

SKB TR-10-13

Spent nuclear fuel for disposal in the KBS-3 repository

In the earlier distributed report, there are errors that have now been corrected. The corrected pages 26, 43, 44, 59, 66, 74, 79, 81, 83, 85, 87, 89, 91, 93 are enclosed. The changed text is marked with a vertical line in the page margin. An updated pdf version of the report, dated 2011-12, can be found at www.skb.se/publications.

Reference SKBdoc 1179234 has been changed to SKBdoc 119314 on the following pages: 31, 42, 51, 52, 53, 67, 68, 69, 73, 78, 80, 82, 84, 86, 88, 90 and 92.

Reference SKBdoc 1193244 has been changed to SKBdoc 1221579 on page 45.

Reference SKBdoc 1222975 has been changed to SKBdoc 1221579 on page 51.

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 250, SE-101 24 Stockholm
Tel +46 8 459 84 00



The sensitivity analyses are based on the assumption that the insert is made of nodular cast iron with an iron content of at least 90%. The iron in the insert acts as a neutron reflector. Alloying elements occurring in nodular iron that are more potent neutron reflectors than iron are silicon (Si) and carbon (C). In the analysis it was concluded that the content of these substances shall be kept below 6% (C) and 4% (Si) in order not to increase the propensity for criticality. Further, the propensity for criticality increases if the assemblies are placed close together. The loading curves presented in Section 4.4.1 are based on the closest possible distances based on the acceptable distances between the channel tubes for the reference design of the canister.

The following requirement and criterion are set for the selection of fuel assemblies to be encapsulated.

- Requirement on handling: *The fuel assemblies to be encapsulated shall be selected with respect to enrichment, burnup, geometrical configuration and materials in the canister so that criticality will not occur during the handling and storage, even if the canister is filled with water.*
- Criterion: *The effective multiplication factor (k_{eff}) must not exceed 0.95 including uncertainties.*

3.1.3 Dimensions and spacing devices

The dimensions of the BWR and PWR fuel assemblies, including alterations that may occur as a result of the irradiation in the nuclear reactor, shall be considered in the design of the canister inserts. Two types of canister inserts with the same length and diameter provided with channel tubes with different inner dimensions to accommodate BWR and PWR fuel assemblies, respectively, will be manufactured; see the **Canister production report**.

SKB has decided that it shall be possible to encapsulate all spent fuel from the Swedish nuclear power programme, i.e. also the Ägesta fuel, the swap MOX fuel, the Studsvik fuel residues and the special boxes containing fuel rods, in either BWR or PWR canisters, and the following design requirement is set for the canister.

- Design requirement: *The dimensions of the fuel channel tubes of the insert shall be adapted to the dimensions of the spent fuel to be deposited.*
- Design premises: *The length of the longest BWR or PWR assembly, including induced length increase. The cross section of the largest BWR and PWR fuel assemblies, including deviations due to deformations during operation.*

The measures that shall be used in the design of the channel tubes of the insert are given in Table 3-1.

Table 3-1. Design measures for the fuel channel tubes of the insert.

Detail	BWR	PWR	Comment
Longest assembly	4,441 mm		Before irradiation.
Induced length increase	14 mm		When determining the length of the longest assembly the length before irradiation and the induced length increase is considered.
Largest cross section	141×141 mm	214×214 mm	Before irradiation.
Deviations due to deformations during operation	145.5×145.5 mm	228×228 mm	Cross sections of BWR transport cask, and PWR storage canister respectively. All assemblies in Clab have been placed in these casks or canisters, i.e. these cross sections are sufficient with respect to occurring deviations due to deformations during operation.

Table 6-1. The total inventory in BWR and PWR assemblies of thirteen radionuclides (Bq) of importance for radiotoxicity and calculated long-term risk (alphabetic order). The inventories are calculated for the calendar year 2045.

Radio-nuclide	Radionuclide inventory (Bq)									
	BWR assemblies					PWR assemblies				
	47,637 BWR UOX ¹ 40.4 MWd/kgU		267 BWR MOX ² 50 MWd/kgHM		6,016 PWR UOX 44.8 MWd/kgU			33 PWR MOX 34 MWd/kgHM		Total activity
	Fuel	Constr. materials/ crud	Fuel	Constr. materials/ crud	Fuel	Constr. materials/ crud	Control rods	Fuel	Constr. materials/ crud	
Am-241	1.2E+18	1.1E+11	4.8E+16	2.4E+09	4.9E+17	6.6E+10		4.5E+15	3.4E+08	1.7E+18
C-14	1.1E+14	2.9E+14	6.2E+11	2.1E+12	3.4E+13	6.9E+13	3.7E+12	9.7E+10	3.3E+11	5.1E+14
Cl-36	1.8E+12	2.8E+10	1.2E+10	2.1E+08	4.9E+11	8.0E+09	1.1E+09	1.4E+09	3.8E+07	2.3E+12
Cs-137	1.7E+19	5.2E+12	8.5E+16	2.7E+10	6.3E+18	1.1E+12	0.0E+00	1.0E+16	3.3E+09	2.3E+19
I-129	1.0E+13	0.0E+00	9.6E+10		3.8E+12			1.3E+10		1.4E+13
Nb-94	4.6E+10	3.6E+13	6.2E+08	2.6E+11	1.7E+10	8.9E+14	3.2E+11	8.8E+07	4.3E+12	9.3E+14
Pu-238	9.5E+17	9.7E+10	2.1E+16	1.3E+09	3.7E+17	6.0E+10		1.6E+15	1.7E+08	1.3E+18
Pu-239	1.0E+17	9.2E+11	2.7E+15	5.3E+09	3.8E+16	2.8E+11	0.0E+00	2.2E+14	1.5E+09	1.4E+17
Pu-240	1.9E+17	1.2E+10	6.4E+15	3.2E+08	6.1E+16	8.2E+09		5.9E+14	3.9E+07	2.5E+17
Pu-241	7.4E+18	6.4E+11	1.3E+17	6.3E+09	3.0E+18	4.0E+11		9.3E+15	7.1E+08	1.1E+19
Sr-90	1.1E+19	4.8E+12	2.8E+16	2.5E+10	4.2E+18	1.0E+12	0.0E+00	3.6E+15	3.1E+09	1.6E+19
U-234	4.0E+14	3.5E+07	3.8E+12	3.5E+05	1.9E+14	2.3E+07		3.3E+11	1.1E+05	6.0E+14
U-238	9.7E+13	7.9E+06	6.5E+12	4.3E+04	3.2E+13	4.4E+06		1.0E+11	2.5E+04	1.3E+14

¹ Includes 222 assemblies from Ägesta.

² Includes 184 Swap BWR MOX.

Table 6-2. Assumed radionuclide inventories in the miscellaneous fuels.

Fuel type	Number	Radionuclide inventory
Spent fuel from Ägesta	222	Set to the same as in the average burnup BWR assembly.
Swap BWR MOX fuel assemblies	184	Set to the same as for the BWR MOX assemblies from Oskarshamn.
Swap PWR MOX	33	Matrix inventory calculated for a swap MOX assembly with a burnup of 34 MWd/kgHM.
Special boxes with fuel residues from Studsvik	25	Set to the same as in the average burnup PWR assembly.

The assumptions in Table 6-2 will result in an overestimation of the radionuclide inventories of the miscellaneous fuels since they contain a smaller amount of heavy metal and have an essentially lower burnup than the average BWR and PWR assemblies and the BWR MOX assemblies from Oskarshamn. However, since the miscellaneous fuels comprise in total 464 assemblies out of about 54,000 assemblies, the impact of their divergent inventories on the total inventory can be neglected.

6.2.3 The type canister approach

At the time for the closure of the final repository when the encapsulation and deposition is finished, the burnup, irradiation and power history and age of the assemblies in each canister will be known and the radionuclide inventory can be calculated for each individual canister. However, at this stage it is not reasonable to calculate the inventory in individual canisters. Therefore, a set of type-canisters has been defined based on the assumption that the criteria for maximum allowed total decay power in a canister will restrict the possible variation in radionuclide inventory. The type-canisters shall provide a representative and adequate description of the canisters' content of fuel, its burnup and age and the resulting radionuclide inventory in each canister.

The radionuclide inventory in each canister will depend on:

- the number of assemblies in the canister,
- the burnup of the assemblies,
- the age of the assemblies when they are encapsulated.

The burnup and the number of assemblies will be the parameters of most importance for the radionuclide inventory. In a long-term perspective, the age of the fuel at deposition is of minor importance for the radionuclide inventory since the short lived nuclides of importance for the decay power will successively decay and no longer remain in the canister.

The part of the inventory located at the fuel grain boundaries and in the gap between the fuel and the cladding is correlated to the fission gas release and power history. This part of the radionuclide inventory is discussed in Section 6.3.

To illustrate the range of burnup and, thus, radionuclide inventory, a set of canisters with reasonable combinations of burnup/age of the assemblies have been selected so that the total decay power in the canisters will not exceed 1,700 W. The ages and burnups of the assemblies are based on the results from the simulation of the encapsulation presented in Section 5.2. The set of canisters and their total activity are presented in Table 6-3. The inventory in the fuel matrix of thirteen radionuclides of importance for decay power, radiotoxicity and calculated long-term risk are given in Table 6-4.

As can be seen from Table 6-3 and Table 6-4 both the total activity content and radionuclide inventory varies within the same order of magnitude. For full PWR canisters, the average and combined canisters have similar total activity and radionuclide inventory. This illustrates that the decay power criterion will restrict the variation in radionuclide content.

Table 6-3. The total activity in the fuel matrix in a set of reasonable BWR and PWR canisters with a total decay power of 1,700 W at time for encapsulation /SKBdoc 1221579/.

Canister	Number of assemblies	Burnup (MWd/kgU)	Age of assemblies (years)	Total activity (10 ¹⁶ Bq/canister)
BWR low	12	30.7	20	2.1
BWR average	12	40.4	37	1.6
BWR high a	12	47.8	48	1.4
BWR high b	12	57	60	1.2
BWR unfilled	9	47.8	32	1.6
BWR-MOX	11	37.7	43	1.4
	1	50	50	
PWR low	4	34.2	20	2.0
PWR average	4	44.8	38	1.6
PWR high	4	57	55	1.3
PWR combination a	1	57	20	1.7
	3	34.2	40	
PWR combination b	2	57	51	1.5
	1	57	20	
PWR-MOX	3	44.8	32	1.6
	1	34.8	57	

7 References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.se/publications.
References to SKB's unpublished documents are listed separately at the end of the reference list.
Unpublished documents will be submitted upon request to document@skb.se.

Canister production report, SKB 2010. Design, production and initial state of the canister. SKB TR-10-14, Svensk Kärnbränslehantering AB.

Design premises long-term safety, SKB 2009. Design premises for a KBS-3V repository based on results from the safety assessment SR-Can and some subsequent analyses. SKB TR-09-22, Svensk Kärnbränslehantering AB.

Repository production report, SKB 2010. Design and production of the KBS-3 repository. SKB TR-10-12, Svensk Kärnbränslehantering AB.

Underground openings construction report, SKB 2010. Design, construction and initial state of the underground openings. SKB TR-10-18, Svensk Kärnbränslehantering AB.

Håkansson R, 2000. Beräkning av nuklidinnehåll, resteffekt, aktivitet samt doshastighet för utbränt kärnbränsle. SKB R-99-74, Svensk Kärnbränslehantering AB (in Swedish).

Nordström E, 2009. Fission gas release data for Ringhals PWRs. SKB TR-09-26, Svensk Kärnbränslehantering AB.

Oldberg K, 2009. Distribution of fission gas release in 10×10 fuel. SKB TR-09-25, Svensk Kärnbränslehantering AB.

SKB, 2006. Measurements of decay heat in spent nuclear fuel at the Swedish interim storage facility, Clab. SKB R-05-62, Svensk Kärnbränslehantering AB.

SKB, 2009. Plan 2008. Costs starting in 2010 for the radioactive residual products from nuclear power. Basis for fees and guarantees in 2010 and 2011. SKB TR-09-23, Svensk Kärnbränslehantering AB.

SKB, 2009. Design premises for a KBS-3V repository based on results from the safety assessment SR-Can and some subsequent analyses. SKB TR-09-22, Svensk Kärnbränslehantering AB.

Werme L, Johnson L H, Oversby V, King F, Spahiu K, Grambow B, Shoesmith D W, 2004. Spent fuel performance under repository conditions: A model for use in SR-Can. SKB TR-04-19, Svensk Kärnbränslehantering AB.

Unpublished documents

SKBdoc id, version	Title	Issuer, year
1077122, 2.0	Strålskärmsberäkningar för kopparkapslar innehållande BWR, MOX och PWR bränsleelement	SKB, 2009
1172138, 1.0	Kontroll av kärnämnen inom KBS-3-systemet	SKB, 2009
1193244, 4.0	Criticality safety calculations of disposal canisters	SKB, 2010
1198314, 1.0	Källstyrkor för bränsleelement under driftskede för Clink, slutförvarsanläggning och slutförvar	SKB, 2009
1221567, 2.0	Simulering av fyllning av kapslar för slutförvaring av utbränt kärnbränsle	SKB, 2010
1221579, 2.0	Aktivitetssinnehall i kapslar för slutförvar	SKB, 2010
1222975, 2.0	Beräkning av fissionsgasfrigörelse för bränslet i slutförvaret	SKB, 2010

Errata to SKB TR-10-13 2011-12

Table B-2. Impurities in the fuel matrix /SKBdoc 1221579/.

Element	Assumed in calculations (ppm)	Representative values for fuel matrices ¹ (ppm)	
Ag	0.05	<0.05	
Al	6	3–6	
B	0.05	<0.05	
Bi	0.5	<0.5	
Ca	3	<3	1/3 above LRV
Cd	0.233	average 0.233	min 0.2 max 0.6
Co	0.5	<0.5	
Cr	1	<1	10% above LRV
Cu	0.5	average 0.5	min 0.2 max 7
F	2	<2	20% above LRV
Fe	5	<5	20% above LRV
In	0.3	<0.3	
Li	0.05	<0.05	
Mg	1	<1	
Mn	2	<2	
Mo	5	<5	
N ²	14	–	
Ni	–	<1	
Pb	0.6	<0.6	20% above LRV
Si	10	<10	
Sn	0.8	0.6–0.8	
Ti	10	<10	
V	0.3	<0.3	
Zn	25	<25	
Dy	10	<10	
Eu	0.02	<0.02	
Gd	0.06	<0.06	
Sm	0.04	<0.04	
C	8.4	average 8.4	min 3 max 28
Cl	2	2	
Ni	5	5	
W	0.2	0.2	

(LRV_Lowest reported value)

¹ Personal communication Westinghouse.

² Assumed in accordance with /SKBdoc 1198314/.

BWR:

- UO2-values from /SKBdoc 1221579, Table 14/.
- Inventory for construction material from /SKBdoc 1198314/ by linear interpolation between 38 and 60 MWd/kg U to find inventory at 40.4 MWd/kg U.
(Data from appendix: folder 'IndAct-Ett element-rev3', files '88_Ind-B38-000.xls' and '89_Ind-B60-000.xls'.)
- Inventory for Crud from /SKBdoc 1198314/ by linear interpolation between 38 and 60 MWd/kg U to find inventory at 40.4 MWd/kg U.
(Data from appendix: folder 'CrudAct-Ett element-rev3', files '95_Crud-B38-000.xls' and '96_Crud-B60-000.xls'.)
- Average age for BWR assemblies 36.3 years and BWRmox assemblies 50 years.

PWR:

- UO2-values from /SKBdoc 1221579, Table 13/.
- Inventory for construction material from /SKBdoc 1198314/ by linear interpolation between 30 and 60 MWd/kg U to find inventory at 44.8 MWd/kg U.
Assumption: At any given burnup or age the construction material data is the same for PWR and PWRMOX.
(Data from appendix: folder 'IndAct-Ett element-rev3', files '90_Ind-P30-000.xls' and '91_Ind-P60-000.xls'.)
- Inventory for Crud from /SKBdoc 1198314/ by linear interpolation between 30 and 60 MWd/kg U to find inventory at 44.8 MWd/kg U.
Assumption: At any given burnup or age the crud data is the same for PWR and PWRMOX.
(Data from appendix: folder 'CrudAct-Ett element-rev3', files '97_Crud-P30-000.xls' and '98_Crud-P60-000.xls'.)
- Inventory for control rods from /SKBdoc 1179234, appendix: folder 'Styrstavar-rev3', file '110_PWR-ss.xls'.
- Average age for PWR assemblies 36.9 years and PWRmox assemblies 57 years.

2,208 BWR I canisters:

- UO₂-values from /SKBdoc 1221579, Table 14/.
- Inventory for construction material from /SKBdoc 1198314/ by linear interpolation between 38 and 60 MWd/kg U to find inventory at 40.4 MWd/kg U.
(Data from appendix: folder 'IndAct-Ett element-rev3', files '88_Ind-B38-000.xls' and '89_Ind-B60-000.xls'.)
- Inventory for Crud from /SKBdoc 1198314/ by linear interpolation between 38 and 60 MWd/kg U to find inventory at 40.4 MWd/kg U.
(Data from appendix: folder 'CrudAct-Ett element-rev3', files '95_Crud-B38-000.xls' and '96_Crud-B60-000.xls'.)

1,024 PWR I canisters:

- UO₂-values from /SKBdoc 1221579, Table 13/.
- Inventory for construction material from /SKBdoc 1198314/ by linear interpolation between 30 and 60 MWd/kg U to find inventory at 44.8 MWd/kg U.
(Data from appendix: folder 'IndAct-Ett element-rev3', files '90_Ind-P30-000.xls' and '91_Ind-P60-000.xls'.)
- Inventory for Crud from /SKBdoc 1198314/ by linear interpolation between 30 and 60 MWd/kg U to find inventory at 44.8 MWd/kg U.
(Data from appendix: folder 'CrudAct-Ett element-rev3', files '97_Crud-P30-000.xls' and '98_Crud-P60-000.xls'.)
- Inventory for control rods from /SKBdoc 1179234, appendix: folder 'Styrstavar-rev3', file '110_PWR-ss.xls'.

321 BWR II canisters:

- UO₂-values from /SKBdoc 1221579, Table 14/.
- Inventory for construction material from /SKBdoc 1198314/ by linear interpolation between 38 and 60 MWd/kg U to find inventory at 47.8 MWd/kg U.
(Data from appendix: folder 'IndAct-Ett element-rev3', files '88_Ind-B38-000.xls' and '89_Ind-B60-000.xls'.)
- Inventory for Crud from /SKBdoc 1198314/ by linear interpolation between 38 and 60 MWd/kg U to find inventory at 47.8 MWd/kg U.
(Data from appendix: folder 'CrudAct-Ett element-rev3', files '95_Crud-B38-000.xls' and '96_Crud-B60-000.xls'.)

1,655 BWR III canisters:

- UO₂-values from /SKBdoc 1221579, Table 14/.
- Inventory for construction material from /SKBdoc 1198314/ by linear interpolation between 38 and 60 MWd/kg U to find inventory at 47.8 MWd/kg U.
(Data from appendix: folder 'IndAct-Ett element-rev3', files '88_Ind-B38-000.xls' and '89_Ind-B60-000.xls'.)
- Inventory for Crud from /SKBdoc 1198314/ by linear interpolation between 38 and 60 MWd/kg U to find inventory at 47.8 MWd/kg U.
(Data from appendix: folder 'CrudAct-Ett element-rev3', files '95_Crud-B38-000.xls' and '96_Crud-B60-000.xls'.)

267 BWRMOX canisters:

- UO₂-values from /SKBdoc 1221579, Table 14/.
- Inventory for construction material from /SKBdoc 1198314/ at 38 MWd/kg U for 11 BWR assemblies and 50 MWd/kg U for 1 MOX assembly.
(Data from appendix: folder 'IndAct-Ett element-rev3', files '88_Ind-B38-000.xls' and '93_Ind-M50-000.xls'.)
- Inventory for Crud from /SKBdoc 1198314/ at 38 MWd/kg U for 11 BWR assemblies and 50 MWd/kg U for 1 MOX assembly.
(Data from appendix: folder 'CrudAct-Ett element-rev3', files '95_Crud-B38-000.xls' and '100_Crud-M50-000.xls'.)

38 PWR II canisters:

- UO₂-values from /SKBdoc 1221579, Table 13/.
- Inventory for construction material from /SKBdoc 1198314/ by linear interpolation between 30 and 60 MWd/kg U to find inventory at 57 MWd/kg U.
(Data from appendix: folder 'IndAct-Ett element-rev3', files '90_Ind-P30-000.xls' and '91_Ind-P60-000.xls'.)
- Inventory for Crud from /SKBdoc 1198314/ by linear interpolation between 30 and 60 MWd/kg U to find inventory at 57 MWd/kg U.
(Data from appendix: folder 'CrudAct-Ett element-rev3', files '97_Crud-P30-000.xls' and '98_Crud-P60-000.xls'.)
- Inventory for control rods from /SKBdoc 1179234, appendix: folder 'Styrstavar-rev3', file '110_PWR-ss.xls').

557 PWR III canisters:

- UO₂-values from /SKBdoc 1221579, Table 13/.
- Inventory for construction material from /SKBdoc 1198314/ by linear interpolation between 30 and 60 MWd/kg U to find inventory at 57 MWd/kg U.
(Data from appendix: folder 'IndAct-Ett element-rev3', files '90_Ind-P30-000.xls' and '91_Ind-P60-000.xls'.)
- Inventory for Crud from /SKBdoc 1198314/ by linear interpolation between 30 and 60 MWd/kg U to find inventory at 57 MWd/kg U.
(Data from appendix: folder 'CrudAct-Ett element-rev3', files '97_Crud-P30-000.xls' and '98_Crud-P60-000.xls'.)
- Inventory for control rods from /SKBdoc 1179234, appendix: folder 'Styrstavar-rev3', file '110_PWR-ss.xls'.

33 PWRMOX canisters:

- UO₂-values from /SKBdoc 1221579, Table 13/.
- Inventory for construction material from /SKBdoc 1198314/ by linear interpolation between 30 and 60 MWd/kg U to find inventory at 44.8 MWd/kg U.
Assumption: At any given burnup or age the construction material data is the same for PWR and PWRMOX.
 (Data from appendix: folder 'IndAct-Ett element-rev3', files '90_Ind-P30-000.xls' and '91_Ind-P60-000.xls'.)
- Inventory for Crud from /SKBdoc 1198314/ by linear interpolation between 30 and 60 MWd/kg U to find inventory at 44.8 MWd/kg U.
Assumption: At any given burnup or age the crud data is the same for PWR and PWRMOX.
 (Data from appendix: folder 'CrudAct-Ett element-rev3', files '97_Crud-P30-000.xls' and '98_Crud-P60-000.xls'.)
- Inventory for control rods from /SKBdoc 1179234, appendix: folder 'Styrstavar-rev3', file '110_PWR-ss.xls'.

Table C-14. Contribution from predominant radionuclides to the total decay power at time for encapsulation /SKBdoc 1221579/.

Radionuclide	Decay power (W)							
	BWR I	BWR II	BWR III	BWR MOX	PWR I	PWR II	PWR III	PWR MOX
Am- 241	270	315	211	404	294	355	238	331
Am- 243	2	3	2	3	2	4	3	3
Ba- 137m	423	381	420	349	411	349	386	387
Cm-242	1	1	1	2		1		1
Cm-243	1	1	1	1	1	1	1	1
Cm-244	80	103	147	108	87	121	185	114
Co-60								1
Cs-134							2	
Cs-137	127	114	126	105	123	105	116	116
Eu-154	8	4	11	5	7	3	13	10
Kr-85	3	2	4	2	3	1	4	4
Pu-238	213	278	238	232	220	316	267	216
Pu-239	21	21	16	28	21	21	16	22
Pu-240	39	45	34	54	34	42	31	41
Pu-241	2	1	2	1	2	1	2	2
Sr-90	88	74	84	70	85	66	75	78
Y-90	420	355	401	334	407	314	358	373