPERA. Outline of a disposal concept in clay*, OPERA report OPERA-PG-COV008, COVRA N.V., First update November 2014.

[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.

[5] Grupa, JB, P Davis, *Report on the OPERA Safety Case structure,* OPERA report OPERA-PU-NRG2111, January 2014.

[6] Schröder TJ, J Hart, JCL Meeussen, *Report on model parameterization - Normal evolution scenario*, OPERA-PU-NRG7251-NES, September 2017.

[7] Rosca-Bocancea, E, TJ Schröder, J Hart, *Safety assessment calculation: Central Assessment Case of the Normal Evolution Scenario*, OPERA-PU-NRG7331, submitted 2017.

[8] Grupa JB, Meeussen JCL, Rosca-Bocancea E, Buhmann D, Laggiard E, Wildenborg AFB, *Report on migration model in Boom Clay*, OPERA report OPERA-PU-NRG7212, March 2017.

[9] Grupa JB, Meeussen JCL, Rosca-Bocancea E, Wildenborg AFB, Buhmann D, Laggiard E, *Report on migration model in rock formations surrounding the host rock*, OPERA report OPERA-PU-GRS7222, January 2017

[10] Grupa JB, Hart J, Meeussen JCL, Rosca-Bocancea E, Sweeck L, Wildenborg AFB, *Migration and uptake of radionuclides in the biosphere. PA-model 'Biosphere'*, OPERA report OPERA-PU-SCK631&NRG7232, February 2017.

[11] Rosca-Bocancea E, Schröder TJ, *Development of Safety and Performance Indicators*, OPERA-PU-NRG7311, January 2016.

[12] Schröder TJ, Rosca-Bocancea E, *Safety and performance indicator calculation methodology*, OPERA-PU-NRG7312, January 2016.

[13] Hart J, TJ Schröder, *ENGAGED - Recommended reference values for the OPERA safety assessment*, OPERA-PU-NRG1222, January 2017.

[14] Schröder TJ, Meeussen JCL, Dijkstra JJ, *Final report on radionuclide sorption in Boom Clay*, OPERA report OPERA-PU-NRG6123, February 2017.

[15] Verhoef E, *Note of the 7th OPERA Safety case group meeting*, 20-21 of April, 2017.

[16] Wikipedia, the free encyclopedia, *Earth*, https://en.wikipedia.org/wiki/Earth

Appendix A: Case overview

Subcases identified as part of preparatory deterministic calculations and the parameter values used

<table>
<tr><th rowspan="2">Case ID</th><th colspan="3">Waste-EBS</th><th colspan="3">Host Rock</th><th colspan="3">Overburden</th><th colspan="2">Biosphere</th></tr>
<tr><th>Time of container failure $T_{failure}$ [a] (Supercontainer/ Konrad container)</th><th>Release rate λ_{rel} [1/a] (Vitrified HLW)</th><th>Solubility limit S for Uranium [mol/l]</th><th>Retardation factors R_{aq} & R_{DOC} [-]</th><th>Diffusion accessible porosity η_i & η_{DOC} [-]</th><th>Pore diffusion rate $D_{pore,i}$ & $D_{pore,DOC}$ [-]</th><th>Travel time [yrs]</th><th>Dilution by dispersion factor F_{disp} [-]</th><th>Retardation factor R [-]</th><th>DCC [Sv/yr per Bq/m^3]</th><th>Dilution factor F_d [-]</th></tr>
<tr><td>DV</td><td>35'000/ 1500</td><td>$5.2\cdot10^{-5}$</td><td>$1.0\cdot10^{-5}$</td><td rowspan="4" colspan="3">median</td><td rowspan="6">30'700</td><td rowspan="6">4.5</td><td rowspan="6">1</td><td rowspan="10">Temperate Climate</td><td rowspan="10">1</td></tr>
<tr><td>EBS-1</td><td>1000/ 150</td><td>$3.8\cdot10^{-3}$</td><td>$1.0\cdot10^{-5}$</td></tr>
<tr><td>EBS-2</td><td>700'000/ 200'000</td><td>$1.6\cdot10^{-7}$</td><td>$1.0\cdot10^{-5}$</td></tr>
<tr><td>EBS-3</td><td>35'000/ 1500</td><td>$5.2\cdot10^{-5}$</td><td>$1.0\cdot10^{-6}$</td></tr>
<tr><td>HR-1</td><td rowspan="10">35'000/ 1500</td><td rowspan="10">$5.2\cdot10^{-5}$</td><td rowspan="10">$1.0\cdot10^{-5}$</td><td>5-percentile</td><td>maximum</td><td>minimum</td></tr>
<tr><td>HR-2</td><td>95-percentile</td><td>maximum</td><td>minimum</td></tr>
<tr><td>OV-1</td><td rowspan="8" colspan="3">median</td><td>1540</td><td>4.5</td><td>1</td></tr>
<tr><td>OV-2</td><td>853'000</td><td>4.5</td><td>1</td></tr>
<tr><td>OV-3</td><td>30'700</td><td>4.5</td><td>minimum</td></tr>
<tr><td>OV-4</td><td>30'700</td><td>100</td><td>1</td></tr>
<tr><td>BIO-1</td><td rowspan="4">30'700</td><td rowspan="4">4.5</td><td rowspan="4">1</td><td>Mediterranean Climate</td><td>1</td></tr>
<tr><td>BIO-2</td><td>Boreal Climate</td><td>1</td></tr>
<tr><td>BIO-3</td><td>Mediterranean climate</td><td>1</td></tr>
<tr><td>BIO-4</td><td>Boreal climate</td><td>$4.9\cdot10^{5}$</td></tr>
<tr><td>'Worst case'</td><td>1000/ 150</td><td>$3.8\cdot10^{-3}$</td><td>$1.0\cdot10^{-5}$</td><td>5-percentile</td><td>maximum</td><td>minimum</td><td>1540</td><td>4.5</td><td>1</td><td>Mediterranean Climate</td><td>1</td></tr>
</table>

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