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Dose rate calculations – project REBUS

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Preface

The reference design on which the licensing of the KBS 3 system for the management of spent nuclear fuel is based includes a reference canister for final disposal. The reference canister, which fulfils all established design requirements for post-closure safety, consists of an outer, corrosion resistant copper shell and a load-bearing nodular cast iron insert. In SKB's continuous efforts to optimise the design of the KBS-3 repository, it is evaluated whether an alternative design of the load-bearing insert can be achieved through a simpler and more cost effective production process. As an alternative to the reference nodular cast iron insert, a design with an outer low-alloy carbon steel tube and an inner framework of carbon steel plates for either 12 BWR or 4 PWR fuel elements is being studied in the so-called Rebus project. Within the project it is evaluated if such a design has the prospects of fulfilling the same design requirements as the reference canister insert, and if this can be achieved efficiently in a full-scale production process. The Rebus insert has the same outer dimensions as the reference insert and is intended to be placed in a copper shell identical to that of the reference design.

The study documented in this report was performed to provide information that will help evaluate post-closure safety aspects of the proposed Rebus insert.

Abstract

Within the ongoing SKB project Rebus, SKB is re-evaluating the current reference design of the cast iron insert of the KBS-3 canister. Design alternative 1 (Concept 1) consists of a cylinder of carbon steel, with a carbon steel framework holding the fuel elements in place.

Due to the differences in both material composition and geometry between the current insert and the design alternatives considered within the REBUS project, new calculations are performed of the radiation fields extending from the encapsulated nuclear fuel and through the canister materials. This report presents calculations of dose to gas inside the canister, dose to steel and cooper and human dose rate at 2 meters.

Sammanfattning

Inom REBUS-projektet pågår en omvärdering av gjutjärnsinsatsen i KBS-3-kapseln. Designalternativ 1 består av en kolstålscylinder med en fackverkskonstruktion för att hålla bränsleelementen. På grund av skillnader i material och konstruktion jämförd med referensdesignen, har nya stråldosberäkningar utförts.

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1 Introduction

Within the ongoing SKB project Rebus, SKB is re-evaluating the current reference design (SKB 2010) of the cast iron insert of the KBS-3 canister. Design alternative 1 (Concept 1) consists of a cylinder of carbon steel, with a carbon steel framework holding the fuel elements in place (Ronneteg 2023).

Due to the differences in both material composition and geometry between the current insert and the design alternative 1 considered within the Rebus project, SKB needs to conduct new calculations of the radiation fields extending from the encapsulated nuclear fuel and through the canister materials. The results will be used to estimate the extent of radiation induced damage in various parts of the canister, and to make bounding calculations for the extent of radiolytic corrosion on the outer canister surface in the assessment of canister integrity and post-closure safety. Additionally, the dose to the encapsulated gas will be used in radiolysis calculations.

This report presents calculation of dose rates to gas, materials and humans for the inserts designs discussed within the Rebus project.

1.1 Basis for dose rate calculations

Data and postulated scenarios for the dose rate calculations are given by Lilja and Evins (2022)[1]. The deliverables for this report are:

- dose to fill gas within fuel assembly (Gy/h),
- dose to material, both steel and copper with bentonite present (Gy/h),
- detailed neutron spectra as presented in Guinan (2001),
- dose to person 2 m from canister without bentonite (mSv/h).

For these calculations source terms corresponding to decay times 0, 1, 10, 20, 50, 100, 1 000, 10^4, 10^5 and 10^6 years after encapsulation are used. Encapsulation is here assumed to take place after 20 years cooling.

[1] Lilja C, Zetterström Evins L, 2022. Basis for dose calculations – project REBUS. SKBdoc 1959879 ver 2.0. (Internal document.)

2 Computational method

In order to model radiation transport the code MCNP6.2 (Werner et al. 2018) with continuous energy neutron cross section data tables based primarily upon ENDF/B-VII.1. A list of used neutron cross section is presented in appendix. For source term determination the code SNF is applied[2]. In order to simplify the calculations in a conservative manner only quarter canister models are used.

2.1 MCNP model

The canister models contain all steel structures of the insert, and top and bottom copper lid. The fuel is modelled with high resolution containing fuel pellet, gap and cladding, see Figure 2-1. Furthermore, guide and instrument tubes (PWR) and box and water channels (BWR) are modelled. For both BWR and PWR, the plenum region above the active height is modelled. Top and bottom structures such as tie plate, transition piece and handles are modelled as a homogenized mixture of steel and air, preserving the weight of the components. The input files to the MCNP model presented here are stored at SKB (svn://svn.skb.se/RS/RSK/).

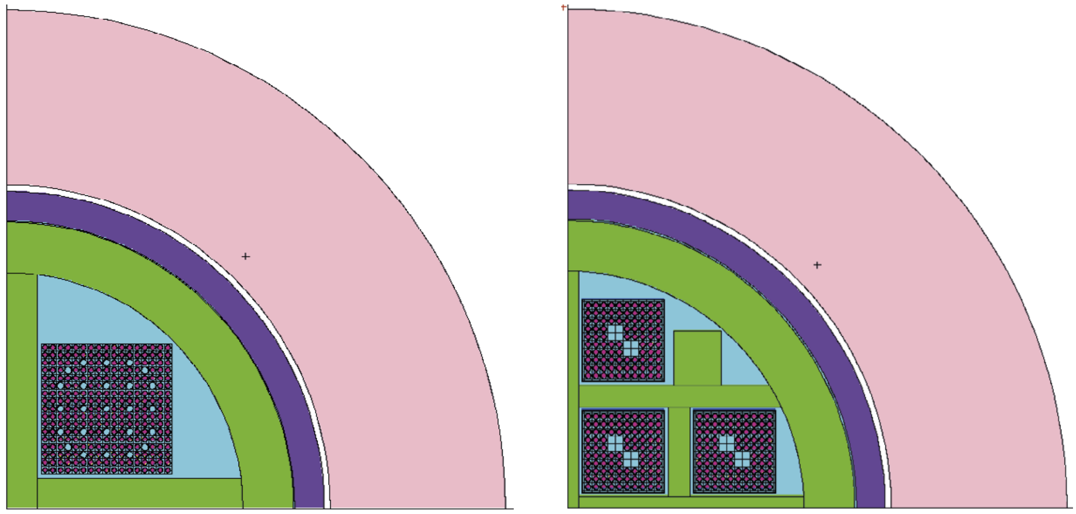

Figure 2-1. *Top view of MCNP models of the Rebus inserts for PWR (left) and BWR (right). Green colour represents steel, blue gas (Ar), purple copper and pink bentonite.*

[2] Resulting spectra are similar, but not identical to the spectra presented in: Zakova J, Pukari M, 2017. Aktivitets-inventarier och källstyrkor för använt kärnbränsle i det svenska avfallsprogrammet. SKBdoc 1198314 ver 4.0. (Internal document.)

2.2 Source terms

Maximum burnup and corresponding source term for PWR and BWR will be analysed at 55 MWd/kgU and 50 MWd/kgU respectively[3]. The radial distribution of the source in the MCNP model is uniformly applied to all pins. For the axial distribution typical power profiles from core follow data are applied, resulting in weaker source terms in the top and bottom of the modelled fuel. The energy resolution of the source term varies over time for gamma. Accordingly, specific source terms regarding gamma energy resolution are used. For the neutron spectra the distribution over energy does not change much over time, only the total intensity. Figures 2-2 and 2-3 show the gamma and neutron energy spectra, normalized to the same average intensity. Source term intensity and spectra for PWR and BWR used for the calculations in this report are presented in Table 2-1.

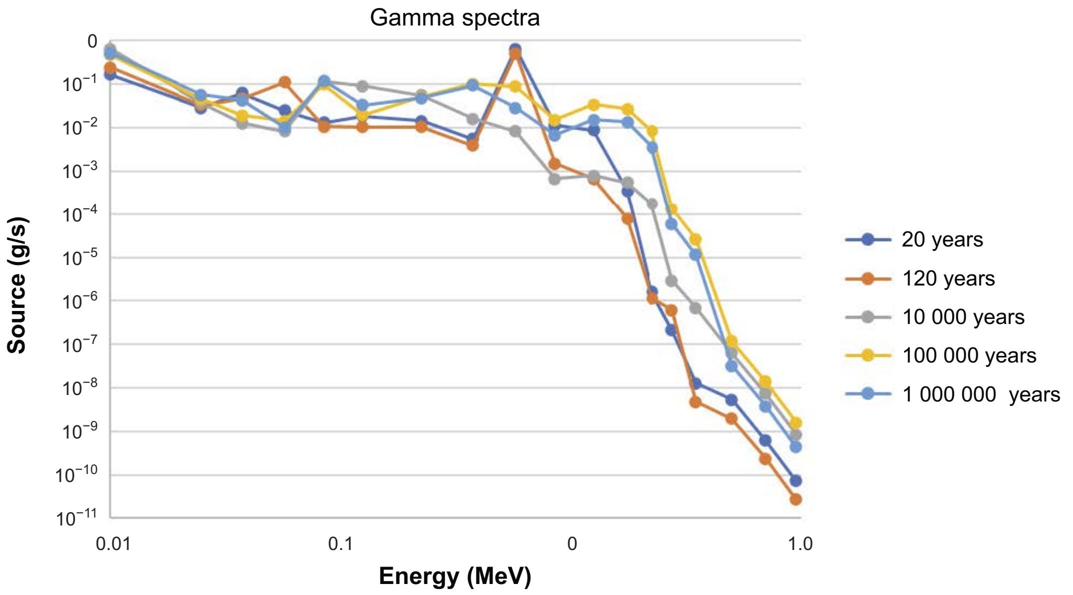

Figure 2-2. *Normalized gamma spectra for different decay times.*

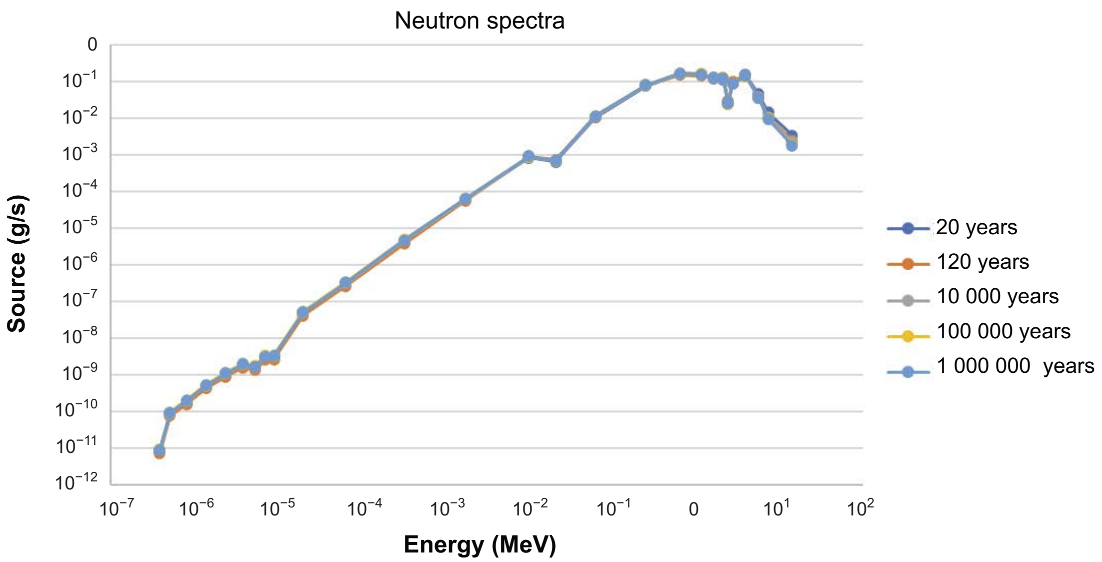

Figure 2-3. *Normalized neutron spectra for different decay times.*

[3] For calculations of gas radiolysis in the canister performed elsewhere, also lower burnup fuels were used.

Table 2-1. Source terms per fuel assembly and gamma- and neutron spectra used for dose rate calculations. The column spectra refer to which decay time spectra is chosen from.

	PWR 55 MWd/kgU			BWR 50 MWd/kgU	
yr after encap.	**g/s**	**n/s**	**spectra**	**g/s**	**n/s**
0	2.00E+15	3.61E+08	120yr	6.50E+14	1.10E+08
1	1.94E+15	3.48E+08	120yr	6.33E+14	1.06E+08
10	1.55E+15	2.50E+08	120yr	5.07E+14	7.63E+07
20	1.23E+15	1.75E+08	120yr	4.00E+14	5.31E+07
50	6.10E+14	6.44E+07	120yr	1.99E+14	1.91E+07
100	1.92E+14	1.99E+07	120yr	6.24E+13	5.62E+06
1 000	1.77E+10	8.39E+06	120yr	2.07E+10	2.90E+06
10 000	2.29E+10	2.99E+06	1e4yr	2.09E+10	1.06E+06
100 000	5.94E+10	7.46E+05	1e5yr	2.26E+10	2.64E+05
1 000 000	1.66E+10	1.50E+05	1e6yr	4.94E+09	5.10E+04

3 Results

3.1 Dose to gas

Table 3-1 presents average and maximum dose rate in the fill gas between the fuel pins for the high burnup fuels. The average dose is calculated over the whole axial length of the fuel assembly whereas the maximum dose corresponds to the maximum nodal value. A node is approximately 15 cm high. For lower burnup fuels the average dose rates at the time of encapsulation are 39 Gy/h (BWR 30 MWd/kgU) and 57 Gy/h (PWR 30 MWd/kgU)[4].

Table 3-1. Average and maximum dose rates in the fill gas between fuel pins.

	PWR 55 MWd/kgU		BWR 50 MWd/kgU	
Years	average (Gy/h)	max (Gy/h)	average (Gy/h)	max (Gy/h)
0	2.46E+02	3.08E+02	1.66E+02	2.07E+02
1	2.40E+02	2.99E+02	1.61E+02	2.02E+02
10	1.92E+02	2.39E+02	1.29E+02	1.62E+02
20	1.51E+02	1.89E+02	1.02E+02	1.27E+02
50	7.52E+01	9.40E+01	5.07E+01	6.33E+01
100	2.37E+01	2.96E+01	1.59E+01	1.99E+01
1 000	2.19E−03	2.73E−03	5.29E−03	6.61E−03
10 000	2.82E−03	3.53E−03	5.34E−03	6.68E−03
100 000	7.33E−03	9.16E−03	5.76E−03	7.20E−03
1 000 000	2.04E−03	2.55E−03	1.26E−03	1.58E−03

3.2 Dose to person at 2 m

Human dose rates are calculated using dose conversion factors from ICRP 116. The MCNP models are used without bentonite. Detailed axial and azimuthal meshes are used to find the location of the maximum dose. Dose from neutron, gamma and neutron induced gamma are computed. However, the contribution from neutron induced gammas are below 0.1 % and are hence omitted. Table 3-2 shows the results of the maximum dose rates in mSv/h at the time 0 years after encapsulation.

Table 3-2. Dose to person 2 m outside of canister.

Type	PWR (mSv/h)	BWR (mSv/h)
gamma	6.1	5.0
neutron	0.7	0.6
Total	6.8	5.6

[4] Loberg J (2022) Canister dose calculations for project REBUS. SKBdoc 1989961 ver 1.0. (Internal document.)

3.3 Dose to materials

Dose to material are calculated in four different locations, called points A–D. The points represent the central frame work (A), the inner surface of the steel cylinder (B), the inner and outer surface of the copper cylinder (C and D). The locations of these points are suggested in the basis for the calculations. In order to find the maximum dose rate related to the surfaces of points A–D for both inserts, detailed meshes are used over all surfaces both axially and radially. Points A–D are illustrated for the PWR insert in Figure 3-1 and for the BWR insert in Figure 3-2. For both inserts there are two azimuthal maxima in the steel and copper ring. However, only one of these is illustrated in Figures 3-1 and 3-2. The corresponding dose rates are presented in Table 3-3 for the PWR insert and Table 3-4 for the BWR insert. Neutron dose rates are neglected, since the gamma dose rate is several orders of magnitude larger.

Table 3-3. Gamma dose rates for the PWR insert, points A–D for different years after encapsulation.

yr after encap.	A (Gy/h)	B (Gy/h)	C (Gy/h)	D (mGy/h)
0	1.50E+02	1.38E+02	1.68E+00	1.27E+02
1	1.46E+02	1.34E+02	1.63E+00	1.24E+02
10	1.17E+02	1.07E+02	1.31E+00	9.90E+01
20	9.24E+01	8.47E+01	1.03E+00	7.81E+01
50	4.60E+01	4.21E+01	5.13E−01	3.89E+01
100	1.45E+01	1.33E+01	1.62E−01	1.23E+01
1 000	1.34E−03	1.23E−03	1.49E−05	1.13E−03
10 000	1.67E−03	1.53E−03	1.74E−05	1.25E−03
100 000	5.76E−03	5.09E−03	1.46E−05	1.46E−02
1 000 000	1.39E−03	1.25E−03	2.04E−05	2.41E−03

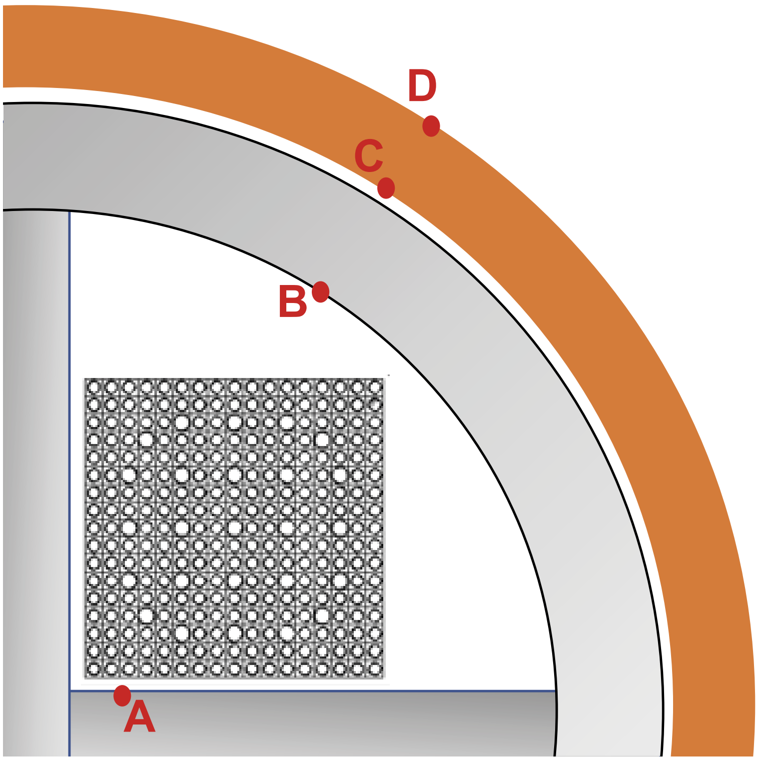

__Figure 3-1.__ Points A–D for the PWR insert where the maximum gamma dose rates are located for the inner structure (A), inner surface of steel cylinder (B), inner and outer surface of copper cylinder (C) and (D). Points B–D are located 36 degrees from the vertical axis.

Table 3-4. Gamma dose rates for the BWR insert, points A–D for different years after encapsulation. Doses in points B, C and D are retrieved using a tally over the entire azimuthal angle. To get the dose rate in the points, B, C and D, the tally-results are multiplied with the azimuthal form factor of 1.6.

yr after encap.	A (Gy/h)	B (Gy/h)	C (Gy/h)	D (mGy/h)
0	1.27E+02	9.97E+01	8.66E−01	9.39E+01
1	1.24E+02	9.70E+01	8.43E−01	9.14E+01
10	9.91E+01	7.77E+01	6.75E−01	7.32E+01
20	7.82E+01	6.13E+01	5.32E−01	5.77E+01
50	3.88E+01	3.04E+01	2.64E−01	2.87E+01
100	1.22E+01	9.57E+00	8.31E−02	9.01E+00
1 000	4.05E−03	3.18E−03	2.76E−05	2.99E−03
10 000	3.95E−03	3.11E−03	2.53E−05	2.52E−03
100 000	5.72E−03	4.41E−03	6.72E−05	1.35E−02
1 000 000	1.08E−03	8.38E−04	9.96E−06	1.66E−03

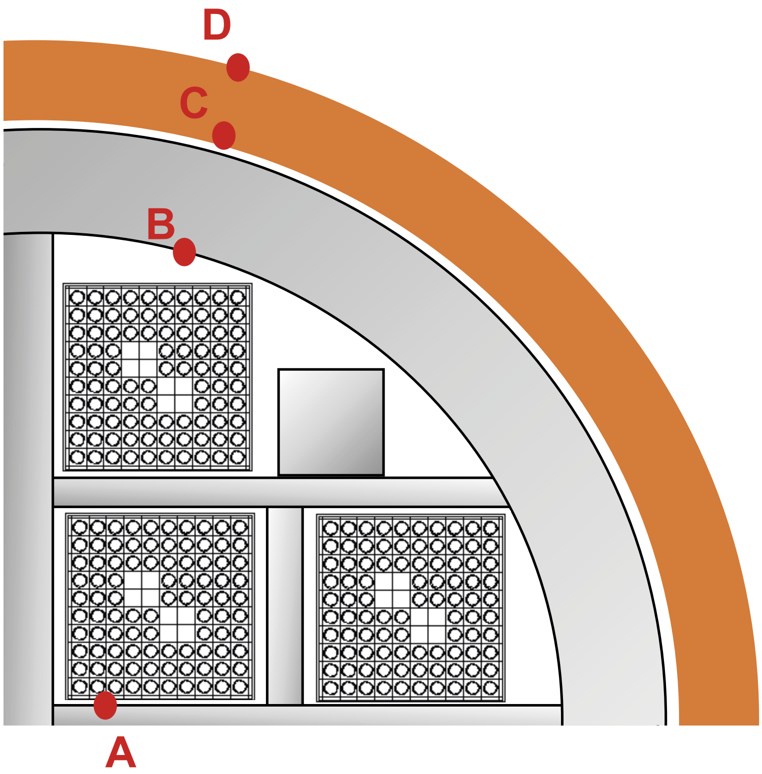

Figure 3-2. *Points A–D where maximum gamma dose rates are located for the inner structure (A), inner surface of steel cylinder (B), inner and outer surface of copper cylinder (C) and (D). Points B–D are located 17 degrees from the vertical axis.*

3.4 Neutron spectra – PWR insert

Detailed neutron spectra are calculated in position A–D for different decay times, in the same energy structure as Guinan (2001). Tables 3-5 to 3-8 show the result for different times after encapsulation.

Table 3-5. Binned neutron flux (n/cm^{2}s) at position A for the PWR insert.

E(MeV)		Time after encapsualtion			
Upper	Lower	0 yr	20 yr	100 yr	1 000 yr
1.00E+01	6.07E+00	3.08E+02	1.50E+02	1.70E+01	7.17E+00
6.07E+00	3.68E+00	1.95E+03	9.47E+02	1.08E+02	4.54E+01
3.68E+00	2.23E+00	4.98E+03	2.42E+03	2.75E+02	1.16E+02
2.23E+00	1.35E+00	8.98E+03	4.36E+03	4.96E+02	2.09E+02
1.35E+00	8.21E−01	1.46E+04	7.09E+03	8.07E+02	3.40E+02
8.21E-01	5.00E−01	3.06E+04	1.48E+04	1.69E+03	7.11E+02
5.00E-01	1.11E−01	9.41E+04	4.57E+04	5.20E+03	2.19E+03
1.11E-01	9.12E−03	8.33E+04	4.04E+04	4.60E+03	1.94E+03
9.12E-03	5.53E−03	4.15E+03	2.01E+03	2.29E+02	9.65E+01
5.53E-03	1.49E−04	1.88E+04	9.14E+03	1.04E+03	4.38E+02
1.49E-04	1.60E−05	3.04E+03	1.48E+03	1.68E+02	7.07E+01
1.60E-05	9.88E−06	3.08E+02	1.49E+02	1.70E+01	7.16E+00
9.88E-06	4.00E−06	3.60E+02	1.75E+02	1.99E+01	8.36E+00
4.00E-06	1.86E−06	1.81E+02	8.77E+01	9.98E+00	4.20E+00
1.86E-06	1.10E−06	7.93E+01	3.85E+01	4.38E+00	1.85E+00
1.10E-06	1.02E−06	7.90E+00	3.83E+00	4.36E−01	1.84E−01
1.02E-06	6.25E−07	3.82E+01	1.86E+01	2.11E+00	8.89E−01
6.25E-07	3.50E−07	2.02E+01	9.82E+00	1.12E+00	4.71E−01
3.50E-07	2.80E−07	3.23E+00	1.57E+00	1.78E−01	7.51E−02
2.80E-07	1.40E−07	3.36E+00	1.63E+00	1.86E−01	7.82E−02
1.40E-07	5.80E−08	5.63E−01	2.73E−01	3.11E−02	1.31E−02
5.80E-08	3.00E−08	2.97E−02	1.44E−02	1.64E−03	6.91E−04
3.00E-08	1.00E−10	4.94E−04	2.40E−04	2.73E−05	1.15E−05

Table 3-6. Binned neutron flux (n/cm^{2}s) at position B for the PWR insert.

E(MeV)		Time after encapsualtion			
Upper	Lower	0 yr	20 yr	100 yr	1 000 yr
1.00E+01	6.07E+00	3.10E+02	1.50E+02	1.71E+01	7.21E+00
6.07E+00	3.68E+00	1.94E+03	9.42E+02	1.07E+02	4.51E+01
3.68E+00	2.23E+00	4.62E+03	2.24E+03	2.55E+02	1.07E+02
2.23E+00	1.35E+00	7.36E+03	3.57E+03	4.07E+02	1.71E+02
1.35E+00	8.21E−01	1.03E+04	4.99E+03	5.68E+02	2.39E+02
8.21E-01	5.00E−01	2.05E+04	9.92E+03	1.13E+03	4.76E+02
5.00E-01	1.11E−01	6.17E+04	2.99E+04	3.41E+03	1.43E+03
1.11E-01	9.12E−03	5.84E+04	2.84E+04	3.23E+03	1.36E+03
9.12E-03	5.53E−03	3.61E+03	1.75E+03	1.99E+02	8.39E+01
5.53E-03	1.49E−04	1.47E+04	7.14E+03	8.13E+02	3.42E+02
1.49E-04	1.60E−05	2.31E+03	1.12E+03	1.28E+02	5.37E+01
1.60E-05	9.88E−06	2.63E+02	1.28E+02	1.45E+01	6.12E+00
9.88E-06	4.00E−06	3.22E+02	1.56E+02	1.78E+01	7.50E+00
4.00E-06	1.86E−06	2.06E+02	9.99E+01	1.14E+01	4.79E+00
1.86E-06	1.10E−06	9.95E+01	4.83E+01	5.50E+00	2.32E+00
1.10E-06	1.02E−06	9.92E+00	4.81E+00	5.48E−01	2.31E−01
1.02E-06	6.25E−07	5.01E+01	2.43E+01	2.77E+00	1.17E+00
6.25E-07	3.50E−07	2.89E+01	1.40E+01	1.60E+00	6.73E−01
3.50E-07	2.80E−07	4.47E+00	2.17E+00	2.47E−01	1.04E−01
2.80E-07	1.40E−07	6.28E+00	3.05E+00	3.47E−01	1.46E−01
1.40E-07	5.80E−08	2.15E+00	1.04E+00	1.19E−01	5.00E−02
5.80E-08	3.00E−08	3.02E−01	1.46E−01	1.67E−02	7.01E−03
3.00E-08	1.00E−10	9.45E−02	4.59E−02	5.22E−03	2.20E−03

Table 3-7. Binned neutron flux (n/cm²s) at position C for the PWR insert.

E(MeV)		Time after encapsualtion			
Upper	Lower	0 yr	20 yr	100 yr	1000 yr
1.00E+01	6.07E+00	3.29E+01	1.59E+01	1.82E+00	7.64E−01
6.07E+00	3.68E+00	2.14E+02	1.04E+02	1.18E+01	4.98E+00
3.68E+00	2.23E+00	6.64E+02	3.22E+02	3.67E+01	1.54E+01
2.23E+00	1.35E+00	1.63E+03	7.93E+02	9.03E+01	3.80E+01
1.35E+00	8.21E−01	4.04E+03	1.96E+03	2.23E+02	9.40E+01
8.21E-01	5.00E−01	1.03E+04	5.01E+03	5.70E+02	2.40E+02
5.00E-01	1.11E−01	3.86E+04	1.87E+04	2.13E+03	8.98E+02
1.11E-01	9.12E−03	3.90E+04	1.89E+04	2.15E+03	9.06E+02
9.12E-03	5.53E−03	2.78E+03	1.35E+03	1.54E+02	6.48E+01
5.53E-03	1.49E−04	1.06E+04	5.15E+03	5.86E+02	2.47E+02
1.49E-04	1.60E−05	3.61E+03	1.75E+03	1.99E+02	8.39E+01
1.60E-05	9.88E−06	5.99E+02	2.91E+02	3.31E+01	1.39E+01
9.88E-06	4.00E−06	9.16E+02	4.45E+02	5.06E+01	2.13E+01
4.00E-06	1.86E−06	5.48E+02	2.66E+02	3.03E+01	1.28E+01
1.86E-06	1.10E−06	2.72E+02	1.32E+02	1.50E+01	6.33E+00
1.10E-06	1.02E−06	3.17E+01	1.54E+01	1.75E+00	7.38E−01
1.02E-06	6.25E−07	1.81E+02	8.77E+01	9.98E+00	4.20E+00
6.25E-07	3.50E−07	1.51E+02	7.33E+01	8.35E+00	3.51E+00
3.50E-07	2.80E−07	4.36E+01	2.12E+01	2.41E+00	1.02E+00
2.80E-07	1.40E−07	1.17E+02	5.69E+01	6.48E+00	2.73E+00
1.40E-07	5.80E−08	1.87E+02	9.07E+01	1.03E+01	4.35E+00
5.80E-08	3.00E−08	8.37E+01	4.06E+01	4.62E+00	1.95E+00
3.00E-08	1.00E−10	2.92E+01	1.42E+01	1.61E+00	6.79E−01

Table 3-8. Binned neutron flux (n/cm²s) at position D for the PWR insert.

E(MeV)		Time after encapsualtion			
Upper	Lower	0 yr	20 yr	100 yr	1000 yr
1.00E+01	6.07E+00	1.22E+01	5.93E+00	6.76E−01	2.84E−01
6.07E+00	3.68E+00	7.57E+01	3.68E+01	4.18E+00	1.76E+00
3.68E+00	2.23E+00	2.44E+02	1.18E+02	1.35E+01	5.67E+00
2.23E+00	1.35E+00	6.24E+02	3.03E+02	3.45E+01	1.45E+01
1.35E+00	8.21E−01	1.64E+03	7.96E+02	9.07E+01	3.82E+01
8.21E−01	5.00E−01	4.15E+03	2.01E+03	2.29E+02	9.65E+01
5.00E−01	1.11E−01	1.53E+04	7.42E+03	8.45E+02	3.56E+02
1.11E−01	9.12E−03	1.48E+04	7.16E+03	8.15E+02	3.43E+02
9.12E−03	5.53E−03	1.97E+03	9.56E+02	1.09E+02	4.58E+01
5.53E−03	1.49E−04	9.38E+03	4.55E+03	5.18E+02	2.18E+02
1.49E−04	1.60E−05	4.40E+03	2.14E+03	2.43E+02	1.02E+02
1.60E−05	9.88E−06	8.33E+02	4.04E+02	4.60E+01	1.94E+01
9.88E−06	4.00E−06	1.44E+03	6.97E+02	7.93E+01	3.34E+01
4.00E−06	1.86E−06	1.08E+03	5.25E+02	5.98E+01	2.52E+01
1.86E−06	1.10E−06	6.67E+02	3.24E+02	3.69E+01	1.55E+01
1.10E−06	1.02E−06	8.73E+01	4.24E+01	4.82E+00	2.03E+00
1.02E−06	6.25E−07	5.66E+02	2.75E+02	3.13E+01	1.32E+01
6.25E−07	3.50E−07	6.24E+02	3.03E+02	3.45E+01	1.45E+01
3.50E−07	2.80E−07	2.30E+02	1.12E+02	1.27E+01	5.36E+00
2.80E−07	1.40E−07	9.05E+02	4.39E+02	5.00E+01	2.11E+01
1.40E−07	5.80E−08	2.91E+03	1.41E+03	1.61E+02	6.77E+01
5.80E−08	3.00E−08	2.34E+03	1.14E+03	1.29E+02	5.44E+01
3.00E−08	1.00E−10	1.77E+03	8.59E+02	9.78E+01	4.12E+01

3.5 Gamma spectra – PWR insert

The same energy structure as for the neutron spectra is used in the calculation. However, due to that no gamma flux appears in the upper and lower bins the results are only presented where there were actual gamma flux, see Tables 3-9 to 3-12 for points A–D.

Table 3-9. Binned gamma flux (g/cm²s) at position A for the PWR insert.

E (KeV)		Time after encapsulation			
Upper	**Lower**	**0 yr**	**20 yr**	**100 yr**	**1 000 yr**
2.23E+03	1.35E+03	6.41E+07	3.94E+07	6.17E+06	5.69E+02
1.35E+03	8.21E+02	2.65E+08	1.63E+08	2.56E+07	2.36E+03
8.21E+02	5.00E+02	7.52E+09	4.62E+09	7.25E+08	6.69E+04
5.00E+02	1.11E+02	9.66E+09	5.93E+09	9.31E+08	8.58E+04
1.11E+02	9.12E+00	4.53E+08	2.78E+08	4.36E+07	4.03E+03
9.12E+00	5.53E+00	1.59E+06	9.75E+05	1.53E+05	1.41E+01
5.53E+00	1.49E−01	7.80E+04	4.79E+04	7.52E+03	6.93E−01

Table 3-10. Binned gamma flux (g/cm²s) at position B for the PWR insert.

E (KeV)		Time after encapsulation			
Upper	**Lower**	**0 yr**	**20 yr**	**100 yr**	**1 000 yr**
2.23E+03	1.35E+03	5.91E+07	3.63E+07	5.69E+06	5.25E+02
1.35E+03	8.21E+02	2.37E+08	1.46E+08	2.29E+07	2.11E+03
8.21E+02	5.00E+02	7.62E+09	4.68E+09	7.35E+08	6.78E+04
5.00E+02	1.11E+02	7.46E+09	4.58E+09	7.19E+08	6.63E+04
1.11E+02	9.12E+00	4.17E+08	2.56E+08	4.02E+07	3.71E+03
9.12E+00	5.53E+00	1.35E+06	8.32E+05	1.31E+05	1.20E+01
5.53E+00	1.49E−01	7.16E+04	4.40E+04	6.90E+03	6.37E−01

Table 3-11. Binned gamma flux (g/cm²s) at position C for the PWR insert.

E (KeV)		Time after encapsulation			
Upper	**Lower**	**0 yr**	**20 yr**	**100 yr**	**1 000 yr**
2.23E+03	1.35E+03	6.80E+05	4.18E+05	6.56E+04	6.05E+00
1.35E+03	8.21E+02	3.33E+06	2.05E+06	3.21E+05	2.96E+01
8.21E+02	5.00E+02	2.83E+07	1.74E+07	2.73E+06	2.52E+02
5.00E+02	1.11E+02	1.34E+08	8.21E+07	1.29E+07	1.19E+03
1.11E+02	9.12E+00	4.77E+06	2.93E+06	4.60E+05	4.24E+01
9.12E+00	5.53E+00	5.09E+04	3.13E+04	4.90E+03	4.52E−01
5.53E+00	1.49E−01	7.42E+02	4.56E+02	7.15E+01	6.60E−03

Table 3-12. Binned gamma flux (g/cm²s) at position D for the PWR insert.

E (KeV)		Time after encapsulation			
Upper	**Lower**	**0 yr**	**20 yr**	**100 yr**	**1 000 yr**
2.23E+03	1.35E+03	8.98E+04	5.52E+04	8.65E+03	7.98E−01
1.35E+03	8.21E+02	4.43E+05	2.72E+05	4.27E+04	3.94E+00
8.21E+02	5.00E+02	1.91E+06	1.17E+06	1.84E+05	1.69E+01
5.00E+02	1.11E+02	9.16E+06	5.63E+06	8.83E+05	8.14E+01
1.11E+02	9.12E+00	5.37E+05	3.30E+05	5.17E+04	4.77E+00
9.12E+00	5.53E+00	4.27E+03	2.62E+03	4.12E+02	3.80E−02
5.53E+00	1.49E−01	7.54E+01	4.63E+01	7.27E+00	6.70E−04

3.6 Neutron spectra – BWR insert

Detailed neutron spectra are calculated in position A–D, in the same energy structure as Guinan (2001). Tables 3-13 to 3-16 show the result for different encapsulation times.

Table 3-13. Binned neutron flux (n/cm²s) at position A for the BWR insert.

E(MeV)		Time after encapsualtion			
Upper	Lower	0 yr	20 yr	100 yr	1 000 yr
1.00E+01	6.07E+00	3.50E+02	1.68E+02	1.78E+01	9.20E+00
6.07E+00	3.68E+00	2.24E+03	1.08E+03	1.14E+02	5.88E+01
3.68E+00	2.23E+00	5.82E+03	2.80E+03	2.97E+02	1.53E+02
2.23E+00	1.35E+00	1.05E+04	5.07E+03	5.37E+02	2.77E+02
1.35E+00	8.21E−01	1.63E+04	7.83E+03	8.29E+02	4.28E+02
8.21E−01	5.00E−01	3.31E+04	1.59E+04	1.69E+03	8.71E+02
5.00E−01	1.11E−01	9.75E+04	4.69E+04	4.97E+03	2.56E+03
1.11E−01	9.12E−03	9.11E+04	4.38E+04	4.64E+03	2.39E+03
9.12E−03	5.53E−03	5.18E+03	2.49E+03	2.64E+02	1.36E+02
5.53E−03	1.49E−04	2.02E+04	9.71E+03	1.03E+03	5.30E+02
1.49E−04	1.60E−05	1.84E+03	8.83E+02	9.36E+01	4.83E+01
1.60E−05	9.88E−06	9.62E+01	4.63E+01	4.90E+00	2.53E+00
9.88E−06	4.00E−06	8.97E+01	4.32E+01	4.57E+00	2.36E+00
4.00E−06	1.86E−06	3.81E+01	1.83E+01	1.94E+00	1.00E+00
1.86E−06	1.10E−06	2.05E+01	9.85E+00	1.04E+00	5.38E−01
1.10E−06	1.02E−06	2.16E+00	1.04E+00	1.10E−01	5.68E−02
1.02E−06	6.25E−07	1.12E+01	5.41E+00	5.73E−01	2.96E−01
6.25E−07	3.50E−07	6.40E+00	3.08E+00	3.27E−01	1.68E−01
3.50E−07	2.80E−07	9.13E−01	4.39E−01	4.65E−02	2.40E−02
2.80E−07	1.40E−07	8.61E−01	4.14E−01	4.39E−02	2.26E−02
1.40E−07	5.80E−08	9.01E−02	4.34E−02	4.60E−03	2.37E−03
5.80E−08	3.00E−08	4.75E−03	2.29E−03	2.42E−04	1.25E−04
3.00E−08	1.00E−10	2.32E−03	1.11E−03	1.18E−04	6.09E−05

Table 3-14. Binned neutron flux (n/cm²s) at position B for the BWR insert.

E(MeV)		Time after encapsualtion			
Upper	Lower	0 yr	20 yr	100 yr	1 000 yr
1.00E+01	6.07E+00	1.67E+02	8.03E+01	8.50E+00	4.38E+00
6.07E+00	3.68E+00	1.06E+03	5.12E+02	5.42E+01	2.80E+01
3.68E+00	2.23E+00	2.71E+03	1.30E+03	1.38E+02	7.12E+01
2.23E+00	1.35E+00	4.85E+03	2.33E+03	2.47E+02	1.28E+02
1.35E+00	8.21E−01	7.67E+03	3.69E+03	3.91E+02	2.02E+02
8.21E−01	5.00E−01	1.64E+04	7.87E+03	8.34E+02	4.30E+02
5.00E−01	1.11E−01	5.23E+04	2.52E+04	2.67E+03	1.38E+03
1.11E−01	9.12E−03	5.36E+04	2.58E+04	2.73E+03	1.41E+03
9.12E−03	5.53E−03	3.23E+03	1.56E+03	1.65E+02	8.50E+01
5.53E−03	1.49E−04	1.55E+04	7.48E+03	7.93E+02	4.09E+02
1.49E−04	1.60E−05	2.72E+03	1.31E+03	1.39E+02	7.16E+01
1.60E−05	9.88E−06	3.07E+02	1.48E+02	1.56E+01	8.07E+00
9.88E−06	4.00E−06	3.89E+02	1.87E+02	1.99E+01	1.02E+01
4.00E−06	1.86E−06	2.11E+02	1.02E+02	1.08E+01	5.56E+00
1.86E−06	1.10E−06	9.55E+01	4.59E+01	4.87E+00	2.51E+00
1.10E−06	1.02E−06	9.89E+00	4.76E+00	5.04E−01	2.60E−01
1.02E−06	6.25E−07	5.02E+01	2.42E+01	2.56E+00	1.32E+00
6.25E−07	3.50E−07	3.01E+01	1.45E+01	1.54E+00	7.92E−01
3.50E−07	2.80E−07	5.47E+00	2.63E+00	2.79E−01	1.44E−01
2.80E−07	1.40E−07	7.63E+00	3.67E+00	3.89E−01	2.01E−01
1.40E−07	5.80E−08	2.49E+00	1.20E+00	1.27E−01	6.54E−02
5.80E−08	3.00E−08	4.10E−01	1.97E−01	2.09E−02	1.08E−02
3.00E−08	1.00E−10	9.19E−02	4.42E−02	4.68E−03	2.41E−03

Table 3-15. Binned neutron flux (n/cm²s) at position C for the BWR insert.

E(MeV)		Time after encapsualtion			
Upper	Lower	0 yr	20 yr	100 yr	1000 yr
1.00E+01	6.07E+00	2.01E+01	9.66E+00	1.02E+00	5.28E−01
6.07E+00	3.68E+00	1.30E+02	6.24E+01	6.61E+00	3.41E+00
3.68E+00	2.23E+00	4.20E+02	2.02E+02	2.14E+01	1.11E+01
2.23E+00	1.35E+00	1.13E+03	5.43E+02	5.75E+01	2.97E+01
1.35E+00	8.21E−01	3.05E+03	1.47E+03	1.56E+02	8.03E+01
8.21E−01	5.00E−01	8.36E+03	4.02E+03	4.26E+02	2.20E+02
5.00E−01	1.11E−01	3.36E+04	1.62E+04	1.71E+03	8.83E+02
1.11E−01	9.12E−03	3.72E+04	1.79E+04	1.90E+03	9.78E+02
9.12E−03	5.53E−03	2.65E+03	1.27E+03	1.35E+02	6.97E+01
5.53E−03	1.49E−04	1.03E+04	4.95E+03	5.24E+02	2.70E+02
1.49E−04	1.60E−05	3.46E+03	1.67E+03	1.77E+02	9.11E+01
1.60E−05	9.88E−06	5.71E+02	2.75E+02	2.91E+01	1.50E+01
9.88E−06	4.00E−06	8.71E+02	4.19E+02	4.44E+01	2.29E+01
4.00E−06	1.86E−06	5.21E+02	2.51E+02	2.65E+01	1.37E+01
1.86E−06	1.10E−06	2.55E+02	1.23E+02	1.30E+01	6.71E+00
1.10E−06	1.02E−06	2.98E+01	1.43E+01	1.52E+00	7.82E−01
1.02E−06	6.25E−07	1.69E+02	8.13E+01	8.61E+00	4.44E+00
6.25E−07	3.50E−07	1.40E+02	6.74E+01	7.14E+00	3.68E+00
3.50E−07	2.80E−07	4.05E+01	1.95E+01	2.07E+00	1.06E+00
2.80E−07	1.40E−07	1.09E+02	5.22E+01	5.53E+00	2.85E+00
1.40E−07	5.80E−08	1.74E+02	8.38E+01	8.88E+00	4.58E+00
5.80E−08	3.00E−08	7.81E+01	3.76E+01	3.98E+00	2.05E+00
3.00E−08	1.00E−10	2.74E+01	1.32E+01	1.40E+00	7.20E−01

Table 3-16. Binned neutron flux (n/cm²s) at position D for the BWR insert.

E(MeV)		Time after encapsualtion			
Upper	Lower	0 yr	20 yr	100 yr	1000 yr
1.00E+01	6.07E+00	7.45E+00	3.58E+00	3.80E−01	1.96E−01
6.07E+00	3.68E+00	4.65E+01	2.24E+01	2.37E+00	1.22E+00
3.68E+00	2.23E+00	1.57E+02	7.54E+01	7.99E+00	4.12E+00
2.23E+00	1.35E+00	4.37E+02	2.10E+02	2.23E+01	1.15E+01
1.35E+00	8.21E−01	1.24E+03	5.97E+02	6.32E+01	3.26E+01
8.21E−01	5.00E−01	3.33E+03	1.60E+03	1.70E+02	8.76E+01
5.00E−01	1.11E−01	1.31E+04	6.32E+03	6.69E+02	3.45E+02
1.11E−01	9.12E−03	1.33E+04	6.42E+03	6.80E+02	3.51E+02
9.12E−03	5.53E−03	1.80E+03	8.67E+02	9.19E+01	4.74E+01
5.53E−03	1.49E−04	8.57E+03	4.13E+03	4.37E+02	2.25E+02
1.49E−04	1.60E−05	4.00E+03	1.92E+03	2.04E+02	1.05E+02
1.60E−05	9.88E−06	7.57E+02	3.64E+02	3.86E+01	1.99E+01
9.88E−06	4.00E−06	1.30E+03	6.28E+02	6.65E+01	3.43E+01
4.00E−06	1.86E−06	9.78E+02	4.71E+02	4.99E+01	2.57E+01
1.86E−06	1.10E−06	6.04E+02	2.91E+02	3.08E+01	1.59E+01
1.10E−06	1.02E−06	7.98E+01	3.84E+01	4.07E+00	2.10E+00
1.02E−06	6.25E−07	5.14E+02	2.48E+02	2.62E+01	1.35E+01
6.25E−07	3.50E−07	5.63E+02	2.71E+02	2.87E+01	1.48E+01
3.50E−07	2.80E−07	2.08E+02	1.00E+02	1.06E+01	5.48E+00
2.80E−07	1.40E−07	8.17E+02	3.93E+02	4.16E+01	2.15E+01
1.40E−07	5.80E−08	2.61E+03	1.26E+03	1.33E+02	6.87E+01
5.80E−08	3.00E−08	2.10E+03	1.01E+03	1.07E+02	5.51E+01
3.00E−08	1.00E−10	1.59E+03	7.65E+02	8.10E+01	4.18E+01

3.7 Gamma spectra – BWR insert

The same energy structure as for the neutron spectra is used in the calculation. However, due to that no gamma flux appears in the upper and lower bins the results are only presented where there were actual gamma flux, see Tables 3-17 to 3-20 for points A–D.

Table 3-17. Binned gamma flux (g/cm²s) at position A for the BWR insert.

E (KeV)		Time after encapsulation			
Upper	Lower	0 yr	20 yr	100 yr	1000 yr
2.23E+03	1.35E+03	5.08E+07	3.12E+07	4.88E+06	1.62E+03
1.35E+03	8.21E+02	2.23E+08	1.37E+08	2.14E+07	7.10E+03
8.21E+02	5.00E+02	5.84E+09	3.59E+09	5.60E+08	1.86E+05
5.00E+02	1.11E+02	9.20E+09	5.66E+09	8.84E+08	2.94E+05
1.11E+02	9.12E+00	3.58E+08	2.20E+08	3.44E+07	1.14E+04
9.12E+00	5.53E+00	1.47E+06	9.02E+05	1.41E+05	4.68E+01
5.53E+00	1.49E−01	6.72E+04	4.13E+04	6.45E+03	2.14E+00

Table 3-18. Binned gamma flux (g/cm²s) at position B for the BWR insert.

E (KeV)		Time after encapsulation			
Upper	Lower	0 yr	20 yr	100 yr	1000 yr
2.23E+03	1.35E+03	6.42E+06	3.95E+06	6.17E+05	2.05E+02
1.35E+03	8.21E+02	2.22E+07	1.36E+07	2.13E+06	7.08E+02
8.21E+02	5.00E+02	4.23E+08	2.60E+08	4.07E+07	1.35E+04
5.00E+02	1.11E+02	1.43E+09	8.78E+08	1.37E+08	4.56E+04
1.11E+02	9.12E+00	7.19E+07	4.42E+07	6.90E+06	2.29E+03
9.12E+00	5.53E+00	2.30E+05	1.41E+05	2.21E+04	7.34E+00
5.53E+00	1.49E−01	8.72E+03	5.36E+03	8.38E+02	2.78E−01

Table 3-19. Binned gamma flux (g/cm²s) at position C for the BWR insert.

E (KeV)		Time after encapsulation			
Upper	Lower	0 yr	20 yr	100 yr	1000 yr
2.23E+03	1.35E+03	9.53E+04	5.86E+04	9.16E+03	3.04E+00
1.35E+03	8.21E+02	8.57E+05	5.27E+05	8.24E+04	2.74E+01
8.21E+02	5.00E+02	4.89E+06	3.01E+06	4.70E+05	1.56E+02
5.00E+02	1.11E+02	2.21E+07	1.36E+07	2.12E+06	7.06E+02
1.11E+02	9.12E+00	9.90E+05	6.09E+05	9.51E+04	3.16E+01
9.12E+00	5.53E+00	6.39E+03	3.93E+03	6.14E+02	2.04E−01
5.53E+00	1.49E−01	1.29E+02	7.93E+01	1.24E+01	4.11E−03

Table 3-20. Binned gamma flux (g/cm²s) at position D for the BWR insert.

E (KeV)		Time after encapsulation			
Upper	Lower	0 yr	20 yr	100 yr	1000 yr
2.23E+03	1.35E+03	2.27E+04	1.40E+04	2.18E+03	7.24E−01
1.35E+03	8.21E+02	6.38E+04	3.93E+04	6.13E+03	2.04E+00
8.21E+02	5.00E+02	4.41E+05	2.71E+05	4.24E+04	1.41E+01
5.00E+02	1.11E+02	1.64E+06	1.01E+06	1.58E+05	5.24E+01
1.11E+02	9.12E+00	2.19E+05	1.35E+05	2.10E+04	6.99E+00
9.12E+00	5.53E+00	1.59E+03	9.80E+02	1.53E+02	5.08E−02
5.53E+00	1.49E−01	–	–	–	–

4 Uncertainties

In accordance with the methodology of Olson (2021)[5], this chapter contains a brief discussion of uncertainties and sources of errors.

4.1 Computational errors

Most MCNP calculations in this report have low statistical errors, typically below 1 %. These statistical errors are in some cases larger, e.g., for spectra calculations. In high or low energy bins where there barely is no flux, the statistical errors increase but not above 5 %. For the source terms computed with SNF a 5 % uncertainty is assumed, based on previous work Loberg (2021)[6].

4.2 Uncertainties in geometry and other data

The MCNP fuel-models have few simplifications but there are some. Spacers are omitted and top and bottom fuel details such as handles, transition pieces and debris filters are simplified. None of this is expected to have any non-conservative impact on bounding dose rates.

The usage of quarter canister models may be somewhat conservative with respect to total decay heat. However, maximum dose rate in the steel and copper ring will always occur in the quarter of a canister where the hottest fuel is loaded.

Elements with concentrations less than 0.2 % in the carbon steel are omitted in this work. Such low concentrations will have negligible effect on neutron and gamma flux. The presence of hydrogen was assumed to be zero inside the canister.

Fuels and power profiles used for source term calculations are conservative, but there is always a possibility that even more conservative fuels may appear in the future. Hence, a 10 % increase of source term intensity could be appropriate.

Regarding uncertainties in calculated dose to person, earlier work by Loberg (2018)[7] where similar dose calculations where performed and compared to measurements suggested a 20 % uncertainty margin to be added to calculated doses. This might be a reasonable margin to add for this work as well, since this work uses the same method, i.e., with source terms from SNF and Monte Carlo calculations for particle transport.

[5] Olson Å, 2021. Generell metodik för beräkning av nuklidinventarium och strålskärmning. SKBdoc 1932653 ver 1.0. (Internal document.)

[6] Loberg J, 2021. SKB – Kontrollberäkning av dimensionerande kapsel. SKBdoc 1942899 ver 2.0. (Internal document.)

[7] Loberg J, 2018. Beräkning av avklingningskurvor för strålning och resteffekt för transportbehållare TN17/2 med MCNP och SNF. SKBdoc 1669101 ver 1.0. (Internal document.)

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Appendix

List of used neutron energy cross sections.

1001.90c
2004.80c
6000.80c
7014.80c
8016.80c
11023.80c
12000.62c
16000.62c
19000.62c
20000.62c
22000.62c
13027.80c
14000.60c
18000.35c
24000.50c
26000.55c
28000.50c
29000.50c
25055.80c
40000.66c
41093.80c
92235.80c
92238.80c
94239.80c

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SKB is responsible for managing spent nuclear fuel and radioactive waste produced by the Swedish nuclear power plants such that man and the environment are protected in the near and distant future.

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