European Joint Programme on Radioactive Waste Management

Deliverable 8.5: Results of the characterisation of SNF samples by NDA and radiochemical analysis: results from subtasks 2.2 and 2.3

Work Package 8

Spent Fuel Characterisation and Evolution until Disposal (SFC)

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Executive Summary

Procedures to characterise spent fuel for the main observables of interest, i.e. the neutron and γ-ray emission properties, decay heat, reactivity, long-term radiotoxicity and the inventory of mobile long-lived radionuclides, strongly rely on theoretical calculations which require two types of input data, i.e. nuclear data and the design properties and operational data of the spent fuel. To validate the procedures high quality experimental data are required. Within deliverable 8.4 of EURAD, experimental methods and data to assess the performance of codes and to verify fuel related input data were studied/improved and produced. This deliverable provides the experimental data that were produced within WP8 of EURAD to assess the performance of depletion calculations and to define procedures to verify the quality of fuel related input data that are provided by the operator. The report includes references to the fuel related data that are required to perform depletion calculations. The results presented in this deliverable are essential input for the EURAD deliverables 8.6 and 8.7.

Keywords

Calorimetry, Decay heat, Depletion calculations, Gamma-ray, Neutron, Non-destructive assay, Radiochemical analysis, Spent nuclear fuel.

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Glossary

BU	Burnup
BWR	Boiling water reactor
Clab	Central interim storage facility for spent nuclear fuel in Sweden
CMSYS	Core management system
CT	Cooling time
EFPD	Effective full power days
ENUSA	Empresa nacional del Uranio
ENRESA	Empresa nacional de residuos radiactivos
EURAD	European joint programme on radioactive waste management
GE	General electric
HLPC	High-performance liquid chromatography
ICP-MS	Inductively coupled plasma mass spectrometry
IE	Initial enrichment
INE	Institute for nuclear waste disposal
JRC	Joint research centre
KIT	Karlsruhe Institute of Technology
LA	Laser ablation
LHMA	Laboratory for high and medium level activity
LWR	Light water reactor
MOX	Mixed oxide fuel
NDA	Non-destructive assay
PIE	Post irradiation examination
PWR	Pressurized water reactor
PSI	Paul Scherrer Institute
REGAL	Rod-extremity and gadolinia analysis
SCK CEN	Belgian nuclear research centre
SFC	Spent fuel characterisation and evolution until disposal
SFCOMPO	Spent fuel isotopic composition
SKB	Swedish nuclear fuel and waste management company
SNF	Spent nuclear fuel
TIMS	Thermal ionisation mass spectrometry
UU	Uppsala university

1. Introduction

Two types of experimental data are important to support the development of validated procedures for spent nuclear fuel characterisation: data to assess and validate the performance of depletion codes and data to verify the design properties/characteristics of the fuel and the operational history of the irradiated fuel.

At present, a performance assessment of depletion codes strongly relies on nuclide inventory data that result from destructive chemical and radiochemical analysis of spent fuel rod segments, also referred to as Post Irradiation Examination (PIE). The SFCOMPO database contains results of PIE together with the design and fuel operational data for a large amount of samples that are required to perform the depletion calculations [1][2]. Most of the high-quality data are for UO_2 PWR fuel. The restricted availability for BWR and MOX is partly due to commercial property rights. Within Task 2 of EURAD WP8 additional data for UO_2 segment samples extracted from assemblies irradiated in BWR and PWR reactors were made available together with the decay power of PWR and BWR SNF assemblies derived from measurements with the Clab calorimeter [3].

The results of depletion calculations strongly depend on the quality of the fuel dependent input data, i.e. design properties and operational history. For spent fuel assemblies from the nuclear power plants in Switzerland this information can be retrieved from the Core Management System (CMSYS) developed at the Paul Scherrer Institute (PSI) [4][5]. It includes full cycle information up to the latest operated cycle and validated models that are used for full reactor core simulations with SIMULATE or lattice calculations with CASMO5, which can be coupled with the SNF code to calculate the nuclide inventory [6]. Unfortunately, such a data base system is not always available In that case the available information to run the depletion calculations can be incomplete which might affect the accuracy of the results. To reduce the impact of limited information and identify possible errors in the input data, an experimental verification of the spent fuel properties by NDA can be done. At Clab gamma-ray spectroscopic measurements and measurements to determine the total gamma-ray and neutron emission rate of a PWR and BWR spent fuel assemblies were performed [6][7][8]. The results of these measurements are included in this report.

In the report, conventional uncertainty propagation based on normal distributions is applied. All uncertainties are standard uncertainties quoted at a 68 % confidence level and are given in standard compact notation. The uncertainty of a quantity X is denoted by u_X and its relative uncertainty by u_X/X. As much as possible the terminology of the International vocabulary of metrology – Basic and general associated terms are used [9].

2. Experimental data of spent nuclear fuel samples

2.1 Nuclide inventory of BWR samples

A set of BWR samples were taken from fuel assemblies that were irradiated in the BWR Forsmark 2 and Forsmark 3 power reactors in Sweden. The samples were analysed by radiochemical analysis. The results of the analysis, the characteristics and irradiation history that are required to perform depletion calculations are specified in [10][11][12].

The results of radiochemical analyses of eight samples taken from a GE14 10 × 10 BWR assembly together with the design properties and irradiation history were provided by ENUSA to the EURAD WP8 partners. The assembly was produced by ENUSA and irradiated in the BWR Forsmark 3 reactor (Sweden). The samples were taken at different axial positions from the same fuel rod, with a peak BU of 54 MWd/kg and average BU of 41 MWd/kg. The characterisation measurements were carried out by the Studsvik Laboratory. These included a gamma-ray spectroscopic rod scan and inductively coupled plasma mass spectrometry (ICP-MS), including isotope dilution analysis, to determine the burnup and inventory of 60 nuclides covering 21 elements. The ICP-MS measurements were performed after separation by high performance liquid chromatography (HPLC). The HPLC is performed to separate elements to avoid isobaric interferences in the ICP-MS measurements. These data were used within EURAD WP8 Task 2 to validate the performance of CASMO5 [13].

The results of this measurement campaign were complemented as part of Task 2 work by an analysis of six samples taken from a GE14 10 × 10 BWR assembly that was irradiated in the BWR Forsmark 2 (Sweden). These samples were used to verify the potential of the laser ablation (LA) technique for the characterisation of irradiated BWR samples. The samples were taken from different axial positions based on the results of a gamma-ray spectroscopic axial scan. They were analysed by using laser ablation (LA) coupled to an ICP-MS. During a first measurement campaign in year 2020 several problems were encountered. Therefore, a new measurement campaign was carried out in 2022 to correct and complete the data from 2020. The experimental nuclide inventory derived from measurements with a LA-ICP-MS was compared with the inventory obtained from depletion calculations using SCALE/POLARIS. The outcome indicates that ICP-MS is a valid technique to determine the nuclide inventory of spent fuel provided that a calibration using a matrix-matched material can be performed. However, LA-ICP-MS cannot manage isobaric overlap. For example, the signal on mass 148 registers both ^{148}Nd and ^{148}Sm, and mass 241 registers ^{241}Pu, ^{241}Am, and ^{240}Pu^{1}H. Prior to elemental separation of dissolved aliquots, e.g. via chromatographic column separation followed by thermal ionisation mass spectrometry (TIMS) or direct coupling of an in-line HPLC with ICP-MS (HLPC-ICP-MS) in-line analysis methods may be preferred. Such methods are quantitatively superior, but since they work with dissolved aliquots, they lack the spatial resolution of an LA-ICP-MS. In nuclear fuels, many of the relevant fission or activation products are affected by isobaric interferences and could thus not reliably be measured by LA-ICP-MS (e.g. ^{241}Am, ^{137}Cs/^{137m}Ba, ^{238}Pu and ^{90}Sr/^{90}Y). Due to the isobaric interference problems with LA-ICP-MS, only the results of the data given in Ref. [10] are recommended for code validation.

2.2 Nuclide inventory of a PWR segment sample

A high burnup UO_2 spent nuclear fuel segment sample with an initial enrichment of 3.8 wt% ^{235}U, previously irradiated in the PWR Gösgen (Switzerland) was used for radiochemical analysis. The examined fuel segment was irradiated to an average rod burnup of 50.4 MWd/kg over the course of 1226 effective full power days. The fuel cladding material consisted of Zircaloy-4. To determine the inventory of actinides, fission and activation products, cladding and fuel samples were prepared from the fuel sample. For the analysis of the irradiated Zircaloy-4 cladding material, a specimen was cut from the plenum section of the segment, not being in contact with the fuel stack. In addition, fuel fragments as well as the cladding material, previously in contact with the fuel, were retrieved from an irradiated pellet. To analyse the nuclide inventory of both cladding samples, i.e., the cladding material previously in contact with the fuel and the pure irradiated Zircaloy-4 extracted from the plenum section, a digestion process was performed using a dilute mixture of HF and H_2SO_4. For the inventory determination of the irradiated UO_X fuel, fragments were sampled from the fuel and digested in either an acidic (HNO_3/HCl) or alkaline ($(NH_4)_2CO_3/H_2O_2$) solution for the analysis of the different radionuclides. The digestion processes of the specimens were performed in the shielded box-line facility of the Institute for Nuclear Waste Disposal (INE) at the Karlsruhe Institute of Technology (KIT). Particular emphasis was given to the volatile activation and fission products ^{36}Cl and ^{129}I, respectively. For the determination of ^{36}Cl, an aliquot of the solution was acidified and ^{137}Cs removed by means of precipitation with ammonium molybdophosphate. Thereafter, ^{36}Cl was separated from the digestion liquor via precipitation with $AgNO_3$ and the Ag^{36}Cl precipitate dissolved in 13% NH_4OH. Eventually, the solution was analysed by liquid scintillation counting (LSC). To analyse ^{129}I, a liquid-liquid extraction process was performed, in which ^{129}I was separated from the digestion liquor into an organic phase and then re-extracted into an aqueous phase for analysis with LSC. In addition to the analysis of ^{36}Cl and ^{129}I, actinides and other fission and activation products (e.g.,^{60}Co, ^{99}Tc, ^{137}Cs, ^{154}Eu) were determined using gamma-ray spectrometry and high resolution sector field ICP-MS. Details of the performed radiochemical separations and the determined inventories are reported in the PhD Thesis of T. König [14]. Details about the sample characteristics and irradiation history were distributed to the EURAD WP8 partners and are given in [15].

2.3 Neutron emission rate of a PWR sample

An innovative NDA method was developed within Task 2 to determine in an absolute way the neutron emission rate of a spent fuel segment sample avoiding any reference to a representative spent nuclear fuel sample to calibrate the device. The method and experimental and analysis procedures are described in [16][17]. The method relies on a transfer procedure that is adapted to the hot cell facilities at the Laboratory for High and Medium level Activity (LHMA) of the SCK CEN in Belgium. A neutron correlation counter was used to separate the contribution of spontaneous fission and (α,n) neutrons.

Measurements of a segment of a spent nuclear fuel rod were carried out at the SCK CEN. A segment sample was taken from a spent fuel rod that was irradiated in the Tihange 1 PWR during cycles 20 (from April 1998 until August 1999) and 21 (from September 1999 until March 2001). The study of this rod is part of the Rod-Extremity and Gadolinia AnaLysis (REGAL) program coordinated by the SCK CEN [18]. The assembly from which the rod (i.e. rod D05) was taken, was an AFA 2G assembly type manufactured by AREVA. It consists of a 15 × 15 array of fuel rods with 21 guide tubes for insertion of control rods or instrumentation. It contains 188 UO_2 rods (4.5 wt% $^{235}U/U$) and 16 $(U,Gd)O_x$ fuel rods (10 wt% $Gd_2O_3/(U,Gd)O_x$ and 2 wt% $^{235}U/U$). At the end of both cycles, after approximately 450 days, stretch-out operations took place for an additional period of about 50 days, showing a progressive decrease of the core power and coolant temperature to maintain core criticality. Because control rods are fully withdrawn during stretch-out, this stage presents power peaking in the upper zone of the core (positive axial off-set). More details on the fuel composition and geometry and irradiation history are given in [19].

The neutron production rate due to spontaneous fission derived from these measurements is 678 (12) $s^{-1}g^{-1}$. This value is within uncertainties in agreement with the one derived from the nuclide inventory determined by radiochemical analysis, which is 699 (28) $s^{-1}g^{-1}$. The uncertainty of the neutron production rate due to spontaneous fission is about 2%, which is a reduction by a factor two compared to the uncertainty of the ^{244}Cm inventory derived by radiochemical analysis of an adjacent sample [18]. The contribution to the uncertainty of the counting statistics, detection efficiency, gate fraction, first and second order factorial moments for ^{244}Cm(sf) and multiplicity are specified in Table 1. This table reveals that the main contributions to the measurement uncertainty are the second order factorial moment, detection efficiency and gate fraction. Results of these measurements were used to study the performance of depletion codes, i.e. ALEPH2, SCALE and Serpent 2. The study includes a code-to-code and code-to-experiment comparison using different nuclear data libraries [17].

Uncertainty component, x_j	$\frac{u_{x_j}}{x_j}$	$\frac{u_{S_{sf},j}}{u_{S_{sf}}}$	$\frac{u_{\alpha,j}}{u_\alpha}$
Totals rate, T	0.0008	< 0.01	0.05
Reals rate, R	0.0027	0.15	0.17
Detection efficiency, ε_{sf}	0.0055	0.60	0.35
Gate fraction, f	0.0071	0.40	0.45
First order factorial moment, $\nu_{sf(1)}$	0.0037	0.20	0.25
Second order factorial moment, $\nu_{sf(1)}$	0.0120	0.67	0.80
Multiplication, M	0.0020	0.01	< 0.01

Table 1 – Contribution of the counting statistics, the detection efficiency, gate fraction, first and second order factorial moments for ^{244}Cm(sf) and neutron multiplication to the uncertainty of the derived neutron production rate due to spontaneous fission and the α-ratio [17].

3. Results of fuel assembly measurements at Clab

A set of BWR and PWR spent fuel assemblies stored in the Clab facility were characterised by NDA to provide an estimate of their decay heat rate and neutron and gamma-ray emission properties. The decay heat rate was obtained from the calorimeter measurement described in [3]. The gamma-ray emission of the assemblies were determined by both gamma-ray spectroscopic measurements described in [6][7] and by total gamma-ray counting using an ionisation chamber of the FORK detector [8]. The FORK detector was also used to determine the total neutron emission rate of the assemblies [8].

The measurement data are part of the SKB-50 experimental campaign on an ensemble of 25 PWR and 25 BWR fuel assemblies with UOX fuel. For each fuel assembly the fuel type, the initial enrichment and initial heavy metal mass was given by the operator together with the stepwise power history and final burnup. The power history was described as an average power per cycle and cycle length together with the shutdown time between cycles. No pin layout or other radial descriptions of the fuel assemblies were given. Hence, the enrichment had to be assumed identical for all fuel pins without any consideration of the presence of burnable absorbers. In addition, control rod insertion times were not provided and for the BWR no information regarding axial flow regimes was given. Additional information was derived from the open literature. A typical radial layout of the fuel assembly types in SKB-50 can be found in [20][21]. More information is available in [3] and reports for the Swedish safety authorities [22]. An example of such an axial profile is shown in Figure 1.

Details about the SKB-50 PWR and BWR assemblies are summarised in Appendix A. The results of the decay heat measurements are reported in Appendix B. These results were derived applying an improved analysis procedure that was developed as part of the EURAD deliverable 8.4. Results of an analysis of gamma-spectroscopic measurements performed at Clab in 2014 and 2019 are summarised in Appendix C. Details about these measurement campaigns can be found in [6] and [23]. In [23] data of axial scanning measurements performed in 2014 are reported together with results of a detailed analysis of the data obtained in 2014 and 2019. Results of measurements collected during September 2016 and March 2019 can be retrieved from [24]. The neutron and gamma-ray response of measurements with the FORK detector [8] are given in Appendix D.

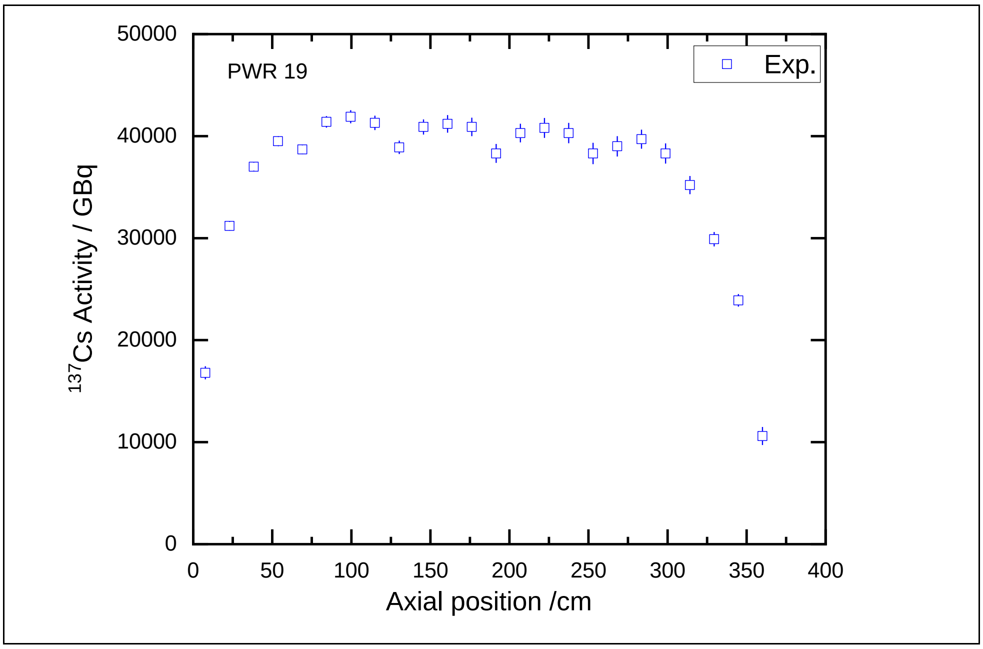

Figure 1 – The ^{137}Cs activity as a function of axial position. The activity is derived from the 662 keV full energy peak obtained from measurements with a HPGe detector. The data are from scanning measurements at Clab with the PWR 19 fuel assembly.

4. Summary

This deliverable describes the experimental data that were produced within WP8 of EURAD to assess the performance of depletion calculations and to define procedures to verify the quality of fuel related input data that are provided by the operator. The report includes experimental data derived from destructive and non-destructive measurements of segment samples of an irradiated fuel rod and of irradiated fuel assemblies. The report includes references to the fuel related data that are required to perform depletion calculations. Results of segment samples together with those from calorimetric measurements of fuel assemblies at Clab can be used to assess the performance of depletion calculations. The results of non-destructive gamma-ray and neutron based measurements of fuel assemblies are valuable to validate procedures to verify the fuel related input data provided by the operator. The results presented in this deliverable are essential input for the EURAD deliverables 8.6 and 8.7.

Appendix A. Specifications of the SKB-50 PWR and BWR assemblies

Details of PWR assemblies that were measured as part of the SKB-50 campaign. The table provides the assembly ID, type, initial enrichment $^{235}U/U$ in wt% (IE), the total initial uranium mass (m), the burnup (BU), the effective full power days (EFPD), expressed as a percentage of the total time between loading and unloading dates, and the date of loading and discharge.

ID	Type	IE (wt%)	Fuel mass (kg)	BU (MWd/kg)	EFPD (%)	Loading date	Discharge date
PWR1	15 × 15 AFA3GAA	4.10	458.9	52.63	89	04/05/2005	28/05/2009
PWR2	15 × 15 AFA3GAA	3.93	454.4	49.56	83	04/05/2005	29/05/2009
PWR3	17 × 17 Fra	3.69	462.2	48.18	83	06/07/1996	21/06/2000
PWR4	17 × 17 HTP	3.93	460.3	46.87	87	26/09/2004	04/06/2008
PWR5	17 × 17 HTP	3.94	460.4	46.87	87	26/09/2004	02/06/2008
PWR6	17 × 17 AA	3.60	462.5	45.66	52	08/07/1993	23/06/1999
PWR7	17 × 17 Siemens	3.94	460.9	44.48	80	05/09/2003	27/06/2007
PWR8	17 × 17 W	3.30	463.0	44.38	75	20/08/1984	11/09/1988
PWR9	15 × 15 W	3.71	457.9	45.85	76	15/06/2003	01/08/2007
PWR10	17 × 17 Fra	3.70	462.3	43.47	75	01/07/1994	17/06/1998
PWR11	17 × 17 Fra	3.51	460.2	43.23	50	01/07/1994	21/06/2000
PWR12	17 × 17 W	3.30	465.0	42.97	72	20/08/1984	11/09/1988
PWR13	15 × 15 KWU	3.20	433.1	40.92	59	25/07/1982	25/04/1987
PWR14	17 × 17 Fra	3.51	459.0	40.75	70	08/07/1993	24/06/1997
PWR15	17 × 17 W	2.80	459.6	40.47	52	17/04/1982	27/08/1987
PWR16	17 × 17 Fra	3.60	460.2	40.41	92	23/06/1993	21/06/1996
PWR17	17 × 17 Fra	3.70	460.5	40.29	56	22/09/1994	01/09/1999
PWR18	17 × 17 Fra	3.52	461.1	39.76	46	09/07/1989	09/06/1995
PWR19	15 × 15 KWU	3.20	433.5	35.03	48	17/05/1980	01/05/1985
PWR20	17 × 17 W	3.10	458.4	34.03	39	04/07/1980	18/06/1986
PWR21	17 × 17 W	3.10	460.1	34.02	39	04/07/1980	18/06/1986
PWR22	17 × 17 W	2.80	460.0	31.17	50	18/04/1982	10/08/1986
PWR23	17 × 17 Fra	3.60	459.3	28.50	66	07/07/1993	21/06/1996
PWR24	17 × 17 W	2.10	462.7	23.15	11	02/07/1980	09/06/1995
PWR25	17 × 17 W	2.10	462.1	19.61	35	03/07/1980	24/05/1984

Details of BWR assemblies that were measured as part of the SKB-50 campaign. The table provides the assembly ID, type, initial enrichment $^{235}U/U$ in wt% (IE), the total initial uranium mass (m), the burnup (BU), the effective full power days (EFPD), expressed as a percentage of the total time between loading and unloading dates,and the date of loading and discharge.

ID	Type	IE (wt%)	Fuel mass (kg)	BU (MWd/kg)	EFPD (%)	Loading date	Discharge date
BWR1	Svea-96S	4.01	169.9	46.41	62	28/10/1999	29/08/2006
BWR2	Svea-100	3.20	176.9	43.76	77	09/06/1999	17/08/2004
BWR3	Svea-100	3.40	180.6	44.36	51	18/08/1996	12/08/2002
BWR4	Svea-100	3.40	180.7	41.89	57	18/08/1996	12/08/2002
BWR5	Svea-96S	3.14	170.0	42.02	56	28/10/1999	29/08/2006
BWR6	8×8-1	2.65	175.1	38.15	48	05/08/1978	12/09/1985
BWR7	Svea-100	3.15	177.1	41.24	73	09/06/1999	17/08/2004
BWR8	Atrium 10B	3.15	174.4	39.75	97	29/08/2001	19/05/2005
BWR9	Svea-96S	4.01	169.9	40.44	61	29/08/2001	07/09/2007
BWR10	Svea-96S	3.14	169.9	39.50	72	29/08/2001	29/08/2006
BWR11	8×8-1	2.09	172.6	31.53	45	08/11/1980	22/08/1992
BWR12	Svea-96	2.96	173.2	33.51	38	24/06/1997	10/06/2005
BWR13	Svea-96	2.96	173.3	36.83	42	24/06/1997	10/06/2005
BWR14	8×8-1	2.65	181.0	30.49	67	05/08/1978	12/09/1985
BWR15	8×8-1	2.09	195.6	29.42	42	05/11/1980	25/08/1989
BWR16	8×8-1	2.09	195.4	26.82	64	05/11/1980	11/06/1987
BWR17	8×8-1	2.31	173.9	32.71	26	01/03/1975	15/07/1986
BWR18	8×8-1	2.09	178.5	21.52	48	14/11/1980	22/08/1992
BWR19	8×8-1	1.27	177.7	30.80	60	17/10/1984	10/06/1989
BWR20	Svea-96	2.96	173.0	26.43	35	02/08/1998	10/06/2005
BWR21	8×8-1	2.31	173.8	27.67	20	01/03/1975	01/07/1987
BWR22	Svea-96	2.96	173.1	20.41	48	14/07/2001	10/06/2005
BWR23	Svea-96	2.96	173.0	15.99	24	24/05/1999	10/06/2005
BWR24	8×8-4	1.27	169.9	13.32	45	17/10/1984	10/07/1987
BWR25	8×8-4	1.27	170.0	9.13	31	17/10/1984	10/07/1987

Appendix B. Results of calorimetric measurements on SKB-50 assemblies at Clab

Results of measurements with the calorimeter at Clab. The decay heat rate (P) derived by two independent analysis procedures are given. The procedure developed within WP8 of EURAD and the one procedure developed as part of an EPRI project.

ID	Measurement date	P (W) EURAD	P (W) EPRI
PWR1	19/02/2018	966.4	965.7
PWR2	31/01/2018	879.0	880.2
PWR3	27/05/2019	652.6	651.1
PWR4	04/03/2019	763.7	762.3
PWR5	16/04/2019	762.7	761.4
PWR6	05/02/2019	605.9	604.7
PWR7	27/02/2019	687.6	686.4
PWR8			
PWR9	25/01/2018	739.2	738.0
PWR10	25/02/2019	548.0	547.0
PWR11	19/02/2018	549.2	548.3
PWR12			
PWR13	12/02/2018	390.4	390.1
PWR14	04/04/2019		
PWR15	30/01/2018		
PWR16	18/02/2019	602.9	
PWR17	17/04/2019	507.0	506.2
PWR18	07/02/2018	460.1	459.1
PWR19	24/01/2018	321.1	321.4
PWR20			
PWR21	15/04/2019	330.8	331.1
PWR22	02/05/2019	297.2	297.9
PWR23	26/02/2019	327.2	326.9
PWR24	06/02/2018	247.9	247.9
PWR25			

ID	Measurement date	P (W) EURAD	P (W) EPRI
BWR1			
BWR2			
BWR3			
BWR4			
BWR5	18/02/2020	209.1	210.2
BWR6			
BWR7			
BWR8			
BWR9	11/03/2021	198.9	199.1
BWR10	09/03/2021	195.3	195.8
BWR11	19/02/2020	116.1	117.1
BWR12	23/03/2021	157.2	157.3
BWR13	25/02/2020	179.6	180.3
BWR14			
BWR15	02/03/2020	104.9	103.4
BWR16	24/02/2020	94.6	96.2
BWR17			
BWR18			
BWR19			
BWR20			
BWR21			
BWR22	25/03/2021	88.2	89.6
BWR23			
BWR24			
BWR25			

Appendix C. Results of gamma-ray spectroscopic measurements on SKB-50 assemblies at Clab

Results of gamma-spectroscopic measurements of PWR assemblies reported by Vaccaro et al. [6] and Solans et al. [23].The net peak area per time unit of the full energy peak corresponding to the 662 keV gamma-ray following the decay of ^{137}Cs, with the relative measurement uncertainty (%). The net peak areas obtained in [6] and [23] result from an analysis by two different persons using results of different experiments with different attenuation plates and a different analysis codes. In addition, the data of Solans et al. [23] are derived from a spectrum that is the results of an integration over the axial length of the assembly. The integration limits correspond approximately to the boundaries of the burnup plateau. The spectra analysed by Vaccaro et al. [6] are obtained from measurements corresponding to the burnup plateau.

ID	Vaccaro et al.			Solans et al.		
	Measurement date	C (1/s)	100 × u_C/C	Measurement date	C (1/s)	100 × u_C/C
PWR1	07/10/2014	1663.4	3.1	09/11/2016	10900.6	2.7
PWR2	07/10/2014	1570.5	2.6	09/11/2016	10578.2	2.5
PWR3	09/10/2014	1253.8	6.0			
PWR4	09/10/2014	1420.2	1.3	28/09/2016	9724.9	1.2
PWR5	10/10/2014	1434.2	2.6	07/11/2016	9717.9	1.7
PWR6	09/10/2014	1129.7	2.7			
PWR7	10/10/2014	1311.3	2.9	28/09/2016	8835.9	2.4
PWR8	13/10/2014	877.0	1.4	07/11/2016	5780.6	0.8
PWR9	07/10/2014	1389.3	3.5	08/11/2016	9285.6	3.8
PWR10	13/10/2014	1081.8	6.4	27/09/2016	7169.0	5.7
PWR11	13/10/2014	1053.0	6.6	27/09/2016	6819.1	7.0
PWR12	15/10/2014	870.4	3.1	08/11/2016	5750.9	3.6
PWR13	08/10/2014	743.9	3.8	09/11/2016	4940.9	3.7
PWR14	14/10/2014	959.6	7.3	27/09/2016	6347.1	6.4
PWR15	08/10/2014	784.5	2.6	29/09/2016	5287.9	4.3
PWR16	15/10/2014	951.1	1.2	28/09/2016	6239.8	1.5
PWR17	14/10/2014	999.8	3.7	08/11/2016	6688.6	7.5
PWR18	08/10/2014	852.5	4.0	28/09/2016	5665.2	2.9
PWR19	08/10/2014	609.6	6.2	08/11/2016	4076.7	5.1
PWR20	14/10/2014	644.8	1.0	29/09/2016	4250.7	1.0
PWR21	15/10/2014	638.6	2.1	29/09/2016	4144.3	3.6
PWR22	15/10/2014	585.8	4.1	08/11/2016	3860.7	3.5
PWR23	15/10/2014	666.4	4.9	28/09/2016	4305.8	4.9
PWR24	09/10/2014	426.9	4.9	29/09/2016	2883.8	4.8
PWR25	13/10/2014	351.3	0.1	07/11/2016	2346.0	1.9

Results of gamma-ray spectroscopic measurements of BWR assemblies reported by Vaccaro et al. [6] and Solans et al. [23].The net peak area per time unit of the full energy peak corresponding to the 662 keV gamma-ray following the decay of ^{137}Cs, with the relative measurement uncertainty (%). The net peak areas obtained in [6] and [23] result from an analysis by two different persons using results of different experiments with different attenuation plates and a different analysis codes. In addition, the data of Solans et al. [23] are derived from a spectrum that is the results of an integration over the axial length of the assembly. The integration limits correspond approximately to the boundaries of the burnup plateau. The spectra analysed by Vaccaro et al. [6] are obtained from measurements corresponding to the burnup plateau.

ID	Vaccaro et al.			Solans et al.		
	Measurement date	C (1/s)	100 × u_C/C	Measurement date	C (1/s)	100 × u_C/C
BWR1	01/12/2014	3082.6	1.4	09/11/2016		
BWR2	02/12/2014	2840.5	0.2	09/11/2016	2927.2	0.3
BWR3	09/12/2014	2724.6	3.9		2847.8	3.6
BWR4	09/12/2014	2572.6	5.0	28/09/2016		
BWR5	02/12/2014	2852.5	2.8	07/11/2016	2935.6	4.1
BWR6	10/12/2014	1447.6	2.1		1426.4	1.2
BWR7	02/12/2014	2665.7	4.6	28/09/2016	2744.3	4.1
BWR8	03/12/2014	2546.4	2.4	07/11/2016		
BWR9	02/12/2014	2772.7	4.0	08/11/2016		
BWR10	01/12/2014	2711.6	1.8	27/09/2016	2849.8	1.6
BWR11	08/12/2014	1279.0	6.0	27/09/2016	1264.1	3.7
BWR12	03/12/2014	2178.2	0.7	08/11/2016	2247.6	0.7
BWR13	02/12/2014	2388.0	2.4	09/11/2016	2425.0	1.0
BWR14	10/12/2014	1161.9	2.2	27/09/2016	1146.6	1.2
BWR15	09/12/2014	1148.2	1.2	29/09/2016	1129.9	1.9
BWR16	09/12/2014	1067.6	3.3	28/09/2016	1013.0	4.0
BWR17	04/12/2014	1203.9	2.5	08/11/2016	1165.3	3.1
BWR18	08/12/2014	900.6	3.8	28/09/2016	874.0	4.0
BWR19	04/12/2014	1277.5	0.8	08/11/2016	1236.8	1.7
BWR20	03/12/2014	1781.2	1.5	29/09/2016		
BWR21	04/12/2014	999.0	3.3	29/09/2016	946.5	2.6
BWR22	02/12/2014	1378.1	2.4	08/11/2016	1408.8	2.8
BWR23	03/12/2014	1097.6	4.2	28/09/2016		
BWR24	03/12/2014	508.4	11.2	29/09/2016	477.9	10.2
BWR25	08/12/2014	327.2	16.2	07/11/2016	294.8	13.6

Appendix D. Results of FORK measurements on SKB-50 assemblies at Clab

Results of measurements with the FORK detector at Clab [8]. The response of one neutron detector (C_n) and the ionisation chamber (C_γ) are given.

ID	Measurement date	C_n (1/s)	C_γ (1/s)	ID	Measurement date	C_n (1/s)	C_γ (1/s)
PWR1	15/10/2014	2162.1	1223182	BWR1	11/03/2015	1034.7	501985
PWR2	15/10/2014	1837.9	1126913	BWR2	11/03/2015	843.2	477075
PWR3	15/10/2014	1264.4	612000	BWR3	11/03/2015	777.3	387406
PWR4	15/10/2014	1522.0	934477	BWR4	11/03/2015	608.1	411583
PWR5				BWR5	11/03/2015	738.4	494300
PWR6	14/10/2014	1049.3	562908	BWR6	11/03/2015	386.3	251645
PWR7	15/10/2014	1169.3	802432	BWR7	11/03/2015	756.7	451088
PWR8				BWR8	12/03/2015	679.0	463648
PWR9	15/10/2014	1395.5	859405	BWR9	12/03/2015	641.0	520513
PWR10	15/10/2014	798.5	531171	BWR10	11/03/2015	629.8	505537
PWR11	15/10/2014	817.4	517900	BWR11	11/03/2015	218.8	231827
PWR12				BWR12	11/03/2015	375.0	397132
PWR13				BWR13	11/03/2015	525.3	427656
PWR14	15/10/2014	666.2	486164	BWR14	11/03/2015	161.4	212962
PWR15				BWR15	11/03/2015	156.0	214262
PWR16	15/10/2014	590.0	480941	BWR16	11/03/2015	118.3	197763
PWR17				BWR17	11/03/2015	188.4	216825
PWR18				BWR18	11/03/2015	69.9	177833
PWR19	15/10/2014	245.8	338518	BWR19	11/03/2015	193.3	234132
PWR20				BWR20	11/03/2015	164.8	341681
PWR21				BWR21	11/03/2015	97.1	185450
PWR22	15/10/2014	206.3	321905	BWR22	11/03/2015	52.9	268423
PWR23	15/10/2014	166.0	363569	BWR23	11/03/2015	23.6	220091
PWR24	15/10/2014	149.9	263198	BWR24	11/03/2015	21.4	109311
PWR25				BWR25	11/03/2015	7.1	81625

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