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Document title**HFR-EU-1-bis Benchmark Report****Executive summary**

HFR-EU1bis is the irradiation experiment for testing spherical High Temperature Reactor (HTR) fuel pebbles with TRISO coated particles (UO₂ fuel kernel with successive isotropic layers of porous carbon, dense carbon, dense silicon carbide and dense carbon) for their potential for high temperature performance and high burn-up. The irradiation has been performed in the High Flux Reactor (HFR) at Petten in the Netherlands for a period of 10 cycles.

Five fuel pebbles from the German AVR production (GLE-4 type) and six mini samples with each 10 coated particles sealed in a niobium tube have been tested in a sample holder that was loaded in a test rig, surrounded by a strongly moderating filler element. During irradiation the central pebble temperature has been kept at a characteristic 1250°C. The irradiation has started on 9 September 2004 and finished on 18 October 2005.

After a cool-down period the experiment has been dismantled and the mini samples and samples taken from the fuel sphere were transported to ITU for analysis of the nuclide inventory. Flux monitors and a scan wire have been measured at NRG-Petten.

The experiment is described in such a way that it is suitable for validation of coupled neutronics and depletion codes. In this benchmark inventories of different samples from pebbles and monitors are requested to be calculated and compared with the measured data.

Revisions

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00	01/04/2007	First issue	J.B.M. de Haas, NRG	A.I. van Heek, NRG <i>Signature</i>	A.I. van Heek, NRG <i>Signature</i>	E. Bogusch, FANP <i>Signature</i>
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02	01/04/2008	Rev.2	F.F. Charpin-Jacobs, NRG	A.I. van Heek, NRG <i>Signature</i>	A.I. van Heek, NRG <i>Signature</i>	E. Bogusch, FANP <i>Signature</i>
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1 Introduction

1.1 Purpose of the benchmark

Many benchmarks have been defined as a computational benchmark based on a well defined set of input data. This benchmark is based on a well defined experiment under well defined conditions, so measured data will become available after finishing, examination and evaluation of the experiment. For the purpose of verification and validation of the neutronics and depletion codes in use by the partners, the HFR-EU1bis irradiation experiment for testing spherical High Temperature Reactor (HTR) fuel pebbles has been made available to the RAPHAEL community. This experiment with pebbles loaded with TRISO coated particles (UO_2 fuel kernel and successive isotropic layers of porous carbon, dense carbon, dense silicon carbide and dense carbon) with their potential for high temperature performance and high burn-up, were irradiated in-core in the High Flux Reactor (HFR) at Petten for a period of 10 cycles.

Five fuel pebbles from German AVR production (GLE-4 type) and six mini samples with each 10 coated particles sealed in a niobium tube have been irradiated and will be tested for their nuclide inventory at JRC-ITU at Karlsruhe.

1.2 Short description of the benchmark

The irradiation has been performed in the facility of the High Flux Reactor (HFR) at Petten, The Netherlands running at its nominal power of 45 MW for a period of 10 cycles in core position G3.

Five fuel pebbles from German AVR production (GLE-4 type) and six mini samples with each 10 coated particles sealed in a niobium tube have been tested in a sample holder that was loaded in a REFA-170 rig, surrounded by a strongly moderating filler element. The irradiation has started on 9 September 2004 and finished on 18 October 2005.

The characteristic irradiation parameters are: constant central fuel temperatures of approx. 1250°C , a target burn-up of 16-19% FIMA in the two central pebbles, and a maximum neutron fluence of approx. $5\text{-}7.3 \text{ E}+25 \text{ m}^{-2}$ ($E > 0.1 \text{ MeV}$).

During all irradiation cycles the irradiation took place in a REFA-170 rig at position G3 in the core of the HFR. A schematic of the HFR-core can be seen in fig. 1.

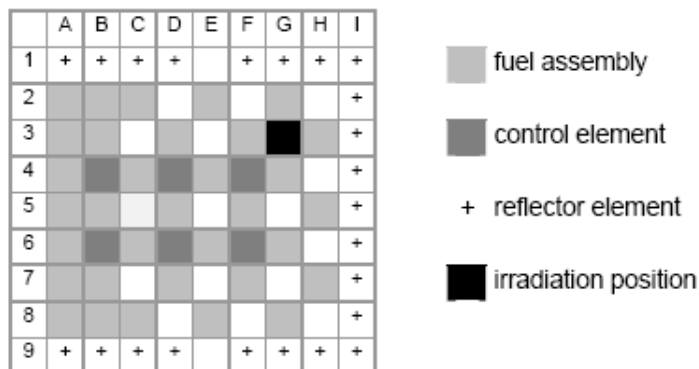


Figure 1: Standard HFR core configuration showing HFR-EU1bis in core position G3

An overview of the irradiation rig containing the HFR-EU1bis experiment can be seen in fig. 2.

For the purpose of describing the surrounding of the experiment in the reactor, a set of group-wise cross sections of the adjacent core positions has been supplied with the benchmark.

A full benchmark description can be found in Appendix A.

Participants are requested to calculate,

to test the neutronics codes:

- Reaction rates of the three flux detectors mounted near the pebbles
- Axial activity distribution over the outer can

to test the depletion codes:

- Nuclide inventories in the mini samples
- Nuclide inventories in the fuel pebbles.

As stated above, five fuel pebbles and six mini samples with each 10 coated particles have been irradiated and have been tested in 2007 for their nuclide inventory at JRC-ITU at Karlsruhe.

The three flux detectors containing different monitor materials have been counted for their gamma-activities at NRG and axial gamma scans of the outer containment can have been provided by the Hot Cell Laboratory (HCL) of NRG at Petten in 2006.

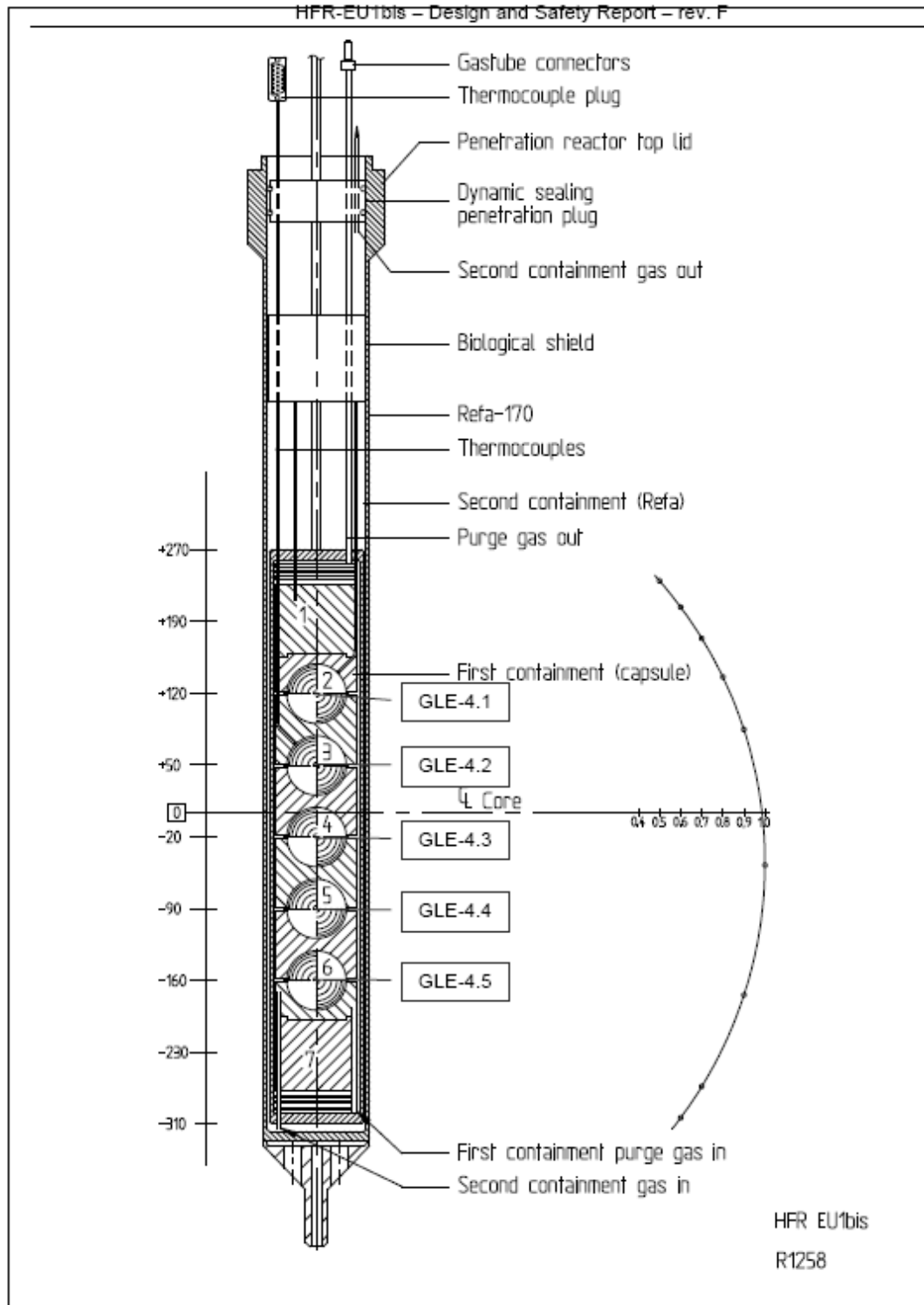


Figure 2: Conceptual sketch of HFR-EU1bis

2 Participants, codes and data

A complete list of the participants with the codes and data libraries they have used is presented below. More details and remarks can be found in Appendix B.

1. NRG, The Netherlands

- o Participants: Florence Charpin-Jacobs, Han de Haas, Alik van Heek, Steven van der Marck
- o Codes: MCNP-OCTOPUS-FISPACT
- o Method: Monte-Carlo
- o Cross sections: ENDF/B-VI and OSCAR-library

2. NRI, Czech Republic

- o Participants: Jan Frybort
- o Codes: MCNP5/MURE
- o Methods: Monte-Carlo
- o Cross sections: ENDF/B-VII

3. AREVA, France

- o Participants: Christos Trakas
- o Codes: MONTEBURNS code system (MCNP5, ORIGEN2, BATEMAN)
- o Method: Monte-Carlo
- o Cross sections: JEFF 3.1

4. IRSN, France

- o Participants: Luis Aguiar
- o Codes: MONTEBURNS code system (MCNP4c2, ORIGEN2.2)
- o Method: Monte-Carlo
- o Cross sections: JEFF 3.1

5. UNIPI, Italy

- o Participants: Eleonora Bomboni, Nicola Cerullo, G. Lomonaco
- o Codes: MONTEBURNS 2.0 code system (MCNP5, ORIGEN2.2)
- o Method: Monte-Carlo
- o Cross sections: JEFF 3.1 or ENDF B4 (this later for ORIGEN only)

Table 1. Summary of submitted results

Partner / Flux / Depl. codes	Flux monitors	Axial scan	Inventories mini samples	Inventories pebbles
NRG / MCNP/FISPACT	Y	Y	Y	Y
NRI/ MCNP5/MURE	Y	Y	Y	Y
AREVA/ MONTEBURNS (MCNP5, ORIGEN2, BATEMAN)		Y	Y	Y
IRSN/ MONTEBURNS (MCNP4c2, ORIGEN2.2)			Y	Y
UNIPI/ MONTEBURNS (MCNP5, ORIGEN2.2)	Y	Y	Y	Y

3 Benchmark Results

3.1 Flux Detectors

During the second cycle a short heat-up event of the experiment occurred at which the FD-2 detector in the middle of the experiment has been lost. Also the Mn activity in FD-3 evaporated and could not be recovered. So there are no experimental values present for these foils. The reaction rate is expressed as reactions per atom monitor material per second, during the irradiation time of 2.17×10^7 seconds. The measured gamma's are from the reaction products listed in table 2.

Table 2. Flux detector reaction rates with uncertainties

Ident	Experimental				NRG		NRI	
Reaction	Foil nr	Mass (mg)	R-Rate (Bq)	Uncert (%)	R-Rate (Bq)	Uncert (%)	R-Rate (Bq)	Uncert (%)
59CO(N,G)60CO	CO1	0.00064	1.82E-09	0.4	1.82E-09	1.27	2.15E-09	0.46
	CO2	0.00065			4.03E-09	0.86	4.06E-09	0.32
	CO3	0.00063	2.89E-09	0.4	2.89E-09	1.05	2.51E-09	0.42
58FE(N,G)59FE	FE1	0.68250	5.33E-11	2.5	5.48E-11	0.76	6.55E-11	0.56
	FE2	0.57170			1.21E-10	0.51	1.26E-10	0.42
	FE3	0.61890	8.25E-11	2.4	8.66E-11	0.67	7.75E-11	0.50
54FE(N,P)54MN	FE1	0.68250	4.59E-12	0.2	4.72E-12	1.37	4.44E-12	0.57
	FE2	0.57170			8.50E-12	1.06	7.57E-12	0.44
	FE3	0.61890			6.62E-12	1.27	4.64E-12	0.56
93NB(N,G)94NB	NB1	0.53380	1.12E-10	0.5	1.08E-10	1.21	1.24E-10	1.23
	NB2	0.43420			2.24E-10	0.82	2.29E-10	0.90
	NB3	0.38740	1.71E-10	0.4	1.63E-10	1.01	1.39E-10	1.1
93NB(N,N)93NBM	NB1	0.53380	9.92E-12	1.5	9.28E-12	0.78	9.15E-12	0.33
	NB2	0.43420			1.71E-11	0.60	1.60E-11	0.24
	NB3	0.38740	1.32E-11	1.5	1.32E-11	0.71	9.66E-12	0.32
Ident	UNIP1							
Reaction	Foil nr	Mass (mg)	R-Rate (Bq)	Uncert (%)				
59CO(N,G)60CO	CO1	0.00064	2.47E-09	0.90				
	CO2	0.00065	-					
	CO3	0.00063	2.85E-09	0.74				
58FE(N,G)59FE	FE1	0.68250	7.45E-11	0.69				
	FE2	0.57170	-					
	FE3	0.61890	8.61E-11	0.65				
54FE(N,P)54MN	FE1	0.68250	4.95E-12	0.95				
	FE2	0.57170	-					
	FE3	0.61890	5.32E-12	0.92				
93NB(N,G)94NB	NB1	0.53380	1.50E-10	1.87				
	NB2	0.43420	-					
	NB3	0.38740	1.70E-10	1.47				
93NB(N,N)93NBM	NB1	0.53380	1.49E-12	0.46				
	NB2	0.43420	-					
	NB3	0.38740	1.69E-12	0.43				

The flux detector activities have been calculated by NRG with the OCTOPUS package, by NRI with the MURE code and by UNIPi with the MONTEBURNS coupling code: the results together with the experimental results by NRG and the uncertainties in measurement and calculation are shown in table 2. The deviation of the calculational results from the experimental values are given in figure 3.

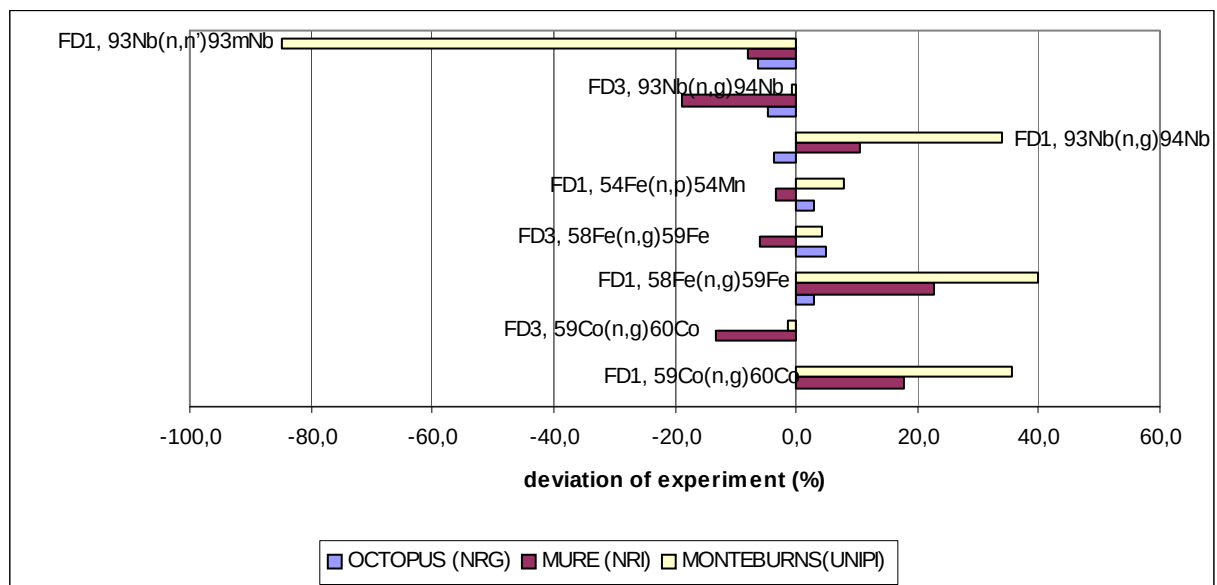


Figure 3. Flux Detectors activities: deviation of the calculational results from the experimental measurements

The method chosen by NRG for the normalization of the results is to normalize all the benchmark simulations to the gamma's measured by the flux detectors FD-1 and FD-3. The normalization constant is determined by the comparison of the measured gamma's from the reaction rate Co-59 (n,g) Co-60 (indicative for the thermal fluence) and the calculated gamma's from the same reaction rate. Between the FD-1 and FD-3 positions, a linear correction is applied. NRI, AREVA have also chosen to normalize their results to the gamma's measured from the reaction rate Co-59 (n,g) Co-60. An average normalization constant for the flux detectors FD-1 and FD-3 was calculated. UNIPi has normalized its results to the data provided per cycle of the HFR total power. Please note that (in UNIPi calculations) each irradiation step consisted of a MCNP calculation with 500 iterations (the first 50 were skipped) each with 5000 starting particles. This has been for UNIPi (also because UNIPi at that time had performed the calculations on a single PC and not on a cluster) the best compromise between accuracy and machine time. However, it seems that in the central part of the sample, where the neutron flux is higher, UNIPi's results fit better with the others (including experimental ones). So, the worst results on the top and the bottom of the sample could be mainly due to bad statistics (lower neutron flux).

The calculational results on the flux detectors should not be compared directly, as NRG and NRI used the Co-59 (n,g) Co-60 reaction rate for the normalization of the MCNP calculations.

Independent from this, it can be seen that all deviations are below 35%, except for the Nb-93(n,n')Nb-93 reaction rate for which UNIPI has deviations of 85%. Most MONTEBURNS results are lower than the experimental results.

3.2 Axial Profile

Table 3. Axial profile of the ^{60}Co reaction rate as calculated along the outer bus.

As no precise value of the Co-content of the stainless steel reaction rates are normalized to unity at maximum value

	NRG	NRI	AREVA	UNIP
Z (cm)	Reaction rate			
-27.5	0.59	0.50	0.63	-
-22.75	0.71	0.64	0.68	0.66
-18.75	0.81	0.76	0.76	0.76
-15.25	0.89	0.85	0.83	0.85
-11.75	0.95	0.92	0.90	0.92
-8.25	0.99	0.97	0.93	0.97
-4.75	1.00	1.00	1.00	1.00
-1.25	0.99	1.00	0.99	1.00
2.25	0.96	0.99	0.95	0.99
5.75	0.91	0.95	0.93	0.95
9.25	0.83	0.88	0.87	0.88
12.75	0.74	0.79	0.78	0.82
16.25	0.64	0.69	0.71	0.69
20	0.52	0.56	0.59	0.58
26	0.39	0.40	0.50	-

The origin (Z=0 cm) is the core centre-line.

3.3 Mini Samples

The results of the mini samples burn-up measurements and calculations can be seen in table 4 and figure 4.

Table 4. Results for the final levels of the burn-up (% FIMA) of the six mini samples 1-6.

FIMA (%)	ITU Measurements	NRG	NRI	AREVA	IRSN	UNIPi
Mini Sample 1 (Position +14.5cm)	Value for one particle from unidentified sample:	6.26	6.10	6.11	9.2	5.05
Mini Sample 2 (Position +7.5cm)		7.31	7.02	7.18	10.4	6.33
Mini Sample 3 (Position 0.5cm)		8.21	7.73	7.45	11.1	7.92
Mini Sample 4 (Position -6.5cm)		8.19	7.36	7.56	11.1	6.81
Mini Sample 5 (Position -13.5cm)	7.23 %	7.31	6.87	7.07	10.7	6.97
Mini Sample 6 (Position -20.5cm)	(based on Cs-137)	6.84	5.92	6.03	9.5	5.69

The MONTEBURNS results by IRSN are higher than the other participants's results, whereas the MONTEBURNS results by UNIPi are lower. The other participants's results are close to each other (deviations per pebble from 0 to 13%). The final level of burn-up in % FIMA calculated by NRG, NRI and AREVA vary between 5.92 for the Mini Sample at the lowest axial position in the experiment and 8.2 for the Mini Sample in the central position. The Mini Sample analyzed at ITU could not be identified. The final level of burn-up estimated by ITU (7,23 % FIMA) is very close to the levels calculated by NRG, NRI and AREVA for the Mini Samples 2 and 5.

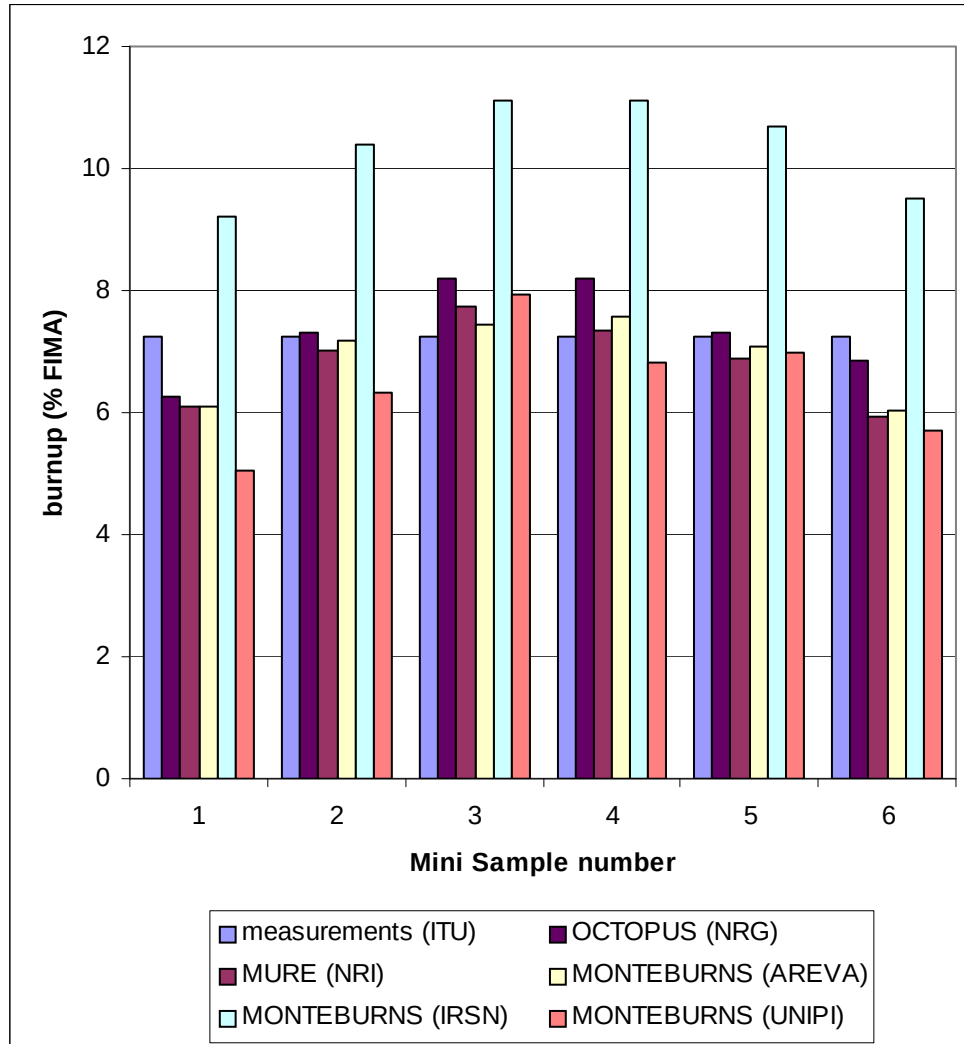


Figure 4. Burn-up in % FIMA of the six irradiated mini samples. The most left column of each mini sample indicates the experimental value, and the other columns the calculational results.

The isotopic inventories (Bq/gram initial HM) of the coated particles in the six mini-samples 1-6 at end of irradiation (EOI) are given in the six following tables (tables 5 to 10). Specific measured data are given for:

the fission products:

the vectors of: Cs, Nd, and Ce-144, Sr-90,

and for the actinides:

the vectors of: U, Pu and Np-237, Am-241, Cm-244.

Table 5. Results for mini sample-1

(*ITU data origin from one particle from an unidentified mini sample)

(** AREVA data given in g/gHM. Converted in Bq/gHM by NRG)

Nuclide	ITU(*) Measurements	End of Irradiation (Bq/gHM)				
		NRG	NRI	AREVA(**)	IRSN	UNIP
Cs						
Cs 133		0	0	0	0	0
Cs 134	8.841E+09 ± 1.54E+09	5.37E+09	5.48E+09	5.75E+09	5.41E+09	2.92E+06
Cs 135		1.13E+04	1.27E+04	1.43E+04	2.00E+04	8.14E+00
Cs 136		1.41E+09	2.83E+09	4.27E+09	5.15E+09	2.24E+06
Cs 137	8.593E+09 ± 1.49E+09	7.09E+09	7.01E+09	7.01E+09	9.80E+09	5.27E+06
Nd						
Nd 142		0	0	0	0	0
Nd 143		0	0	0	0	0
Nd 144		3.20E-05	4.40E-05	4.42E-05	6.81E-05	3.41E-08
Nd 145		0	0	0	0	0
Nd 146		0	0	0	0	0
Nd 147		1.67E+11	1.20E+11	1.26E+11	1.77E+11	1.68E+07
Nd 148		0	0	0	0	0
Nd 150		0	0	0	0	0
U						
U 234		1.79E+04	3.16E+02	1.74E+05	1.72E+05	3.66E-01
U 235		3.34E+03	3.33E+03	3.34E+03	6.06E+03	3.88E+00
U 236		2.13E+04	2.14E+04	2.24E+04	3.54E+04	2.12E+01
U 237		7.27E+10	3.93E+10	0	1.70E+11	0
U 238		1.08E+04	1.08E+04	1.08E+04	1.01E+04	1.16E+01
Pu						
Pu 238		2.84E+07	2.85E+07	3.57E+07	1.01E+08	1.15E+04
Pu 239		2.93E+07	2.42E+07	2.15E+07	1.48E+07	1.12E+04
Pu 240		3.19E+07	2.56E+07	2.80E+07	2.00E+07	1.12E+04
Pu 241		7.82E+09	6.83E+09	6.99E+09	3.92E+09	2.19E+06
Pu 242		6.36E+04	5.15E+04	6.81E+04	3.27E+04	1.94E+01
Ce 144	1.275E+11 ± 2.09E+10	1.44E+11	1.38E+11	1.38E+11	2.03E+11	1.06E+08
Sr 90		4.37E+09	5.86E+09	5.77E+09	8.86E+09	4.82E+06
Np 237			1.01E+04	9.19E+03	2.46E+04	6.05E+00
Am 241		2.23E+06	2.72E+06	2.60E+06	1.43E+06	9.07E+02
Cm 244		8.73E+06	5.54E+06	1.69E+07	3.45E+06	6.29E+02

Table 6. Results for mini sample-2

(*ITU data origin from one particle from an unidentified mini sample)

(** AREVA data given in g/gHM. Converted in Bq/gHM by NRG)

Nuclide	ITU(*) Measurements	End of Irradiation (Bq/gHM)				
		NRG	NRI	AREVA(**)	IRSN	UNIP
Cs						
Cs 133		0	0	0	0	0
Cs 134	8.841E+09 ± 1.54E+09	7.88E+09	6.92E+09	8.34E+09	7.94E+09	6.78E+06
Cs 135		1.08E+04	1.24E+04	1.47E+04	2.00E+04	9.13E+00
Cs 136		1.61E+09	2.79E+09	4.92E+09	6.19E+09	1.12E+06
Cs 137	8.593E+09 ± 1.49E+09	8.29E+09	8.07E+09	8.37E+09	1.15E+10	6.78E+06
Nd						
Nd 142		0	0	0	0	0
Nd 143		0	0	0	0	0
Nd 144		4.23E-05	5.51E-05	5.62E-05	8.57E-05	4.51E-08
Nd 145		0	0	0	0	0
Nd 146		0	0	0	0	0
Nd 147		1.74E+11	1.20E+11	1.42E+11	1.86E+11	2.45E+07
Nd 148		0	0	0	0	0
Nd 150		0	0	0	0	0
U						
U 234		1.66E+04	3.10E+02	1.63E+05	1.86E+04	2.99E-01
U 235		2.64E+03	2.72E+03	2.78E+03	5.07E+03	3.20E+00
U 236		2.42E+04	2.41E+04	2.47E+04	4.02E+04	2.43E+01
U 237		1.48E+11	1.38E+11	0	2.06E+11	0
U 238		1.08E+04	1.08E+04	1.07E+04	9.99E+03	1.15E+01
Pu						
Pu 238		4.77E+07	3.43E+07	5.31E+07	1.41E+08	1.97E+04
Pu 239		2.31E+07	1.99E+07	2.20E+07	1.55E+07	2.31E+04
Pu 240		3.26E+07	2.70E+07	3.01E+07	2.02E+07	2.95E+04
Pu 241		8.84E+09	7.70E+09	1.03E+10	6.40E+09	5.99E+06
Pu 242		9.83E+04	7.39E+04	1.17E+05	7.12E+04	4.75E+01
Ce 144	1.275E+11 ± 2.09E+10	1.67E+11	1.56E+11	1.60E+11	2.31E+11	1.33E+08
Sr 90		5.10E+09	6.68E+09	6.64E+09	1.01E+10	5.82E+06
Np 237		1.28E+04	1.09E+04	1.31E+04	2.85E+04	7.15E+00
Am 241		2.43E+06	3.03E+06	3.36E+06	2.56E+06	1.67E+03
Cm 244		2.06E+07	1.26E+07	4.25E+07	1.41E+07	2.76E+03

Table 7. Results for mini sample-3

(*ITU data origin from one particle from an unidentified mini sample)

(** AREVA data given in g/gHM. Converted in Bq/gHM by NRG)

Nuclide	ITU(*) Measurements	End of Irradiation (Bq/gHM)				
		NRG	NRI	AREVA(**)	IRSN	UNIP
Cs						
Cs 133		0	0	0	0	0
Cs 134	8.841E+09 ± 1.54E+09	9.89E+09	8.95E+09	1.02E+10	8.17E+09	4.35E+06
Cs 135		1.11E+04	1.30E+04	1.44E+04	1.91E+04	1.01E+01
Cs 136		1.88E+09	3.83E+09	4.49E+09	6.83E+09	1.76E+06
Cs 137	8.593E+09 ± 1.49E+09	9.31E+09	8.91E+09	8.66E+09	1.21E+10	8.51E+06
Nd						
Nd 142		0	0	0	0	0
Nd 143		0	0	0	0	0
Nd 144		4.97E-05	6.24E-05	6.02E-05	9.47E-05	5.25E-08
Nd 145		0	0	0	0	0
Nd 146		0	0	0	0	0
Nd 147		1.96E+11	1.31E+11	1.40E+11	1.85E+11	2.74E+07
Nd 148		0	0	0	0	0
Nd 150		0	0	0	0	0
U						
U 234		1.65E+04	3.28E+02	1.63E+05	1.87E+04	3.01E-01
U 235		2.30E+03	2.47E+03	2.57E+03	4.55E+03	2.86E+00
U 236		2.56E+04	2.51E+04	2.54E+04	4.21E+04	2.53E+01
U 237		7.64E+10	1.31E+11	0	2.04E+11	0
U 238		1.07E+04	1.08E+04	1.08E+04	1.00E+04	1.12E+01
Pu						
Pu 238		6.69E+07	4.88E+07	6.20E+07	1.63E+08	2.79E+04
Pu 239		2.87E+07	2.05E+07	1.86E+07	1.31E+07	2.54E+04
Pu 240		4.09E+07	3.44E+07	2.77E+07	2.20E+07	4.48E+04
Pu 241		1.06E+10	8.40E+09	9.60E+09	5.23E+09	1.13E+07
Pu 242		1.38E+05	1.07E+05	1.36E+05	6.80E+04	1.38E+02
Ce 144	1.275E+11 ± 2.09E+10	1.86E+11	1.69E+11	1.66E+11	2.44E+11	1.62E+08
Sr 90		5.71E+09	7.15E+09	6.90E+09	1.08E+10	6.60E+06
Np 237		1.41E+04	1.26E+04	1.43E+04	3.35E+04	1.26E+01
Am 241		2.81E+06	3.72E+06	3.40E+06	2.07E+06	4.39E+03
Cm 244		3.31E+07	2.16E+07	5.09E+07	1.43E+07	5.08E+03

Table 8. Results for mini sample-4

(*ITU data origin from one particle from an unidentified mini sample)

(** AREVA data given in g/gHM. Converted in Bq/gHM by NRG)

Nuclide	ITU(*) Measurements	End of Irradiation (Bq/gHM)				
		NRG	NRI	AREVA(**)	IRSN	UNIPi
Cs						
Cs 133		0	0	0	0	0
Cs 134	8.841E+09 ± 1.54E+09	9.68E+09	7.50E+09	9.97E+09	8.77E+09	8.76E+06
Cs 135		1.10E+04	1.24E+04	1.47E+04	1.90E+04	8.82E+00
Cs 136		1.88E+09	3.02E+09	4.94E+09	6.45E+09	1.65E+06
Cs 137	8.593E+09 ± 1.49E+09	9.32E+09	8.47E+09	8.78E+09	1.21E+10	7.28E+06
Nd						
Nd 142		0	0	0	0	0
Nd 143		0	0	0	0	0
Nd 144		5.08E-05	5.95E-05	6.06E-05	9.61E-05	4.49E-08
Nd 145		0	0	0	0	0
Nd 146		0	0	0	0	0
Nd 147		1.94E+11	1.30E+11	1.48E+11	1.81E+11	2.78E+07
Nd 148		0	0	0	0	0
Nd 150		0	0	0	0	0
U						
U 234		1.57E+04	2.64E+02	1.63E+05	1.82E+04	3.85E-01
U 235		2.26E+03	2.50E+03	2.57E+03	4.52E+03	3.02E+00
U 236		2.59E+04	2.53E+04	2.56E+04	4.25E+04	2.41E+01
U 237		1.61E+11	1.02E+11	0	2.18E+11	0
U 238		1.07E+04	1.08E+04	1.07E+04	1.00E+04	1.15E+01
Pu						
Pu 238		5.30E+07	3.61E+07	5.79E+07	1.56E+08	4.53E+04
Pu 239		2.35E+07	2.15E+07	2.17E+07	1.37E+07	1.58E+04
Pu 240		3.58E+07	3.24E+07	3.17E+07	2.06E+07	1.83E+04
Pu 241		1.08E+10	6.40E+09	1.01E+10	5.90E+09	1.02E+07
Pu 242		1.44E+05	8.08E+04	1.37E+05	6.66E+04	8.70E+01
Ce 144	1.275E+11 ± 2.09E+10	1.86E+11	1.63E+11	1.68E+11	2.42E+11	1.41E+08
Sr 90		5.72E+09	6.98E+09	6.95E+09	1.08E+10	6.08E+06
Np 237		1.42E+04	1.08E+04	1.30E+04	2.98E+04	1.78E+01
Am 241		2.87E+06	2.91E+06	3.40E+06	2.00E+06	2.41E+03
Cm 244		4.03E+07	1.58E+07	4.82E+07	1.76E+07	2.60E+03

Table 9. Results for mini sample-5

(*ITU data origin from one particle from an unidentified mini sample)

(** AREVA data given in g/gHM. Converted in Bq/gHM by NRG)

Nuclide	ITU(*) Measurements	End of Irradiation (Bq/gHM)				
		NRG	NRI	AREVA(**)	IRSN	UNIP
Cs						
Cs 133		0	0	0	0	0
Cs 134	8.841E+09 ± 1.54E+09	7.82E+09	6.29E+09	8.10E+09	7.31E+09	6.01E+06
Cs 135		1.02E+04	1.23E+04	1.48E+04	1.90E+04	9.93E+00
Cs 136		1.66E+09	3.35E+09	4.65E+09	6.27E+09	4.46E+06
Cs 137	8.593E+09 ± 1.49E+09	8.29E+09	7.89E+09	8.24E+09	1.16E+10	7.28E+06
Nd						
Nd 142		0	0	0	0	0
Nd 143		0	0	0	0	0
Nd 144		4.37E-05	5.37E-05	5.38E-05	8.99E-05	4.58E-08
Nd 145		0	0	0	0	0
Nd 146		0	0	0	0	0
Nd 147		1.72E+11	1.19E+11	1.46E+11	1.78E+11	2.52E+07
Nd 148		0	0	0	0	0
Nd 150		0	0	0	0	0
U						
U 234		1.64E+04	2.70E+02	1.68E+05	1.77E+04	2.78E-01
U 235		2.47E+03	2.79E+03	2.89E+03	4.82E+03	3.07E+00
U 236		2.51E+04	2.36E+04	2.42E+04	4.06E+04	2.58E+01
U 237		7.63E+10	7.85E+10	0	1.96E+11	0
U 238		1.08E+04	1.08E+04	1.07E+04	1.00E+04	1.13E+01
Pu						
Pu 238		4.57E+07	3.82E+07	4.44E+07	1.65E+08	1.05E+04
Pu 239		1.86E+07	2.09E+07	2.22E+07	1.40E+07	2.42E+04
Pu 240		2.35E+07	2.65E+07	3.13E+07	1.84E+07	3.08E+04
Pu 241		9.33E+09	7.31E+09	1.06E+10	5.76E+09	9.50E+06
Pu 242		9.55E+04	6.89E+04	1.15E+05	5.84E+04	9.25E+01
Ce 144	1.275E+11 ± 2.09E+10	1.66E+11	1.53E+11	1.59E+11	2.33E+11	1.42E+08
Sr 90		5.10E+09	6.57E+09	6.49E+09	1.04E+10	5.99E+06
Np 237		9.92E+03	1.18E+04	1.09E+04	3.18E+04	4.06E+00
Am 241		2.17E+06	2.83E+06	3.51E+06	1.96E+06	2.98E+03
Cm 244		2.02E+07	1.08E+07	3.29E+07	1.12E+07	2.69E+03

Table 10. Results for mini sample-6

(*ITU data origin from one particle from an unidentified mini sample)

(** AREVA data given in g/gHM. Converted in Bq/gHM by NRG)

Nuclide	ITU(*) Measurements	NRG	NRI	AREVA(**)	IRSN	UNIPI
Cs						
Cs 133		0	0	0	0	0
Cs 134	8.841E+09 ± 1.54E+09	6.67E+09	4.53E+09	6.09E+09	5.62E+09	6.29E+06
Cs 135		1.11E+04	1.24E+04	1.44E+04	1.99E+04	8.88E+00
Cs 136		1.59E+09	2.33E+09	3.97E+09	4.97E+09	2.28E+06
Cs 137	8.593E+09 ± 1.49E+09	7.76E+09	6.69E+09	6.98E+09	1.02E+10	5.88E+06
Nd						
Nd 142		0	0	0	0	0
Nd 143		0	0	0	0	0
Nd 144		3.76E-05	4.19E-05	4.29E-05	7.26E-05	3.79E-08
Nd 145		0	0	0	0	0
Nd 146		0	0	0	0	0
Nd 147		1.59E+11	1.17E+11	1.29E+11	1.72E+11	1.89E+07
Nd 148		0	0	0	0	0
Nd 150		0	0	0	0	0
U						
U 234		1.70E+04	2.12E+02	1.79E+05	1.60E+04	1.74E-01
U 235		2.96E+03	3.46E+03	3.45E+03	5.79E+03	3.69E+00
U 236		2.24E+04	2.11E+04	2.12E+04	3.65E+04	2.21E+01
U 237		1.53E+11	4.38E+10	0	1.88E+11	0
U 238		1.08E+04	1.09E+04	1.08E+04	1.01E+04	1.15E+01
Pu						
Pu 238		4.56E+07	1.70E+07	3.22E+07	9.88E+07	1.02E+04
Pu 239		2.58E+07	1.98E+07	2.09E+07	1.25E+07	2.29E+04
Pu 240		3.03E+07	2.54E+07	3.04E+07	1.76E+07	2.58E+04
Pu 241		8.18E+09	5.22E+09	7.45E+09	4.86E+09	4.05E+06
Pu 242		8.88E+04	4.22E+04	6.97E+04	4.38E+04	2.97E+01
Ce 144	1.275E+11 ± 2.09E+10	1.56E+11	1.32E+11	1.38E+11	2.11E+11	1.16E+08
Sr 90		4.78E+09	5.65E+09	5.67E+09	9.26E+09	5.14E+06
Np 237		1.29E+04	6.12E+03	9.71E+03	2.36E+04	5.98E+00
Am 241		2.73E+06	2.38E+06	2.85E+06	1.80E+06	1.49E+03
Cm 244		1.82E+07	5.50E+06	1.32E+07	5.91E+06	9.07E+02

ITU has provided results of measurements for 3 isotopes: Cs 134, Cs 137 and Ce 144. Figure 5 shows the experimental values with their uncertainty obtained for these 3 isotopes and the results of the calculations. Figure 6 shows the deviation of the calculational results of each participant from the experimental values. The results are given for the Mini Sample 2.

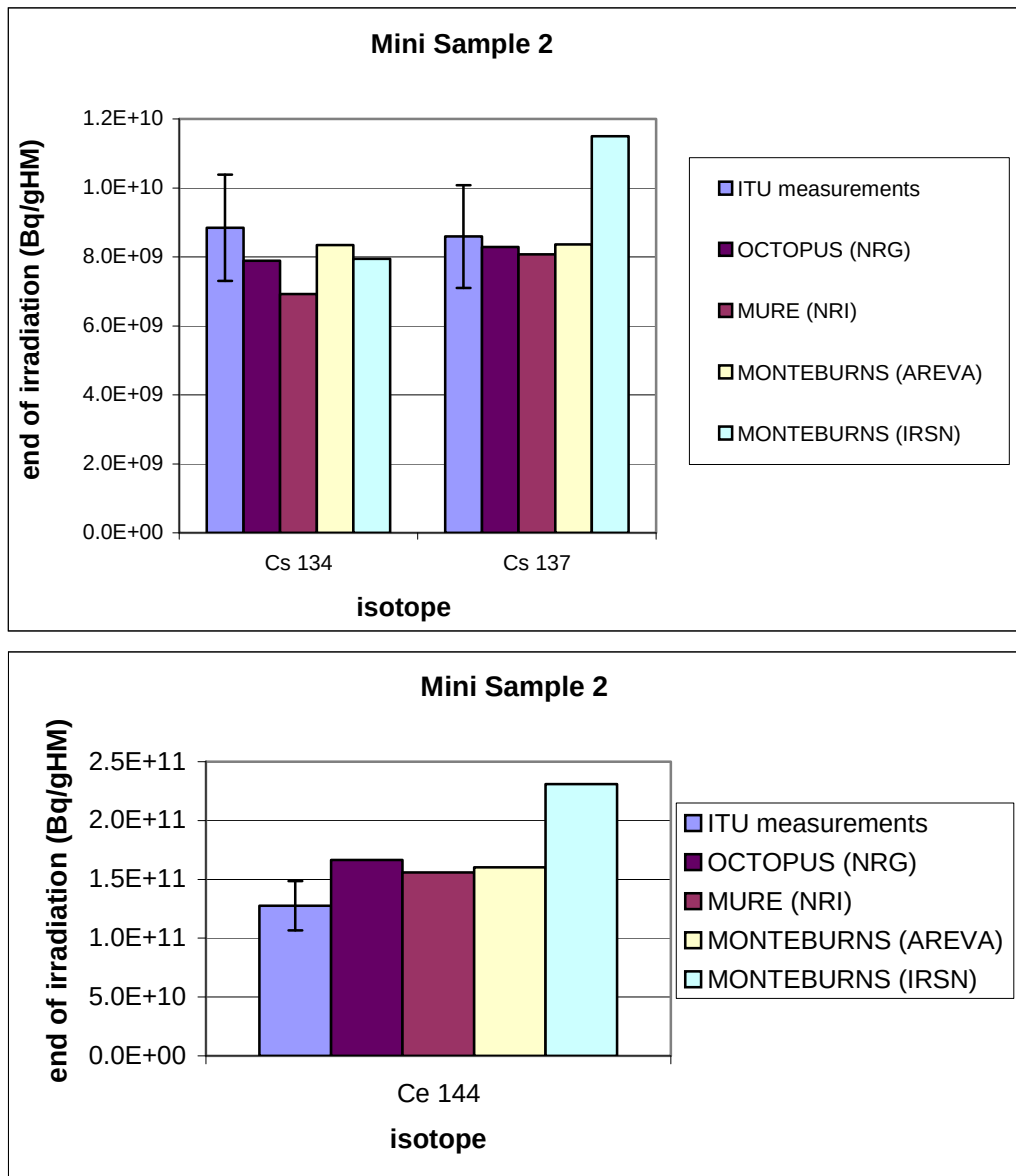


Figure 5. Experimental and calculational results for Cs 134, Cs 137 and Ce 144. Mini Sample 2.

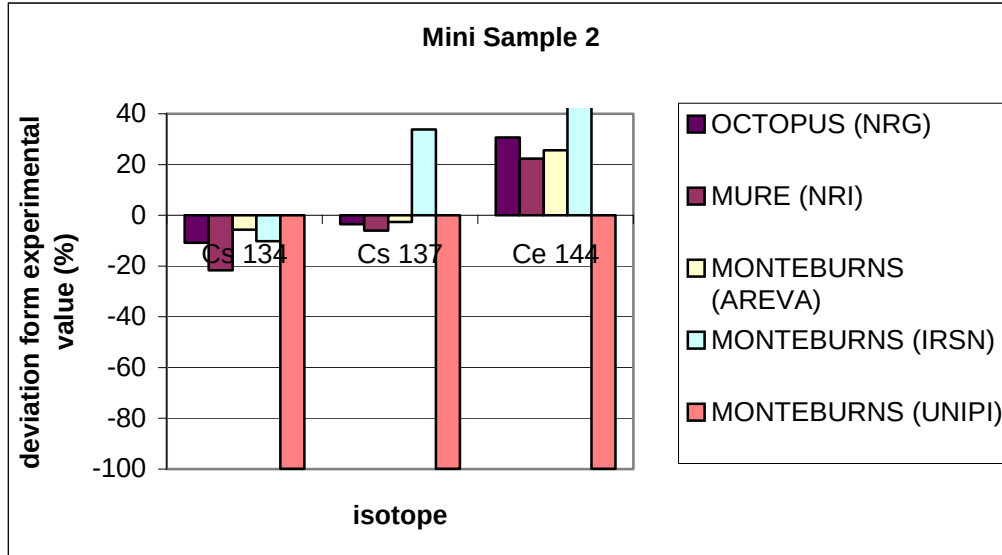


Figure 6. Deviation of the calculational results from the experimental value.

The MONTEBURNS results by UNIP are very low compared to the experimental values. The MONTEBURNS results for Cs 137 and Ce 144 calculated by IRSN are high compared to the experimental values. For the other participants, the deviation from measurements is 6% or lower for Cs 137 and between 20 and 30% for Ce 144. The experimental results for Cs 134 and Cs 137 are higher than the calculational results, whereas the experimental results for Ce 144 are lower.

3.4 Fuel Pebbles

The results of the pebbles burn-up measurements and calculations can be seen in table 11 and figure 7. Table 12 shows the deviation from the experimental values of each participant's results.

Table 11. Results for the final levels of the burn-up (% FIMA) of the five pebbles 1-5.

FIMA (%)	ITU Measurements	NRG	NRI	AREVA	IRSN	UNIP
Pebble 1 (Position +11cm)	9.34	9.3	9.54	9.81	9.55	8.76
Pebble 2 (Position +4cm)	10.92 ± 0.163	10.6	10.58	10.87	10.61	9.93
Pebble 3 (Position -3cm)	11.07	11.0	10.82	11.07	10.93	10.44
Pebble 4 (Position -10cm)	11.07	10.8	10.39	10.60	10.69	10.10
Pebble 5 (Position -17cm)	9.70	9.9	9.25	9.42	9.87	9.26

The final level of burn-up in % FIMA measured by ITU vary between 9.34 for the Pebble 1 (located at the highest axial position from the core centre-line) and 11.07 for the Pebbles 3 and 4, located close to the core centre-line and just below.

As indicated in Table 11, the final levels of burn-up in % FIMA calculated by the different participants are close to the experimental values. Table 12 shows that the average deviation from the experimental results is below 7% for all participants. The OCTOPUS results by NRG show the smallest deviation from the experiment (1.7%).

Table 12. Average deviation from experiment (absolute values).

Code package	Average deviation (%)
OCTOPUS	1.7
MURE	3.7
MONTEBURNS (AREVA)	2.5
MONTEBURNS (IRSN)	2.3
MONTEBURNS (UNIP)	6.9

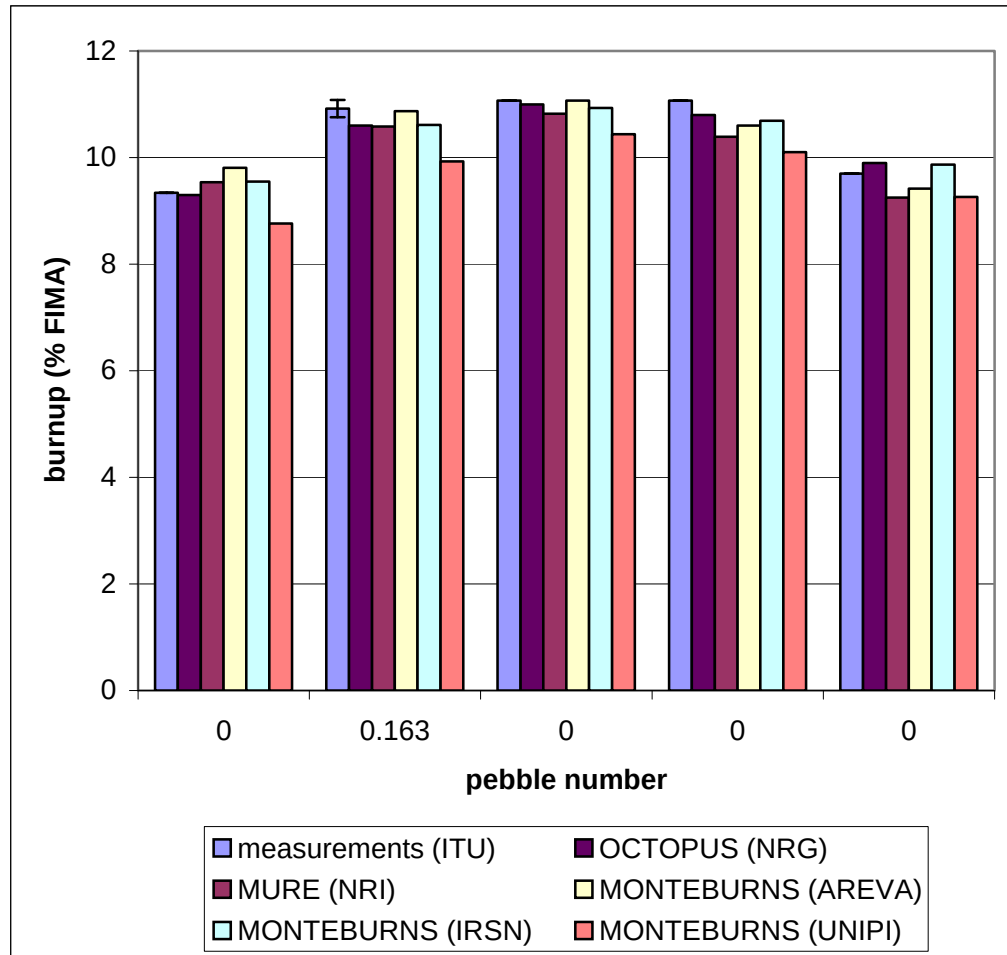


Figure 7. Burn-up in % FIMA of the five irradiated pebbles. The most left column of each pebble indicates the experimental value, and the other columns the calculational results.

The isotopic inventories (Bq/gram initial HM) of the five pebbles 1-5 at EOI are given in the five following tables (Table 13 to 17). Specific measured data are given for pebble GLE-4.2 for:

the fission products:

the vectors of: Cs, Nd, and Ce-144, Sr-90,

and for the actinides:

the vectors of: U, Pu and Np-237, Am-241, Cm-244.

Table 13. Results for pebble GLE-4.1

(*ITU data origin from one particle from an unidentified mini sample)

(** AREVA data given in g/gHM. Converted in Bq/gHM by NRG)

Nuclide	ITU(*) Measurements	End of Irradiation (Bq/gHM)				
		NRG	NRI	AREVA(**)	IRSN	UNIP
Cs						
Cs 133		0	0	0	0	0
Cs 134	1.038E+10 ± 3.32E+08	9.21E+09	8.76E+09	1.11E+10	6.00E+09	5.98E+09
Cs 135		1.73E+04	1.90E+04	2.17E+04	2.02E+04	1.38E+04
Cs 136		2.29E+09	3.14E+09	5.00E+09	5.67E+09	2.04E+09
Cs 137	1.082E+10 ± 9.74E+08	1.06E+10	1.09E+10	1.13E+10	1.02E+10	8.57E+09
Nd						
Nd 142		0	0	0	0	0
Nd 143		0	0	0	0	0
Nd 144		5.06E-05	7.38E-05	7.63E-05	7.26E-05	5.35E-05
Nd 145		0	0	0	0	0
Nd 146		0	0	0	0	0
Nd 147		2.18E+11	1.70E+11	1.83E+11	1.81E+11	2.89E+10
Nd 148		0	0	0	0	0
Nd 150		0	0	0	0	0
U						
U 234		1.77E+04	5.35E+02	2.90E+05	1.84E+04	5.18E+02
U 235		5.66E+03	5.43E+03	5.34E+03	5.79E+03	6.17E+03
U 236		3.66E+04	3.81E+04	3.95E+04	3.69E+04	3.52E+04
U 237		1.55E+11	1.29E+11	0	1.97E+11	0
U 238		1.00E+04	1.00E+04	9.96E+03	1.01E+04	1.01E+04
Pu						
Pu 238		5.70E+07	4.50E+07	6.97E+07	1.21E+08	2.47E+07
Pu 239		2.13E+07	1.88E+07	1.84E+07	1.32E+07	1.58E+07
Pu 240		2.47E+07	2.24E+07	2.49E+07	1.82E+07	1.95E+07
Pu 241		7.51E+09	5.58E+09	7.68E+09	5.06E+09	4.74E+09
Pu 242		6.41E+04	4.82E+04	7.96E+04	4.56E+04	3.82E+04
Ce 144	2.297E+11 ± 2.07E+10	2.14E+11	2.19E+11	2.26E+11	2.11E+11	1.74E+11
Sr 90		6.76E+09	9.80E+09	9.86E+09	9.19E+09	7.77E+09
Np 237		1.62E+04	1.46E+04	1.79E+04	2.69E+04	1.20E+04
Am 241		2.07E+06	2.26E+06	2.64E+06	1.84E+06	1.60E+06
Cm 244		1.23E+07	6.39E+06	1.18E+07	6.90E+06	1.47E+06

Table 14. Results for pebble GLE-4.2

(*ITU data origin from one particle from an unidentified mini sample)

(** AREVA data given in g/gHM. Converted in Bq/gHM by NRG)

Nuclide	ITU(*) Measurements	End of Irradiation (Bq/gHM)				
		NRG	NRI	AREVA(**)	IRSN	UNIPI
Cs						
Cs 133		0	0	0	0	0
Cs 134		1.17E+10	1.09E+10	1.37E+10	7.78E+09	8.20E+09
Cs 135		1.70E+04	1.88E+04	2.16E+04	1.98E+04	1.36E+04
Cs 136		2.59E+09	3.54E+09	5.59E+09	6.54E+09	2.24E+09
Cs 137		1.20E+10	1.21E+10	1.24E+10	1.15E+10	9.68E+09
Nd						
Nd 142		0	0	0	0	0
Nd 143		0	0	0	0	0
Nd 144	1.534E-04	6.19E-05	8.70E-05	8.95E-05	8.69E-05	6.48E-05
Nd 145		0	0	0	0	0
Nd 146		0	0	0	0	0
Nd 147		2.33E+11	1.77E+11	1.91E+11	1.89E+11	3.15E+10
Nd 148		0	0	0	0	0
Nd 150	3.846E-12	0	0	0	0	0
U						
U 234	2.396E+05 ± 1.209E+03	1.70E+04	5.53E+02	2.83E+05	1.90E+04	5.57E+02
U 235	4.830E+03 ± 2.450E+01	4.83E+03	4.68E+03	4.65E+03	4.96E+03	5.43E+03
U 236	4.300E+04 ± 2.179E+02	4.00E+04	4.13E+04	4.24E+04	4.05E+04	3.86E+04
U 237		1.86E+11	1.58E+11	0	2.27E+11	0
U 238	9.900E+03 ± 5.335E+00	9.97E+03	1.00E+04	9.94E+03	1.00E+04	1.01E+04
Pu						
Pu 238	1.150E+08 ± 1.168E+06	8.14E+07	5.98E+07	9.13E+07	1.52E+08	3.70E+07
Pu 239	2.047E+07 ± 8.023E+03	2.08E+07	1.87E+07	1.82E+07	1.30E+07	1.55E+07
Pu 240	2.760E+07 ± 1.021E+04	2.71E+07	2.47E+07	2.75E+07	1.96E+07	2.13E+07
Pu 241	8.638E+09 ± 4.966E+06	8.90E+09	6.47E+09	8.45E+09	5.87E+09	5.86E+09
Pu 242	1.026E+05 ± 1.113E+02	9.41E+04	6.76E+04	1.07E+05	6.55E+04	5.70E+04
Ce 144		2.40E+11	2.40E+11	2.45E+11	2.34E+11	1.94E+11
Sr 90		7.62E+09	1.08E+10	1.08E+10	1.03E+10	8.70E+09
Np 237		1.99E+04	1.74E+04	2.10E+04	3.01E+04	1.53E+04
Am 241		2.40E+06	2.60E+06	2.84E+06	2.08E+06	1.88E+06
Cm 244		2.54E+07	1.16E+07	2.13E+07	1.32E+07	3.01E+06

Table 15. Results for pebble GLE-4.3

(*ITU data origin from one particle from an unidentified mini sample)

(** AREVA data given in g/gHM. Converted in Bq/gHM by NRG)

Nuclide	ITU(*) Measurements	End of Irradiation (Bq/gHM)				
		NRG	NRI	AREVA(**)	IRSN	UNIPi
Cs						0
Cs 133		0	0	0	0	0
Cs 134	1.511E+10 ± 4.84E+08	1.27E+10	1.15E+10	1.40E+10	8.37E+09	9.37E+09
Cs 135		1.68E+04	1.87E+04	2.14E+04	1.91E+04	1.36E+04
Cs 136		2.67E+09	3.61E+09	5.76E+09	4.72E+09	2.41E+09
Cs 137	1.284E+10 ± 1.16E+09	1.25E+10	1.24E+10	1.26E+10	1.10E+10	1.02E+10
Nd						
Nd 142		0	0	0	0	0
Nd 143		0	0	0	0	0
Nd 144		6.66E-05	9.05E-05	9.23E-05	9.17E-05	6.91E-05
Nd 145		0	0	0	0	0
Nd 146		0	0	0	0	0
Nd 147		2.35E+11	1.78E+11	1.93E+11	3.03E+10	3.24E+10
Nd 148		0	0	0	0	0
Nd 150		0	0	0	0	0
U						
U 234		1.68E+04	5.51E+02	2.79E+05	1.90E+04	5.66E+02
U 235		4.52E+03	4.50E+03	4.50E+03	4.70E+03	5.11E+03
U 236		4.13E+04	4.19E+04	4.31E+04	4.16E+04	4.00E+04
U 237		1.94E+11	1.59E+11	0	2.34E+11	0
U 238		9.95E+03	1.00E+04	9.92E+03	1.00E+04	9.99E+03
Pu						
Pu 238		9.13E+07	6.34E+07	9.38E+07	1.61E+08	4.29E+07
Pu 239		2.03E+07	1.86E+07	1.76E+07	1.28E+07	1.58E+07
Pu 240		2.76E+07	2.50E+07	2.71E+07	2.01E+07	2.23E+07
Pu 241		9.18E+09	6.58E+09	8.64E+09	6.06E+09	6.48E+09
Pu 242		1.06E+05	7.19E+04	1.12E+05	7.00E+04	6.91E+04
Ce 144	2.704E+11 ± 2.43E+10	2.50E+11	2.44E+11	2.50E+11	2.13E+11	2.03E+11
Sr 90		7.93E+09	1.10E+10	1.10E+10	1.06E+10	9.13E+09
Np 237		2.11E+04	1.81E+04	2.13E+04	3.09E+04	1.71E+04
Am 241		2.47E+06	2.65E+06	2.83E+06	2.14E+06	2.10E+06
Cm 244		3.20E+07	1.29E+07	2.24E+07	1.61E+07	4.34E+06

Table 16. Results for pebble GLE-4.4

(*ITU data origin from one particle from an unidentified mini sample)

(** AREVA data given in g/gHM. Converted in Bq/gHM by NRG)

		End of Irradiation (Bq/gHM)				
Nuclide	ITU(*) Measurements	NRG	NRI	AREVA(**)	IRSN	UNIP
Cs						
Cs 133		0	0	0	0	0
Cs 134	1.469E+10 ± 4.70E+08	1.22E+10	1.04E+10	1.27E+10	7.81E+09	8.76E+09
Cs 135		1.68E+04	1.87E+04	2.14E+04	1.95E+04	1.36E+04
Cs 136		2.59E+09	3.34E+09	5.48E+09	6.40E+09	2.42E+09
Cs 137	1.284E+10 ± 1.16E+09	1.23E+10	1.19E+10	1.21E+10	1.16E+10	9.99E+09
Nd						
Nd 142		0	0	0	0	0
Nd 143		0	0	0	0	0
Nd 144		6.46E-05	8.49E-05	8.63E-05	8.84E-05	6.72E-05
Nd 145		0	0	0	0	0
Nd 146		0	0	0	0	0
Nd 147		2.33E+11	1.73E+11	1.90E+11	1.88E+11	3.21E+10
Nd 148		0	0	0	0	0
Nd 150		0	0	0	0	0
U						
U 234		1.69E+04	5.37E+02	2.85E+05	1.84E+04	5.65E+02
U 235		4.64E+03	4.79E+03	4.80E+03	4.89E+03	5.23E+03
U 236		4.07E+04	4.07E+04	4.19E+04	4.09E+04	3.94E+04
U 237		1.87E+11	1.48E+11	0	2.20E+11	0
U 238		9.96E+03	1.00E+04	9.94E+03	1.00E+04	9.99E+03
Pu						
Pu 238		8.72E+07	5.48E+07	7.86E+07	1.49E+08	4.13E+07
Pu 239		2.05E+07	1.82E+07	1.79E+07	1.26E+07	1.55E+07
Pu 240		2.69E+07	2.39E+07	2.59E+07	1.96E+07	2.21E+07
Pu 241		9.04E+09	6.04E+09	8.14E+09	5.73E+09	6.17E+09
Pu 242		9.91E+04	6.14E+04	9.72E+04	6.57E+04	6.35E+04
Ce 144	2.674E+11 ± 2.38E+10	2.45E+11	2.36E+11	2.42E+11	2.34E+11	2.00E+11
Sr 90		7.79E+09	1.06E+10	1.06E+10	1.04E+10	8.94E+09
Np 237		2.06E+04	1.64E+04	1.86E+04	2.94E+04	1.65E+04
Am 241		2.40E+06	2.46E+06	2.70E+06	2.05E+06	1.97E+06
Cm 244		2.83E+07	9.73E+06	1.66E+07	1.31E+07	3.76E+06

Table 17. Results for pebble GLE-4.5

(*ITU data origin from one particle from an unidentified mini sample)

(** AREVA data given in g/gHM. Converted in Bq/gHM by NRG)

Nuclide	ITU(*) Measurements	End of Irradiation (Bq/gHM)				
		NRG	NRI	AREVA(**)	IRSN	UNIP
Cs						
Cs 133		0	0	0	0	0
Cs 134	1.150E+10 ± 3.68E+08	1.01E+10	7.89E+09	9.59E+09	6.23E+09	7.09E+09
Cs 135		1.70E+04	1.87E+04	2.13E+04	1.98E+04	1.37E+04
Cs 136		2.35E+09	2.85E+09	4.59E+09	5.53E+09	2.14E+09
Cs 137	1.124E+10 ± 1.01E+09	1.12E+10	1.06E+10	1.07E+10	1.05E+10	9.13E+09
Nd						
Nd 142		0	0	0	0	0
Nd 143		0	0	0	0	0
Nd 144		5.58E-05	7.10E-05	7.22E-05	7.60E-05	5.80E-05
Nd 145		0	0	0	0	0
Nd 146		0	0	0	0	0
Nd 147		2.22E+11	1.64E+11	1.77E+11	1.79E+11	3.06E+10
Nd 148		0	0	0	0	0
Nd 150		0	0	0	0	0
U						
U 234		1.74E+04	5.01E+02	2.99E+05	1.75E+04	5.17E+02
U 235		5.25E+03	5.61E+03	5.60E+03	5.57E+03	5.80E+03
U 236		3.82E+04	3.72E+04	3.83E+04	3.77E+04	3.69E+04
U 237		1.65E+11	1.12E+11	0	1.90E+11	0
U 238		1.00E+04	1.01E+04	1.00E+04	1.01E+04	1.01E+04
Pu						
Pu 238		6.52E+07	3.79E+07	5.55E+08	1.18E+08	2.04E+07
Pu 239		2.08E+07	1.81E+07	1.78E+07	1.25E+07	1.54E+07
Pu 240		2.57E+07	2.13E+07	2.38E+07	1.82E+07	2.04E+07
Pu 241		7.79E+09	4.94E+09	6.80E+09	4.88E+09	5.27E+09
Pu 242		7.44E+04	4.07E+04	6.41E+05	4.68E+04	4.67E+04
Ce 144	2.384E+11 ± 2.15E+10	2.26E+11	2.13E+11	2.16E+11	2.17E+11	1.84E+11
Sr 90		7.14E+09	9.55E+09	9.56E+09	9.45E+09	8.26E+09
Np 237		1.75E+04	1.30E+04	1.54E+04	2.61E+04	9.00E+03
Am 241		2.15E+06	2.03E+06	2.32E+06	1.78E+06	1.75E+06
Cm 244		1.57E+07	4.51E+06	7.64E+06	6.95E+06	2.10E+06

Figure 8 shows the deviation of the calculational results from the experimental values. The results are for Pebble 2, except for the results for Cs 134, Cs 137 and Ce 144 which are given for Pebble 3. Table 18 shows the deviation of the calculational results from the experimental results.

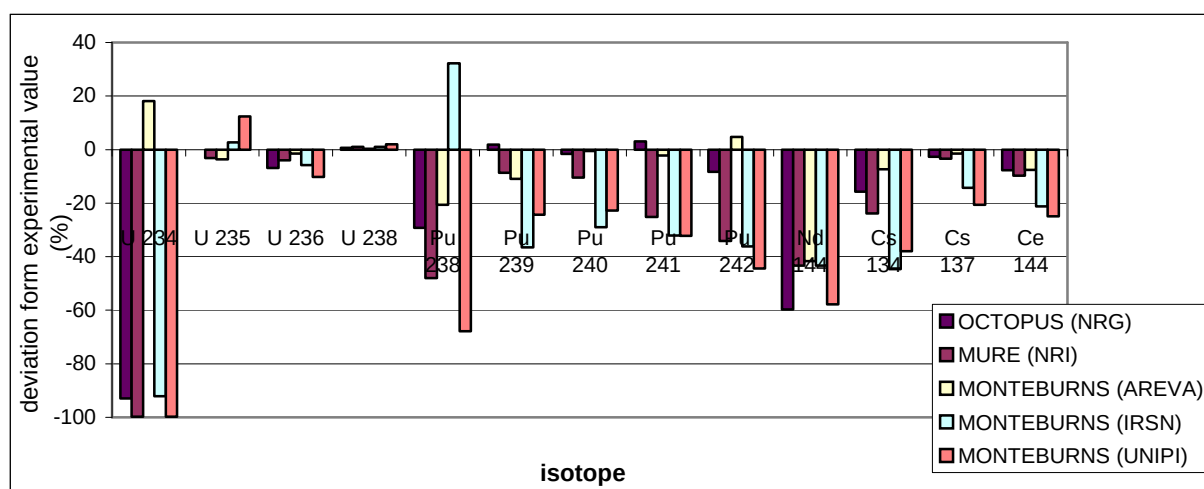


Figure 8. Deviation of the calculational results from the experimental values.

Table 18. Deviation from experiment.

	OCTOPUS (NRG)	MURE (NRI)	MONTEBURNS (AREVA)	MONTEBURNS (IRSN)	MONTEBURNS (UNIPI)
U 234	-92.9	-99.8	18.2	-92.1	-99.8
U 235	0.0	-3.1	-3.7	2.7	12.4
U 236	-6.9	-4.0	-1.5	-5.8	-10.2
U 238	0.7	1.0	0.4	1.0	2.0
Pu 238	-29.2	-48.0	-20.6	32.2	-67.8
Pu 239	1.9	-8.6	-11.0	-36.5	-24.3
Pu 240	-1.6	-10.5	-0.5	-29.0	-22.8
Pu 241	3.0	-25.1	-2.2	-32.0	-32.2
Pu 242	-8.3	-34.1	4.7	-36.2	-44.4
Nd 144	-59.7	-43.3	-41.7	-43.4	-57.8
Cs 134	-15.8	-23.9	-7.3	-44.6	-38.0
Cs 137	-2.6	-3.4	-1.5	-14.3	-20.6
Ce 144	-7.7	-9.7	-7.6	-21.2	-24.9

As can be seen in Figure 8 and Table 18,

- Most experimental results show higher figures than the calculational results.
- For the uranium isotopes, the deviation found with the experimental results is very low: less than 4% for U 235 (12% for UNIPi), less than 2% for U 238. For U 234, the calculational results are very consistent between each other, but are very different from the experimental result.
- For the plutonium isotopes, the participants's results are very different from each other. The IRSN and UNIPi results with the MONTEBURNS code package show the largest deviation with the experimental results (more than 20%). For Pu 238, the deviations are balanced in both directions: UNIPi and NRI have large (order of magnitude respectively 68% and 48%) negative deviations, whereas IRSN has a large positive deviation.
- The NRG, NRI and AREVA results for Cs 134, Cs 137 and Ce 144 are relatively close to the experimental results.

4 Conclusions

A discussion of the conditions of the calculations has taken place between the different participants to the benchmark. Some reasons to explain the differences between the results of the calculations and the experiments have been identified.

- The differences between the experimental results and the calculational results observed for U 234 is due to a wrong calculational input data for U 234 at the beginning of irradiation. The U 234 content in the enriched U was not available and the participants assumed in their calculations that the U 234 isotopic abundance was the one of U 234 in natural uranium. The complementary information asked to the Institute for Energy Research (FZ-Juelich) after the calculations show that the initial uranium enrichment of the AVR GLE-4 pebbles is in reality:

0.14 wt% for U 234, 16.77 wt% for U 235, 0.09 wt% for U 236, 83.00 wt% for U 238.

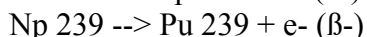
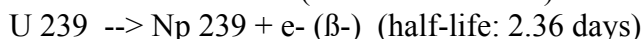
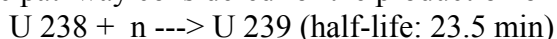
A late calculational check has showed that the U 234 concentration and activity at the end of irradiation would be higher than the results given here and closer to the experimental results.

- The differences in the final results for the plutonium isotopes have also been discussed.

* Pu 239:

The reaction rates as function of energy leading to the production of Pu 239 (via U 238) and the reaction rate leading to the fission of Pu 239 have been compared.

The pathway considered for the production of Pu 239 is:



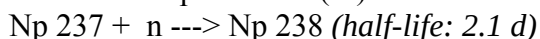
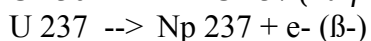
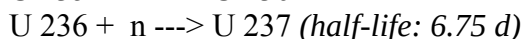
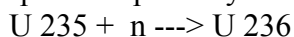
The differences seen for the reaction of capture in U 238 originate from nuclear data.

The differences seen for the reaction of fission in Pu 239 are observed around $3.15 \cdot 10^{-1}$ eV, thus in the thermal part of the spectrum. The difference in the thermal flux peak of the spectrum seen between UNIPi and NRG spectra in particular can explain this difference and is very likely related to the different normalization method chosen by the different participants.

* Pu 238:

The reaction rates as function of energy leading to the production and to the decrease of Pu 238 have been compared.

The possible pathway considered for the production of Pu 238 is:



$\text{Np 238} \rightarrow \text{Pu 238} + e^-(\beta^-)$

- The differences seen for the reaction of capture in U 235 are observed before 1 eV, thus in the thermal part of the spectrum and is very likely due to the different normalization method chosen by the different participants.
 - Not a lot of differences were observed for the reaction of capture in U 236 and Np 237.
 - The reason to explain the differences for the reaction of capture in Pu 238 could not be clearly identified.
- The differences between the experimental result and the calculational results observed for Nd 144 have also been explained. The isotopic inventories of the five pebbles and of the six mini samples have been calculated at the end of the last irradiation cycle. No further decay has been calculated. The measurements of the irradiated samples was done 2 years later. To compare the composition of the depleted materials within the pebbles and within the mini samples with the results of the calculations, ITU has calculated the inventories backwards from the measurement date to the end of irradiation. For Nd 144, ITU has assumed that the Nd 144 mass was constant in time because of the long half-life of Nd 144 ($2.1 \cdot 10^5$ years). In reality, the Nd 144 mass has grown significantly with time between the end of irradiation and the measurement date due to the Ce 144 decay (half-life of Ce 144: 284.5 days) and the Nd 144 mass at the end of irradiation is much lower than the value measured 2 years later.

5 References

General Reference:

Michael A. Fütterer, Gerard Berg, Alain Marmier, Enrique Toscano, Klaas Bakker
IRRADIATION RESULTS OF AVR FUEL PEBBLES AT INCREASED TEMPERATURE
AND BURN-UP IN THE HFR PETTEN,
Proceedings HTR2006 3rd International Topical Meeting on High Temperature Reactor
Technology October 1-4, 2006, Johannesburg, South Africa

Appendix A: Benchmark specifications

6 Introduction

6.1 Purpose of experiment

A description is given of the HFR-EU1bis irradiation experiment for testing spherical High Temperature Reactor (HTR) fuel pebbles with TRISO coated particles (UO₂ fuel kernel with successive isotropic layers of porous carbon, dense carbon, dense silicon carbide and dense carbon) for their potential for high temperature performance and high burn-up. The irradiation has been performed in the High Flux Reactor (HFR) at Petten for a period of 10 cycles in core position G3.

Five fuel pebbles from German AVR production (GLE-4 type) and six mini samples with each 10 coated particles sealed in a niobium tube have been tested in a sample holder that was loaded in a REFA-170 rig, surrounded by a strongly moderating filler element. The irradiation has started on 9 September 2004 and finished on 18 October 2005.

The characteristic irradiation parameters are: constant central fuel temperatures of approx. 1250°C, a target burn-up of 16-19% FIMA in the two central pebbles, and a maximum neutron fluence of approx. $5\text{--}7.3 \times 10^{25} \text{ m}^{-2}$ ($E > 0.1 \text{ MeV}$).

6.2 Phenomena measured and scope

During experiment: Temperatures, gas release

During the experiment, the sample holder and the REFA-containment have been connected to independent circuits for process control, in particular for manual temperature control and batch wise surveillance of fission gas release from the fuel elements.

Post_irradiation Experiments (PIE): Nuclide inventories, flux monitors, outer can

The flux monitors and the outer can are analysed at NRG-Petten in 2006.

Analysis of the nuclide inventory of the mini samples and samples taken from the fuel sphere is taking place at JRC-ITU in 2007.

7 Description of HFR facility

The irradiation has been performed in the facility of the High Flux Reactor (HFR) at Petten, The Netherlands running at its nominal power of 45 MW.

During all irradiation cycles the irradiation took place in a REFA-170 rig at position G3 in the core of the HFR. A schematic of the HFR-core can be seen in fig. 1.

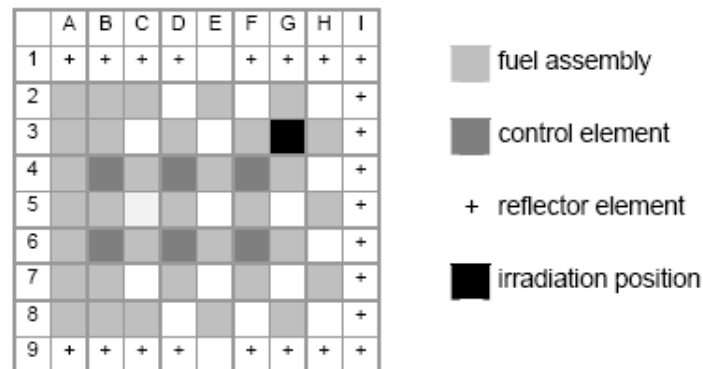


Figure 1: Standard HFR core configuration showing HFR-EU1bis in core position G3

8 Description of experiment

The experiment was housed in a REFA-170 rig with extra water in the filler space. The outer dimensions of the filler can be taken as rectangular with sizes 8.05 cm by 7.61 cm fitting in the core grid with an 8.10 cm by 7.71 cm pitch.

8.1 Experimental configuration

8.1.1 Type of assembly

A schematic of the REFA-rig with the HFR-EU1bis experiment can be seen in fig. 2.

For each cycle the orientation of the experiment was turned half a turn in order to flatten the fluence due to the fluence rate gradient near the reactor core wall.

The filler has a bore of 72.2 mm, is made of aluminium and, by milling out the corners to a rectangular section, provides a larger water fraction to enhance the thermal neutron fluence rate in the capsule, thus enhancing the pebble power and burn-up and reducing the fast neutron fluence and damage.

A cross sectional view of the REFA-filler with extra water can be seen in fig. 3.

Simplifications made are that only the portion from –27 to +27 cm below or above centre line core (between items 11 and 20 in drawing GCO-66866) of the experiment will be represented in detail.



For the surroundings only homogenized macroscopic cross sections are given (see chapter 10).

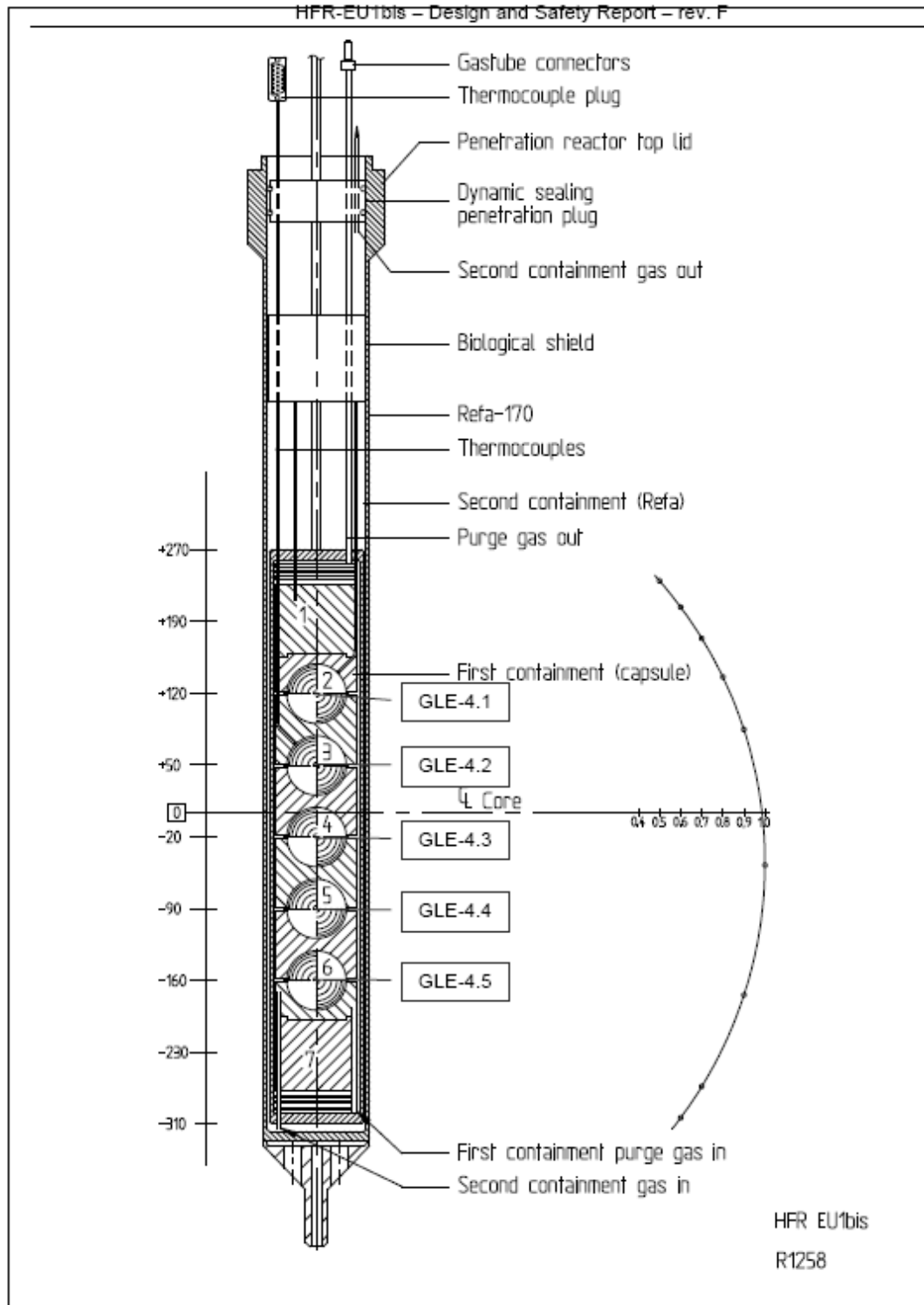


Figure 2: Conceptual sketch of HFR-EU1bis

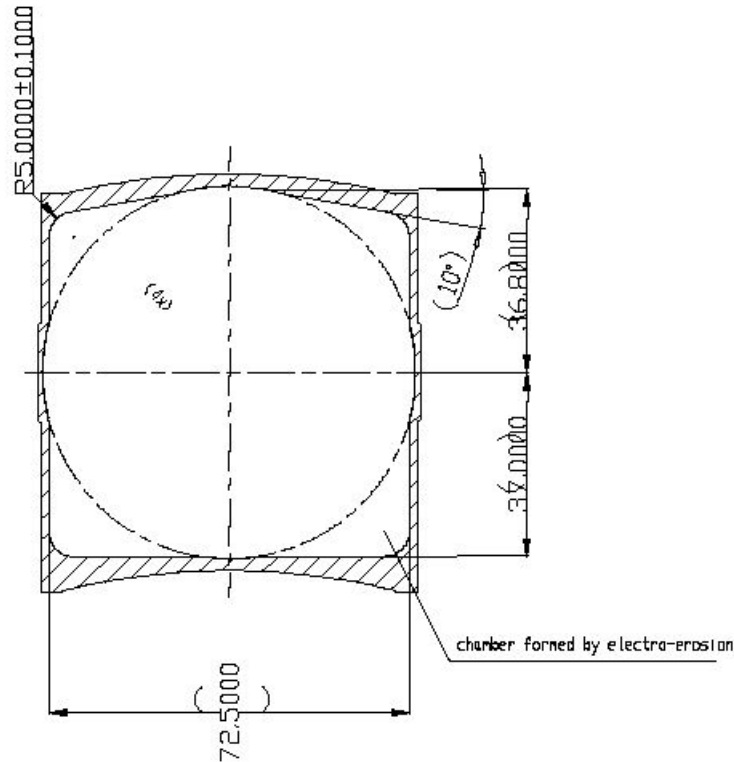


Figure 3: cross sectional view of the REFA-filler

8.1.2 Assembly details

A detailed drawing of the experiment showing the positions of the thermo-couples, mini samples and flux detectors, can be seen in fig. 4 and at a better resolution, in the drawings appendix. A reference of the parts to their drawings can be found in table 1 and 2.

item no (cf. GCO-66866 C)	description	external diameter [mm]	length [mm]	corresponding drawing no.
12	bottom plug	65.63 – 67.07 cf. Table 8	55	66871
13	½ shell		49.5	66872
14	2 ½ shells		69	66873
15	2 ½ shells		69	66874
16	2 ½ shells		69	66875
17	2 ½ shells		69	66876
18	½ shell		50.5	66877
19	top plug		74	66878

Table 1: Reference for drawings and dimensions for the half shells and end plugs

axial position low [mm]	axial position high [mm]	half shell outer diameter [mm]	cold gas gap [μ m]
-269.0	-214.0	66.24	780
-214.0	-134.0	66.24	780
-134.0	-64.0	67.05	375
-64.0	+6.0	67.07	365
+6.0	+76.0	67.01	395
+76.0	+156.0	65.63	1085
+156.0	+231.0	65.63	1085

Table 2: Axial positions referred to centre line core and diameters of the graphite parts

Atomic densities ($\cdot 10^{24}$) for the graphite of the half shells, the stainless steel (AISI 316), the aluminium parts and some structural materials are given in table 3.

Graphite		Steel 316		Aluminium	
C	8.774E-02	C	3.129E-04	Al	5.805E-02
Structurals		Cu	1.673E-03	Mg	6.021E-04
		Cr	1.536E-02	Si	5.934E-04
		Mn	1.710E-03	Ti	3.395E-05
		Fe	5.503E-02	Cr	4.691E-05
Niobium	5.555E-02	Ni	9.602E-03	Mn	2.072E-04
Nb (nat)		Mo	1.224E-03	Fe	1.456E-04
Molybden		Co	traces	Cu	2.559E-05
Mo (nat)	6.402E-02				

Table 3: Atomic densities of structural materials (atoms $\cdot 10^{24}$)

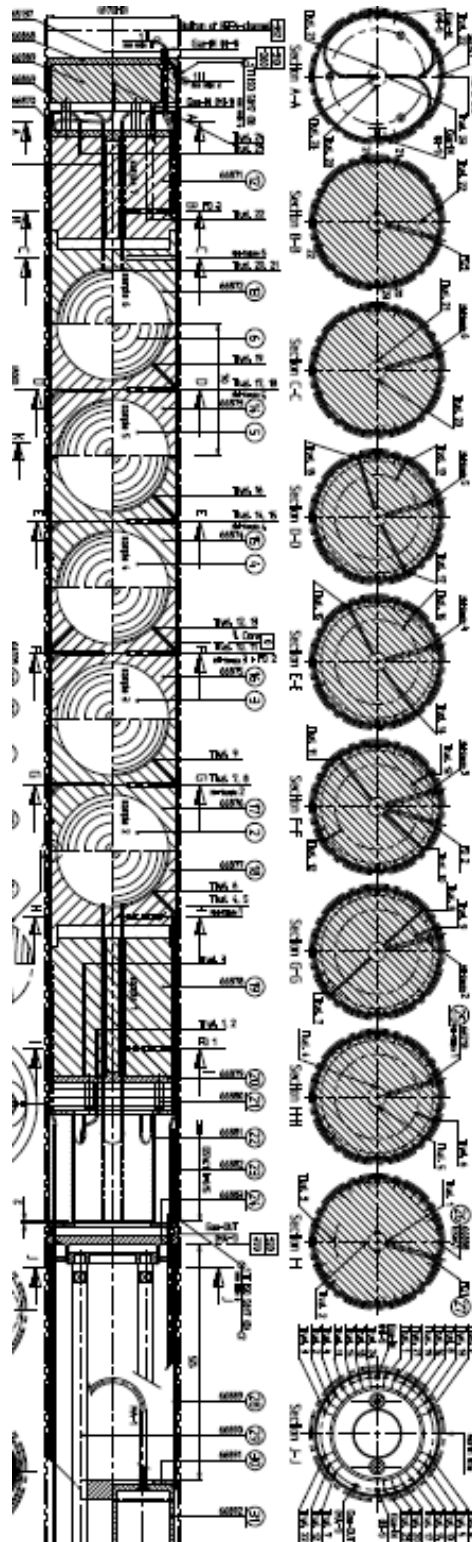


Figure 4 drawing of the HTR-EU experiment in the REFA-capsule.

8.1.2.1 Type of fuel pebbles

The irradiated fuel consists of pebbles of 60 mm diameter with LEU-TRISO coated particles of former German production, type AVR GLE-4. The fuelled zone containing the coated particles has a diameter of 4.4 cm. The pebbles are embedded in graphite shells for extra neutron moderation. Pebble and kernel characteristics can be found in table 4.

Coated Particle	
Particle batch	HT 354-383
Kernel composition	UO ₂
Kernel diameter (µm)	501
Enrichment (U-235 w%)	16.75
Thickness of coatings (µm)	
buffer	92
Inner PyC	38
SiC	33
outer PyC	41
Particle diameter (µm)	909
Pebble	
Diameter (cm)	6.0
Diameter fuelled region (cm)	4.4
Heavy metal loading (g/pebble)	6.0
U-235 content (g/pebble)	1.00 ± 1%
Matrix graphite grade	A3-3
Matrix density (kg/m ³)	1750
Temperature at final heat treatment (°C)	1900

Densities:

kernel UO ₂	= 10880 kg/m ³
buffer	= 1020
inner PyC	= 1920
SiC	= 3200
outer PyC	= 1920

Table 4: Nominal characteristic data of AVR GLE-4 pebbles

8.1.2.2 Mini samples

Six mini samples were installed in the experiment at different axial levels over the graphite moderator shells. Each contained 10 coated particles, identical to the particles in the pebbles, as shown in fig. 5. Tube and stops are made of Niobium ($\rho=8.57 \text{ g/cm}^3$).

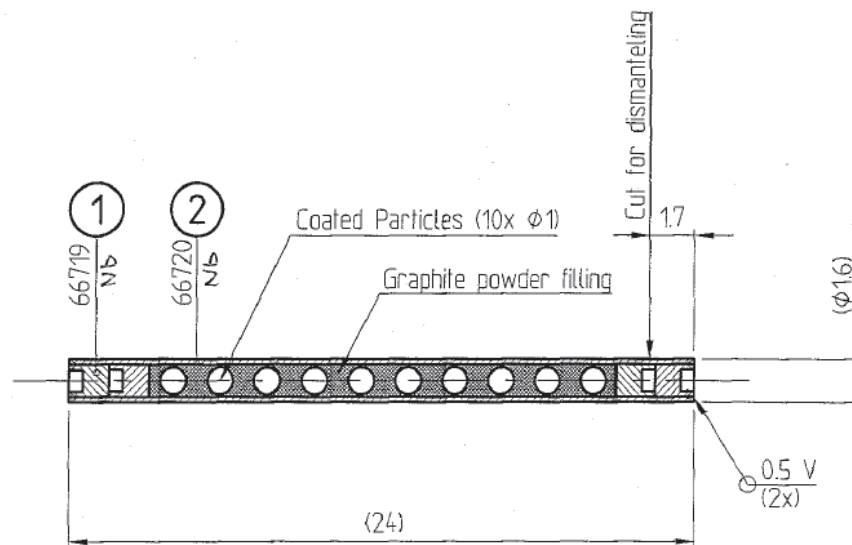


Figure 5: Drawing of the mini sample

8.1.2.3 Flux monitors and scan wire

Three flux detectors (FD) are mounted over the length of the experiment. Their contents are (masses in mg):

Code	NiCo	Fe	Ti	Nb (in mg)
FD1	0.0640	0.6825	0.9773	0.5338
FD2	0.0654	0.5717	1.0718	0.4342
FD3	0.0631	0.6189	0.9810	0.3874

Dimensions:

NiCo (1% Co) wire piece ^{*)}	d=0.1 mm, l=1.0 mm,
Fe wire piece ^{*)}	d=0.25 mm, l=1.5 mm,
Ti wire piece	d=0.56 mm, l=1.0 mm,
Nb wire piece ^{*)}	d=0.2 mm, l=1.5mm.

^{*)} encapsulated in a quartz mini-tube, d=0.9/0.6 mm, l=5 mm.

The overall arrangement of the flux detectors (monitors) is given in fig. 6.

Encapsulation of monitor set:

- quartz outer mini-tube ($\phi=1.4/1.0$ mm, $l\approx 20$ mm), closed by melting;
- quartz inner mini-tube ($\phi=0.9/0.6$ mm, $l\approx 5$ mm), closed by melting;
- stainless steel outer tube ($\phi=2.0/1.6$ mm, $l\approx 25$ mm), closed by welding.

The density of the quartz (SiO_2) is 2.20 g/cm^3

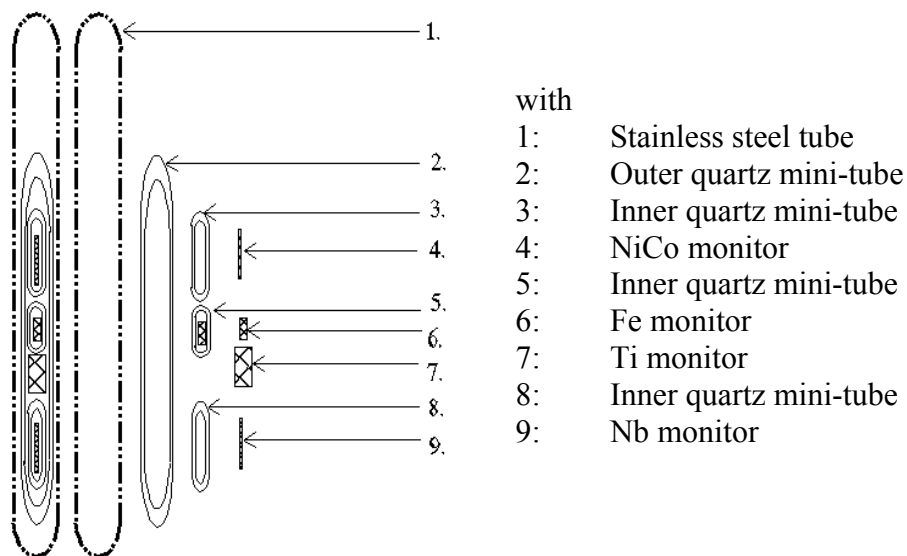


Figure 6 Composition and encapsulation details of activation monitor sets

The measured gamma's are from the following reaction products:

Fe-58 (n,g) Fe-59	Fe-54 (n,p) Mn-54
Co-59 (n,g) Co-60	Ti-46 (n,p) Sc-46
Nb-93 (n,g) Nb-94	Nb-93 (n,n') Nb-93m
Ni-58 (n,p) Co-58	

A gamma scan wire made of stainless steel AISI-316 of well known composition (table 3) was mounted in the length of the experiment in the graphite directly at the north line adjacent to the outer tube of the experiment. Its purpose was to monitor the axial distribution of the neutron fluence, but during the second irradiation cycle a short heating-up of the experiment occurred due to which the wire has been molten and made non-recoverable. Instead of this wire, gamma scans of the outer stainless steel (AISI-316L) can of the experiment (item 23 in drawing GCO-66866) have been made.

8.2 Core irradiation cycles

Surroundings, orientation of the experiment, power fractions (P-frac, in percentage of the total reactor power of 45 MW) of the different surrounding fuel and control assemblies, surrounding other experiments, duration of cycle and duration of outage (Zero power days) of the experiment are given in table 5.

Legend of the table

Cycle number			Full Power days			Zero Power days		
Exp name	Fuel ass.	Exp name				Rig type	P-frac	Rig type
Fuel ass.	HTR-EU	Fuel ass.				P-frac	Orient.	P-frac
Contrl. Ass.	Fuel ass.	Exp name				P-frac	P-frac	P-frac

Table 5: Surroundings during irradiation of HTR-EU1bis

Cyclus 04-08		24.970		3.245	
Al/Al	F1474	Al/Al	Al/Al	1.415	Al/Al
F1526	HTR-EU	CHIP	2.660	NORTH	0.615
C525C	F1530	HCPB	1.710	2.345	REFA-172
Cyclus 04-09		24.720		58.628	
Al/Al	F1465	Al/Al	Al/Al	1.415	Al/Al
F1532	HTR-EU	CHIP	2.660	SOUTH	0.590
C526C	F1523	HCPB	1.680	2.260	REFA-172
Cyclus 05-01		25.990		2.330	
Al/Al	F1476	Al/Al	Al/Al	1.515	Al/Al
F1546	HTR-EU	F1489	2.785	NORTH	1.325
C529C	F1547	Al/Al	1.750	2.540	Al/Al
Cyclus 05-02		25.670		2.210	
Al/Al	F1518	Al/Al	Al/Al	1.580	Al/Al
F1552	HTR-EU	F1470	2.740	SOUTH	1.355
C530C	F1522	Al/Al	1.710	2.420	Al/Al
Cyclus 05-03		25.790		2.330	
Al/Al	F1339	Al/Al	Al/Al	1.460	Al/Al
F1577	HTR-EU	F1338	3.010	NORTH	1.265
C531C	F1558	Al/Al	1.705	2.530	Al/Al
Cyclus 05-04		25.670		52.740	
Al/Al	F1526	EXOTIC	Al/Al	1.500	TETRA-124
F1561	HTR-EU	F1525	2.725	SOUTH	1.290
C532C	F1556	Al/Al	1.715	2.480	Al/Al
Cyclus 05-06		24.260		2.810	
Al/Al	F1521	EXOTIC	Al/Al	1.490	TETRA-124
F1568	HTR-EU	F1539	2.865	NORTH	1.255
C534C	F1574	Al/Al	1.720	2.475	Al/Al
Cyclus 05-07		25.190		26.810	
Al/Al	F1495	EXOTIC	Al/Al	1.605	TETRA-124
F1576	HTR-EU	F1513	3.205	SOUTH	1.290
C535C	F1569	Al/Al	1.800	2.560	Al/Al
Cyclus 05-08		22.190		2.400	
Al/Al	F1542	Al/Al	Al/Al	1.765	Al/Al
F1573	HTR-EU	F1546	3.245	NORTH	1.465
C536C	F1583	Al/Al	1.815	2.590	Al/Al
Cyclus 05-09		25.600		EOI	18-okt-05 8:00:00
Al/Al	F1508	EXOTIC	Al/Al	1.665	TETRA-124
F1586	HTR-EU	F1454	3.205	SOUTH	1.375
C537C	F1585	Al/Al	1.830	2.545	Al/Al

8.3 Experiment temperatures

During the irradiation the temperatures at the centres of the pebbles have been kept constant at about 1250 °C by means of adjusting the composition of a He/Ne gas mixture. The central temperature was calculated by means of the pebble surface temperature plus the (parabolic) temperature profile due to the power generated in the pebble. Surface temperatures were monitored by thermo-couples touching the non-fuelled outer region of the pebble. These temperatures were raised for every cycle to compensate for the reduction of the pebble power due to depletion.

For the 10 cycles the temperatures of the half shells (surrounding graphite) was measured as (table 6):

Cycle	T (C°)
1	967
2	1041
3	1055
4	1022
5	1071
6	1096
7	1105
8	1139
9	1104
10	1147

Table 6: Cycle averaged temperatures of the graphite that surrounds the pebbles.

These temperatures resulted in averaged central pebble temperatures for the pebbles GLE-4.1 – GLE-4.5 of:

1209, 1242, 1251, 1248, 1224 °C respectively for all cycles.

The temperature during the irradiation cycles for the mini samples and flux detectors can be taken the same as the graphite temperatures.

The graphite block on top of the sample holder (sample 1) measured 750 C° while the graphite at the bottom (sample 7) had an average temperature of 850 C° during irradiation.

The stainless steel REFA containment tube and the aluminium filler with moderating water are on cooling water temperature of 50 C°.

9 Experimental limitations or shortcomings

The entire experiment was housed in a closed containment, which prohibited flux monitor replacements by cycle.

The HFR-core is too complex to be given in detail and third party experiments are placed in it as well, of which the characteristics are not public. Therefore the HTR-EU experiment is given in detail and the eight surrounding core positions are given as sets of homogenised macroscopic cross sections. The marked area in fig. 7 indicates the region of interest.

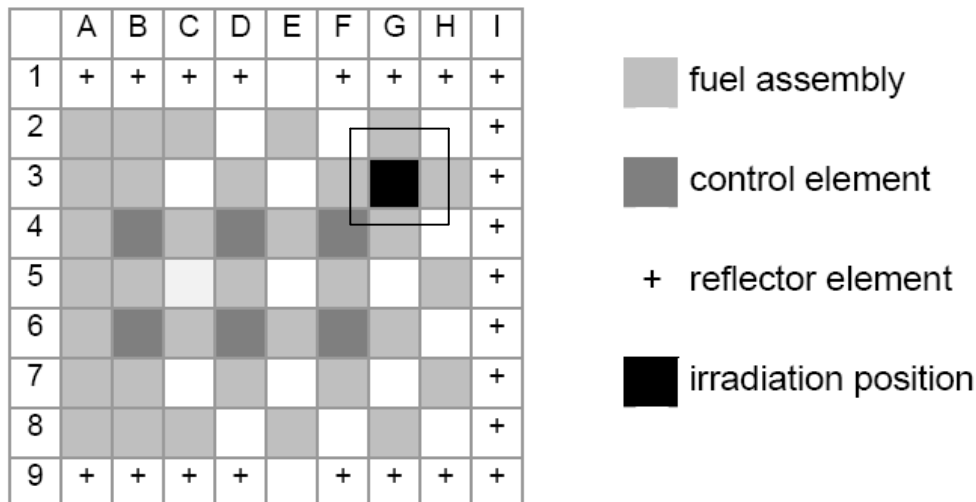


Figure 7: Area of interest for core position G-3.

10 Neutron cross sections

Group wise neutron cross sections will be provided for the eight surrounding positions for core position G-3. Materials for which macroscopic cross sections will be defined for each cycle consist of a quarter of the corner neighbours and for half of the side neighbours (fig. 8). By means of MCNP calculations with detailed descriptions of these surroundings, homogenised cross sections are generated for a number of levels (16) in the axial direction and in a number of neutron energy groups (172): the file CSXfiles.zip. An ASCII-file with the group wise macroscopic cross sections and a MCNP-library, with the same cross sections in ACE format is delivered as well: the file CSXfiles_group.zip. Used material or zone numbers can be found in table 7.

Axial position [cm]	F4	G4	H4	F3	G3	H3	F2	G2	H2
30 → 45	136	137	138	139	140	141	142	143	144
22 → 30	127	128	129	130	131	132	133	134	135
14.5 → 22	118	119	120	121	122	123	124	125	126
11 → 14.5	109	110	111	112	113	114	115	116	117
7.5 → 11	100	101	102	103	104	205	106	107	108
4 → 7.5	91	92	93	94	95	96	97	98	99
0.5 → 4	82	83	84	85	86	87	88	89	90
-3 → 0.5	73	74	75	76	77	78	79	80	81
-6.5 → -3	64	65	66	67	68	69	70	71	72
-10 → -6.5	55	56	57	58	59	60	61	62	63
-13.5 → -10	46	47	48	49	50	51	52	53	54
-17 → -13.5	37	38	39	40	41	42	43	44	45
-20.5 → -17	28	29	30	31	32	33	34	35	36
-25 → -20.5	19	20	21	22	23	24	25	26	27
-30 → -25	10	11	12	13	14	15	16	17	18
-45 → -30	1	2	3	4	5	6	7	8	9

Table 7: Zone numbers for the homogenised group cross sections as used in the data files

Four sets of cross sections are given and should be used for the following cycles:

CYCLE0408: for cycle 04-08,

CYCLE0409: for cycle 04-09,

CYCLE0503: for cycles 05-01, 05-02, 05-03, 05-08,

CYCLE0504: for cycles 05-04, 05-06, 05-07, 05-09.

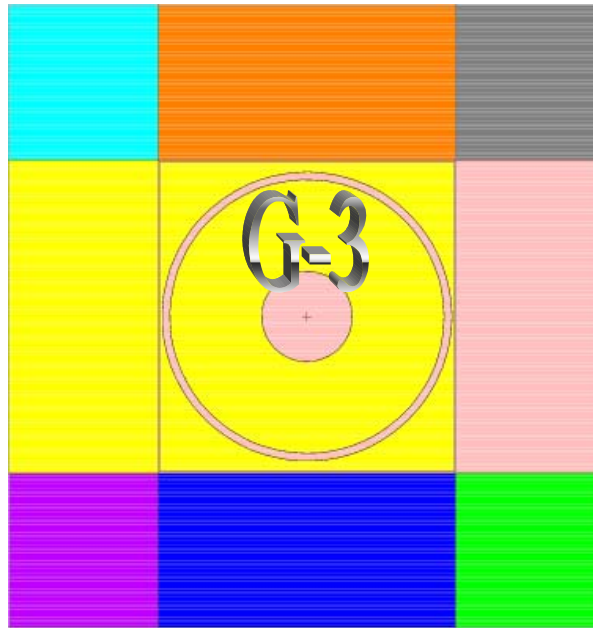


Figure 8: Material definition areas around core position G-3.

11 Phenomena to be calculated

11.1 Description of results and analysis

11.1.1 Flux monitors

The reaction rates of the flux monitor sets are to be calculated. Spectral indices can be obtained from the different monitor material activities as stated in chapter 3.1.2.3 above.

The specific reaction rates are to be given in reactions per atom per second for the monitor material.

Measured values are to be found in file MONITORS at the SINTER-RAPHAEL site.

Due to an erroneous handling of the gas mixture system to control the temperature, during a short time in the second cycle a fast heat-up caused the flux monitor in the middle of the experiment (FD2) to melt and is not available anymore for experimental verification.

11.1.2 Outer can

Also due to this fast heat-up caused the scan wire to melt and is not available anymore for experimental verification, but instead of this wire the outer can of the experiment has been scanned.

Results of a scan of the entire experiment, including the fuel spheres and the half-spheres are given in EXCEL-file T01085b which shows the distribution of a number of fission products and the activity of Mn-54 and Co-60, typical for the stainless steel outer can, revealing the position of the fuel spheres in relation to the outer can.

After removing the content of the experiment from the can new scans have been obtained using an insert of lead in the can to avoid to 'see' the backside of the tube. First a scan along an arbitrarily orientation (65° clockwise from North) of the tube, then one circumferential scan at the height of maximum Co-60 activity and a scan along the 200° orientation where the Co-60 and Mn-54 activities are in anti-phase.

Results of the axial scans can be found in the EXCEL-file T01263b and for the circumferential scan in file T01258b.

Note that the axial position in the scans of T01085b and T01263b do not coincide but can be matched by means of the Mn-54 and/or Co-60 distribution present in both files. Doing so one finds a shift of 75 mm.

The left side of the distributions is always the bottom of the experiment. All countings are relative and are not corrected for decay during/after irradiation.

The 'dog-bones' at either end-sides in the axial scans of T01263 are due to the limited length of the lead pillar central in the tube, so part of the activity seen are from the rear-side of the can. The EXCEL-files can be found on the SINTER-RAPHAEL site.

The relevance of the Mn-54 activity distribution is the sensitivity for the fast neutron fluence ($E > 2$ MeV) whereas the activity of Co-60 is indicative for the thermal fluence.

The activity of Co-58 which is an indicator for the fast fluence as well is hampered by the fact that due to its short life-time (70 days) relative to the duration of the irradiation it is only sensitive for the final stage of the experiment and by the effect that the intermediately formed Co-58m has a huge cross section of 145000 barns (2200 m/s) and will be partly depleted during its life-time of about 9 hours.

To be calculated are the axial profiles (relative) of the thermal and fast fluence by means of the activity in a relevant number of points along the experiment (from -20 cm to + 20 cm from centre-line core) for the relevant isotopes Co-60 and Mn-54.

11.1.3 Mini samples

To be calculated are the isotopic inventories (gram/gram initial HM) of the coated particles in the six mini-samples 1-10 at end of irradiation (EOI). Specific measured data to be obtained for:

the fission products:

the vectors of: Cs, Nd, and Ce-144, Sr-90,

and for the actinides:

the vectors of: U, Pu and Np-237, Am-241, Cm-244.

Measured data can be found on the file SAMPLES on the SINTER-RAPHAEL site.

11.1.4 Fuel pebbles

To be calculated are the isotopic inventories (gram/gram initial HM) of the five pebbles 1-5 at EOI. Specific measured data to be obtained for:

the fission products:

the vectors of: Cs, Nd, and Ce-144, Sr-90,

and for the actinides:

the vectors of: U, Pu and Np-237, Am-241, Cm-244.

With a hollow drill (inner/outer diameter 7.0/9.0 mm) samples have been drilled from the GLE-4.2 pebble in the vertical orientation through the middle point of the sphere. Measured data from these samples can be found on the file PEBBLES on the SINTER-RAPHAEL site.

Appendix B Details provided by participants

NRG

1. Name and address of participants

Florence Charpin-Jacobs, charpin@nrg-nl.com
Alik van Heek, vanheek@nrg-nl.com
Steven van der Marck, vandermarck@nrg-nl.com

2. Establishment

NRG-Petten, The Netherlands

3. Name of code system and computational method

MCNP Monte Carlo code iteratively coupled via OCTOPUS to depletion code FISPACT

4. Reference to the code system

J.F. Briesmeister (Ed.), MCNP - A general Monte Carlo N-Particle transport code, Version 4C, Technical Report LA-13709-M, LANL, USA (2000); J.S. Hendricks, MCNP4C3, Report X-5:RN(U)-JSH-01-17, LANL, USA (2001)

5. Cross section libraries

ENDF/B-VI and special purpose OSCAR-library

6. Further useful remarks

Number of cycles: 1000
Number of histories per cycle: 300000

Next Participant

IRSN

1. Name and address of participants

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2. Establishment

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Leclerc 92262 Fontenay-aux-Roses

3. Name of code system and computational method

MCNP5 Monte Carlo code iteratively coupled via MONTEBURNS 2.0 or VESTA to
depletion code ORIGEN 2.2

4. Reference to the code system

J.F. Briesmeister (Ed.), MCNP - A general Monte Carlo N-Particle transport code, Version 4C, Technical Report LA-13709-M, LANL, USA (2000)

D. L. Poston, and H. R. Trellue:

User's Manual, Version 2.0 for MONTEBURNS Version 1.0, LA-UR-99-4999 (September 1999)

S. Ludwig:

ORIGEN2, Version 2.1 (August 1, 1991) Release Notes (revised May 1999)

5. Cross section libraries

JEF-2.2 continuous cross section generated with NJOY 99.259.