

BENCHMARK COMPARISONS OF CALCULATIONS OF LWR FUEL CELLS WITH URANIUM-FREE FUELS

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ABSTRACT

An effective way to reduce the large quantities of Pu currently accumulated worldwide would be to use uranium-free fuel in LWRs so that no new Pu is produced. Such a possibility could be provided by an LWR fuel consisting of Pu in a neutronically inert matrix. It may be necessary to add a burnable absorber in order to reduce the reactivity swing during burnup. The methods and data currently used for LWR analyses have not been tested in conjunction with such exotic fuel materials. A benchmark exercise has accordingly been launched in order to compare the relative performance of different code systems and the accuracy of the basic data. The results obtained indicate a fair agreement in k_{∞} both at beginning of life (BOL) and after 1200 days of irradiation (end of life, EOL) under conditions representative of a present-day PWR. At BOL, the fuel temperature coefficients agree fairly well among the different contributions, but unacceptably large differences are observed at EOL. The void coefficients agree well for low voidage, but for void fractions greater than 90% there are significant effects due to the cross sections libraries used. The agreement in the calculated boron worths is good.

I INTRODUCTION

The operation of nuclear power plants has led to the accumulation of large quantities of plutonium worldwide. The dismantling of nuclear weapons contributes further to the currently recognised need to reduce plutonium stocks. It is also acknowledged that the accumulated Pu-quantities represent a large energy resource if used in power reactors. Since several years, some LWRs have been partially loaded with mixed-oxide (MOX) fuel assemblies. However, this method allows to stabilize the total quantity of Pu, but not to reduce it, the production of new Pu through conversion of ²³⁸U being approximately the same as the amount destroyed ("self-generated mode").

The reduction of Pu would be much more efficient if uranium were replaced by an inert matrix. Several studies have identified inert matrix materials which could be suitable from the viewpoint of irradiation behaviour [1], [2], [3], [4], [5]. From the point of view of the neutron physics, these fuels are characterized by reduced values for the fuel temperature coefficient (FTC) and the delayed-neutron fraction β_{eff} [3].

However, it seems possible to design a reactor core entirely

consisting of inert matrix fuel assemblies, on condition that the reactivity changes with burnup are reduced by adding a suitable burnable poison [6], [7], [8] or thorium [3] to the fuel. However, it is important to point out that, from the neutron physics viewpoint, such new types of LWR fuel cells are very different from standard UO₂ or MOX cells. Computational methods and data are well tested and qualified for the latter, but there exist no appropriate experiments for validating calculations for the former. The need to check the accuracy of design calculations for Pu-burning LWRs without uranium has led to the definition of a numerical benchmark exercise, results for which are presented in the present paper.

II BENCHMARK DESCRIPTION

The configurations considered are infinite arrays of fuel rods with fuel materials of different compositions. The rods have an outer diameter of 9.5 mm, the fuel in each case being 8.2 mm-diameter pellets of PuO₂ mixed with other ceramic materials. Four different compositions covering - from neutronic as well as material technology points of view - a range of potential candidates for U-free fuels have been studied:

1. PuO₂-Al₂O₃-ZrO₂-MgO (0.5 g Pu/cm³)
2. PuO₂-Al₂O₃-ThO₂-MgO (0.6 g Pu/cm³)
3. PuO₂-ZrO₂-Er₂O₃(0.7 g Pu/cm³)
4. PuO₂-ZrO₂-¹⁰B (0.7 g Pu/cm³)

Reactor-grade (RG) plutonium was considered for all compositions (the corresponding cells are called RG-1, RG-2, RG-3 and RG-4 respectively). In addition, compositions 1 and 2 were also calculated with weapons-grade (WG) Pu (the corresponding cells are called WG-1 and WG-2). The clad is zircaloy, and the moderator is water under operating conditions typical of a PWR. The burnup calculations were done with a power density of 15 kW/m for fuels 1 and 2, and 19 kW/m for fuels 3 and 4. The temperatures in fuel, clad and moderator are 600, 350 and 300°C respectively. The results compared are the multiplication factor k_{∞} , the isotopic densities of the ten most important actinides as well as those of the burnable poisons, and the reactivity coefficients for fuel temperature, void and boron. The reaction rates and the fluxes in six energy groups are also given in order to explain possible discrepancies between the participants' results.

III PARTICIPANTS AND CALCULATIONAL METHODS

Table I below shows the list of the participants and the methods and data used:

Table I: Participants and methods used

No.	Participant	Code	Basic cross sections
1	CEA	APOLLO-2	JEF-2.2
2	ECN	SCALE	JEF-2.2
3	JAERI	SRAC-95	JENDL-3.2
4	POLIMI	WIMS	WIMS-86
5	PSI	BOXER	JEF-1*

*The cross sections for zirconium are taken from ENDF/B-4

ECN, JAERI and PSI produced all the results requested. Some fuel cells were not calculated by the other participants due to missing nuclides in their cross section libraries.

IV COMPARISON AND DISCUSSION OF THE RESULTS

The results to be provided by the participants at seven irradiation points (0, 20, 100, 300, 600, 900 and 1200 days), are:

- the infinite multiplication factors k_{∞} ;

- the isotopic densities of the main actinides, and the burnable poisons in the case of RG-3 and RG-4;
- the most important reactivity coefficients:
 - the fuel temperature coefficients (FTC) for a variation of the fuel temperature of -300°C and $+300^{\circ}\text{C}$;
 - the void coefficients for four void fractions ranging from 0% to 99.9%;
 - the boron worth.

The following paragraphs describe the present situation.

A Multiplication factors k_{∞}

Table II gives the k_{∞} values and the relative differences for all cells at beginning of life (BOL, part a) and at end of life (EOL, part b). As an example, Figure 1 shows the k_{∞} curves as functions of the irradiation time for the RG-1 cell, as well as the differences of each participant's results with respect to the mean value.

At BOL, in general the discrepancies are fairly small. The influence of the cross sections libraries used are noticeable:

- the k_{∞} of both calculations based on JEF-2.2 (CEA and ECN) agree within 0.1%, except in the RG-4 case where the difference reaches 0.3%;
- the k_{∞} based on JEF-1 (PSI) are systematically $\sim 0.6\%$ higher compared to the JEF-2.2 results;
- the k_{∞} obtained with JENDL-3.2 (JAERI) are $\sim 0.3\%$ higher than the ones obtained with JEF-2.2 cross sections and they show a behaviour similar as the ones from JEF-1 (PSI), except in the RG-1 and RG-4 cases;

Table II: Infinite multiplication factors k_{∞} for each cell, and relative differences $\Delta k_{\infty}/k_{\infty}$ (%) with respect to the mean value

	WG-1		RG-1		WG-2		RG-2		RG-3		RG-4	
	k_{∞}	Δ	k_{∞}	Δ	k_{∞}	Δ	k_{∞}	Δ	k_{∞}	Δ	k_{∞}	Δ
a) at BOL:												
CEA	1.6157	-0.2	1.4511	0.0	1.4123	-0.2	1.2628	0.1	1.1001	-0.3	1.1111	0.4
ECN	1.6178	-0.1	1.4521	0.1	1.4131	-0.2	1.2628	0.1	1.0979	-0.5	1.1071	0.1
JAERI	1.6232	0.2	1.4504	-0.0	1.4245	0.6	1.2665	0.4	1.1092	0.5	1.1101	0.4
POLIMI	1.6138	-0.3	1.4373	-0.9	1.4082	-0.5	1.2499	-1.0			1.1087	-1.7
PSI	1.6263	0.4	1.4615	0.8	1.4187	0.2	1.2682	0.5	1.1085	0.4	1.1151	0.8
mean	1.61935		1.45048		1.41535		1.26206		1.10391		1.10609	
b) at EOL:												
CEA	1.0075	-1.6	0.7937	-2.6	1.0863	-1.0	0.9999	-0.4	0.8922	-1.3	0.9460	-0.7
ECN	1.0282	0.4	0.8170	0.2	1.1305	3.1	1.0427	3.9	0.9103	0.7	0.9579	0.6
JAERI	1.0337	1.0	0.8152	0.0	1.0938	-0.3	0.9954	-0.8	0.9168	1.4	0.9541	0.2
POLIMI	1.0205	-0.3	0.8391	3.0	1.0842	-1.2	0.9872	-1.7			0.9523	0.2
PSI	1.0296	0.6	0.8099	-0.6	1.0894	-0.7	0.9936	-1.0	0.8981	-0.7	0.9496	-0.3
mean	1.02391		0.81497		1.09683		1.00375		0.90437		0.95238	

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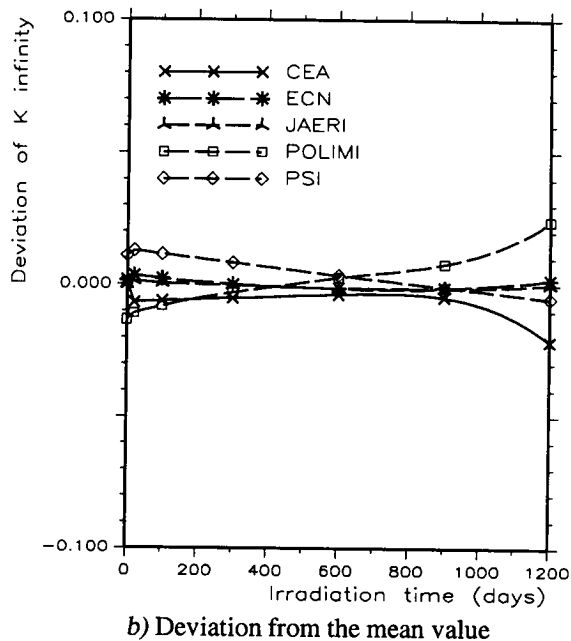
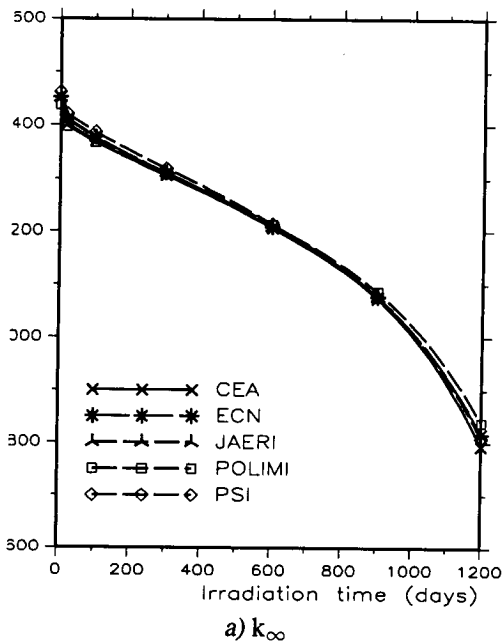


Figure 1: Fuel RG-1: infinite multiplication factor k_{∞} as a function of irradiation time

- the WIMS results (POLIMI) are systematically lower than all the others, with the largest difference (1.7%) being for RG-4.

At EOL the discrepancies increase up to about 4%. It is no longer possible to recognize trends due to the libraries: the discrepancies come mostly from the calculational methods:

- the CEA k_{∞} results are systematically lower than the mean values;
- on the contrary, the ECN values are systematically larger. In spite of using the same cross section libraries (JEF-2.2), both sets of results produced by APOLLO-2 and SCALE, respectively, show large discrepancies of $\sim 4\%$, which are caused by the burnup calculation method;
- for the other participants, the differences seem to be more random. For instance, POLIMI gives the largest k_{∞} in the RG-1 case and the smallest one for RG-2. The mean scatter in the results is large for RG-1 ($\pm 1.8\%$), WG-2 ($\pm 1.6\%$) and RG-2 ($\pm 2.0\%$). It is smallest in the RG-4 case ($\pm 0.5\%$). The presence of erbium (RG-3) does not seem to increase difficulty in the calculations: the scatter in the k_{∞} values ($\pm 1.1\%$) is more or less the same as for WG-1 ($\pm 0.9\%$).

B Isotopic densities

Table III gives the mean Pu-isotopic densities at EOL, relative to the values at BOL (N_0). Also indicated (in absolute terms) are the mean densities for the Am isotopes at EOL. In each case, relative differences for the individual results are reported with respect to the corresponding mean values. Large discrepancies are noticed for ^{239}Pu . The smaller the

rest density of ^{239}Pu , the more discrepant are the results. For the other Pu isotopes, the differences are of the order 3–4%^a. The discrepancies for the densities of ^{241}Am are considerably larger, and ^{242m}Am . These can partly be explained by the differences in the cross section libraries: both series of results based on JEF-2.2 (CEA and ECN) show similar trends. It is interesting to observe the relatively satisfactory agreement in the densities of ^{243}Am . The reason is that the production of ^{243}Am is due more to captures in ^{242}Pu than in ^{242m}Am .

C Reactivity coefficients

The reactivity coefficient with respect to a given variable V is calculated according to the following formula:

$$C_V = \frac{k_{\infty}(V_0 + \Delta V) - k_{\infty}(V_0)}{k_{\infty}(V_0)} \cdot \frac{1}{\Delta V}$$

V_0 : value of the variable V in the reference case

In the following paragraphs, reactivity coefficients are considered for an increase of the fuel temperature from 600 to 900°C, for the reduction of the moderator density by 10% and by 95%, and for the addition of 500 ppm natural boron into the moderator.

C.1 Fuel temperature coefficients

The results for the fuel temperature coefficient (FTC) between 600 and 900°C are given in Table IV at both BOL and EOL. At BOL, good agreement is achieved in the two cases WG-2 and RG-2: the discrepancies do not exceed 10%. Differences are larger in the four other cases, e.g.:

^aThe POLIMI results often show larger discrepancies since, in the WIMS model, the self-shielding of the Pu isotopes higher than ^{240}Pu is not taken into account.

Table III: Pu-isotopic densities at EOL, relative to BOL values, and absolute Am-isotopic densities at EOL

Fuel	Results	$N/N_0, \Delta N/N(\%)$				$N(10^{-24}/\text{cm}^3), \Delta N/N(\%)$		
		^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu	^{241}Am	^{242m}Am	^{243}Am
WG-1	Mean	0.067101	2.0567	8.4547	18.191	$3.8320 \cdot 10^{-6}$	$6.2270 \cdot 10^{-8}$	$9.0209 \cdot 10^{-6}$
	CEA	-10.4	-0.2	-3.7	1.4	-26.5	-35.5	3.0
	ECN	-4.2	-6.1	1.4	-0.5	5.1	-12.6	7.7
	JAERI	5.0	0.5	4.1	-1.7	15.6	12.0	-3.5
	POLIMI	4.9	1.5	-0.7	5.6			
	PSI	4.7	4.3	-1.2	-4.8	5.8	36.2	-7.2
RG-1	Mean	0.015710	0.38071	0.38314	2.1340	$3.4942 \cdot 10^{-6}$	$5.1241 \cdot 10^{-8}$	$3.1758 \cdot 10^{-5}$
	CEA	-19.6	-2.3	-7.8	1.3	-13.7	-24.9	-0.7
	ECN	-5.4	-8.5	-1.9	-2.0	-2.2	-18.1	3.4
	JAERI	-4.2	-3.6	1.6	2.7	13.4	1-6	-0.9
	POLIMI	31.9	12.5	10.1	-3.5			
	PSI	-2.7	1.9	-2.1	1.4	2.5	32.4	-1.9
WG-2	Mean	0.23513	2.4256	10.092	9.3202	$7.1671 \cdot 10^{-6}$	$1.4618 \cdot 10^{-7}$	$5.8713 \cdot 10^{-6}$
	CEA							
	ECN	-0.7	-2.3	2.3	-1.8	-0.1	-18.6	4.7
	JAERI	1.1	-0.8	2.5	-1.9	3.4	-4.0	-0.7
	POLIMI	-1.7	1.1	-2.4	8.6			
	PSI	1.3	2.0	-2.4	-4.9	-3.2	22.6	-3.9
RG-2	Mean	0.14516	0.69879	0.83641	1.5788	$1.3519 \cdot 10^{-5}$	$2.8864 \cdot 10^{-7}$	$2.9594 \cdot 10^{-5}$
	CEA							
	ECN	2.6	-1.1	2.1	-1.5	-2.4	-21.8	1.4
	JAERI	1.2	-1.2	3.7	1.7	4.1	-2.5	-0.4
	POLIMI	-6.6	0.0	-5.4	-1.2			
	PSI	2.7	2.3	-0.4	0.9	-1.7	24.3	-1.1
RG-3	Mean	0.055666	0.49149	0.60900	1.7881	$9.1489 \cdot 10^{-6}$	$1.7012 \cdot 10^{-7}$	$4.1204 \cdot 10^{-5}$
	CEA	-1.7	2.9	-3.2	-2.3	-6.3	-16.2	2.5
	ECN	3.9	-3.4	2.5	-2.9	-0.9	-16.4	0.9
	JAERI	-0.9	-2.4	2.6	3.0	8.1	4.8	-2.5
	POLIMI							
	PSI	-1.3	2.9	-1.9	2.2	-0.8	27.8	-1.9
RG-4	Mean	0.053030	0.50407	0.59906	1.8031	$8.6328 \cdot 10^{-6}$	$1.5901 \cdot 10^{-7}$	$4.0638 \cdot 10^{-5}$
	CEA	-8.7	-0.1	-4.4	1.2	-15.0	-24.8	-0.3
	ECN	-0.4	-5.1	1.7	-1.9	0.2	-15.8	2.3
	JAERI	-1.0	-3.2	3.5	3.2	12.2	8.9	-0.7
	POLIMI	11.4	6.1	0.9	-4.9			
	PSI	-1.4	2.3	-1.6	2.5	2.6	31.7	-1.3

- In the cases with reactor-grade Pu, the POLIMI FTCs are greater than the mean values by $\sim 0.25 \text{ pcm}/^\circ\text{C}$ (see the footnote a above).
- In the case RG-4, the PSI result is $0.26 \text{ pcm}/^\circ\text{C}$ (36%) more negative than the mean value.
- In the case RG-3, the ECN results is $0.21 \text{ pcm}/^\circ\text{C}$ (12%) higher than the mean value; nevertheless, the presence of erbium (RG-3) does not seem to increase the uncertainty.

At EOL, the discrepancies become much larger. As at BOL, they are the smallest in the two thorium-containing cells, where only the POLIMI result for RG-2 differs more than 10% from the mean value: it seems that the presence of thorium in the fuel stabilizes the neutron spectrum. For the other fuels, the following comments can be made:

- for the WG-1, RG-1 and RG-3 cells, the JAERI FTCs are much less negative than the others. The most outstanding difference is to be seen in the RG-1 case, for which the JAERI result is almost zero;
- in all cells, the PSI FTCs are the most negative ones;
- the CEA results are nearest to the mean values.

C.2 Void coefficients

At BOL, the void coefficients are all negative up to about 50% void fraction (see Table V for 10% void). For 95% void fraction (Table VI), the mean values are positive for the RG-1 cell, as well as for both poisoned cells, RG-3 and RG-4. For all cells, these void coefficients become strongly negative at high burnup. The relative differences between the participants are small for low voidage (up to about 50% void): $\sim 4 \text{ pcm}/\%$ void at BOL and $\sim 6-8 \text{ pcm}/\%$ void at EOL.

Table IV

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Table IV: Fuel Temperature Coefficients (C_D , pcm/ $^{\circ}$ C) between 600 and 900 $^{\circ}$ C, and differences with respect to the mean values

	WG-1		RG-1		WG-2		RG-2		RG-3		RG-4	
	C_D	ΔC_D	C_D	ΔC_D	C_D	ΔC_D	C_D	ΔC_D	C_D	ΔC_D	C_D	ΔC_D
a) at BOL:												
CEA	-1.18	0.03	-1.31	0.03					-1.63	0.03	-0.79	-0.06
ECN	-1.21	0.01	-1.32	0.02	-3.18	-0.01	-3.26	0.00	-1.45	0.21	-0.74	-0.01
JAERI	-1.37	-0.16	-1.58	-0.24	-3.23	-0.07	-3.41	-0.15	-1.73	-0.07	-0.64	0.08
POLIMI	-1.16	0.05	-1.10	0.24	-3.10	0.06	-2.98	0.28			-0.49	0.24
PSI	-1.16	0.06	-1.39	-0.05	-3.14	0.02	-3.39	-0.13	-1.83	-0.17	-0.99	-0.26
mean	-1.217		-1.340		-3.165		-3.262		-1.661		-0.730	
b) at EOL:												
CEA	-0.64	0.02	-0.69	-0.10					-1.29	0.00	-1.12	-0.06
ECN	-0.74	-0.08	-0.77	-0.18	-3.00	-0.05	-3.24	-0.14	-1.34	-0.05	-1.24	-0.18
JAERI	-0.36	0.31	-0.04	0.55	-2.88	0.07	-3.06	0.04	-1.04	0.25	-0.87	0.19
POLIMI	-0.67	-0.01	-0.49	0.10	-2.82	0.13	-2.78	0.32			-0.70	0.36
PSI	-0.90	-0.24	-0.96	-0.37	-3.09	-0.14	-3.33	-0.22	-1.49	-0.20	-1.37	-0.31
mean	-0.663		-0.592		-2.946		-3.102		-1.289		-1.060	

Table V: Void Coefficients (C_V^{10} , pcm/% void) between 0 and 10% void

	WG-1		RG-1		WG-2		RG-2		RG-3		RG-4	
	C_V^{10}	ΔC_V^{10}	C_V^{10}	ΔC_V^{10}	C_V^{10}	ΔC_V^{10}	C_V^{10}	ΔC_V^{10}	C_V^{10}	ΔC_V^{10}	C_V^{10}	ΔC_V^{10}
a) at BOL:												
CEA	-50.9	1.2	-86.5	0.8					-134	-0.2	-54.5	3.9
ECN	-50.9	1.2	-87.1	0.2	-133	0.0	-163	-1.7	-137	-2.9	-58.3	0.1
JAERI	-49.1	3.0	-85.9	1.4	-128	5.4	-158	3.5	-129	4.8	-55.7	2.7
POLIMI	-58.0	-5.9	-91.0	-3.7	-139	-5.7	-163	-1.8			-65.3	-6.8
PSI	-51.5	0.6	-86.0	1.3	-133	0.3	-161	-0.0	-136	-1.6	-58.3	0.1
mean	-52.07		-87.30		-133.0		-161.3		-134.1		-58.44	
b) at EOL:												
CEA	-114	-2.4	-89	0.0					-206	-6.7	-170	-2.4
ECN	-110	1.2	-89	-0.6	-164	6.0	-175	3.1	-198	0.9	-171	-3.0
JAERI	-113	-2.2	-90	-1.9	-171	-1.3	-182	-3.7	-194	5.3	-171	-3.0
POLIMI	-107	4.4	-85	3.4	-169	1.4	-170	8.0			-156	11.9
PSI	-112	-1.0	-89	-0.9	-176	-6.1	-186	-7.4	-199	0.4	-172	-3.5
mean	-111.2		-88.5		-170.0		-178.1		-198.9		-168.0	

For larger voidage, the discrepancies increase, the PSI values being more negative than the other ones by 10–20 pcm/% void. For the main part, this discrepancy comes from the cross section library. Although the cross section library used by PSI is based on JEF-1, the data for zirconium are taken from ENDF/B-4: in ENDF/B-4, Zr has much larger resonances than in JEF-1 in the energy range of 10–60 keV, which enhances the absorption in this nuclide when the neutron spectrum becomes very hard [9]. Thus, the calculated k_{∞} in a highly voided case is much smaller, and as a consequence the void coefficient is significantly more negative.

C.3 Boron worths:

There is good agreement at BOL between the results of all participants (see Table VII). The CEA results are systematically ~6–7% more negative than the mean values. At EOL, the discrepancies are a little larger, the largest difference (11%) being for the CEA results in the RG-1 case. Once again, the CEA values are systematically more negative than the mean values (by ~10%), while discrepancies for the other results are less than ~5%.

Table VI: Void Coefficients (C_V^{95} , pcm/% void) between 0 and 95% void

	WG-1		RG-1		WG-2		RG-2		RG-3		RG-4	
	C_V^{95}	ΔC_V^{95}	C_V^{95}	ΔC_V^{95}	C_V^{95}	ΔC_V^{95}	C_V^{95}	ΔC_V^{95}	C_V^{95}	ΔC_V^{95}	C_V^{95}	ΔC_V^{95}
a) at BOL:												
CEA	-33.0	8.7	12.2	10.2					81.4	7.8	126.6	18.6
ECN	-35.3	6.4	8.3	6.3	-296	4.3	-267	5.1	69.2	-4.4	105.0	-3.0
JAERI	-43.3	-1.6	1.0	-1.0	-298	1.8	-269	2.7	97.2	23.6	116.4	8.3
POLIMI												
PSI	-55.3	-13.5	-13.4	-15.4	-306	-6.1	-280	-7.7	46.6	-27.0	84.1	-23.9
mean	-41.73		2.01		-300.29		-272.07		73.59		108.02	
b) at EOL:												
CEA	-417	-12.3	-506	-8.8					-444	-13.2	-406	0.3
ECN	-403	1.7	-493	4.1	-362	16.2	-363	17.9	-420	10.8	-404	2.6
JAERI	-391	13.6	-491	6.5	-383	-4.8	-387	-6.2	-418	13.3	-392	14.2
POLIMI												
PSI	-408	-3.0	-499	-1.8	-390	-11.4	-393	-11.8	-442	-10.9	-424	-17.1
mean	-404.7		-497.1		-378.2		-380.9		-430.8		-406.6	

Table VII: Boron Coefficients (C_B , pcm/ppm B_{nat}) between 0 and 500 ppm B_{nat}

	WG-1		RG-1		WG-2		RG-2		RG-3		RG-4	
	C_B	ΔC_B	C_B	ΔC_B	C_B	ΔC_B	C_B	ΔC_B	C_B	ΔC_B	C_B	ΔC_B
a) at BOL:												
CEA	-4.11	-0.26	-4.40	-0.28					-3.00	-0.17	-2.61	-0.17
ECN	-3.77	0.07	-4.04	0.07	-3.21	0.01	-3.35	0.01	-2.73	0.10	-2.38	0.05
JAERI	-3.80	0.05	-4.07	0.04	-3.25	-0.03	-3.40	-0.04	-2.80	0.03	-2.43	0.00
POLIMI	-3.73	0.11	-3.96	0.15	-3.18	0.04	-3.29	0.07			-2.33	0.10
PSI	-3.82	0.03	-4.09	0.02	-3.25	-0.03	-3.40	-0.04	-2.78	0.04	-2.42	0.01
mean	-3.844		-4.113		-3.223		-3.359		-2.829		-2.435	
b) at EOL:												
CEA	-13.15	-1.28	-20.89	-2.09					-9.98	-0.69	-10.70	-0.97
ECN	-11.80	0.07	-18.60	0.20	-4.57	0.06	-5.37	0.15	-8.87	0.43	-9.41	0.31
JAERI	-11.36	0.51	-18.41	0.38	-4.66	-0.03	-5.52	0.01	-9.16	0.13	-9.46	0.26
POLIMI	-11.45	0.42	-17.49	1.31	-4.61	0.02	-5.68	-0.16			-9.43	0.30
PSI	-11.61	0.27	-18.59	0.21	-4.68	-0.05	-5.53	-0.00	-9.17	0.12	-9.62	0.10
mean	-11.874		-18.797		-4.629		-5.525		-9.297		-9.724	

V CONCLUSIONS

The neutronics analysis of the U-free fuel cells proved to be more difficult than might be expected for such "simple" cells. The calculated multiplication factors k_{∞} agree fairly well. At BOL, effects of the different cross sections libraries can be observed. On the contrary, the differences at EOL are mainly due to the calculational methods. The results are very sensitive, for example, to the time steps used during the burnup calculation.

At EOL, the differences of each participant's isotopic densities with respect to the mean values are more or less inversely proportional to the value of these densities. This effect being considered, the agreement is not worse than for a normal UO_2 or MOX fuel cell.

There is a fair agreement on the FTCs at BOL. In the case of fuel 1 (without thorium nor burnable poisons), the FTCs are reduced by a factor of ~ 2 from BOL to EOL. For fuels 2 and 3, they remain almost constant, while they increase in the case of fuel 4. The discrepancies at EOL are quite large.

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For large voidages, the void coefficients of the poisoned cells become positive. Some effects of the cross sections libraries can be noticed. In general, the void coefficients become more negative with increased burnup, except for the RG-1 case at low voidage, for which the coefficient remains almost unchanged. Discrepancies are significant mainly for the large voidage cases.

The agreement on the boron worths is good for all cells at both BOL and EOL.

This benchmark is an interesting and useful exercise in a new field of reactor physics. However, the significant spread in the present results for several important parameters of the fuel cells investigated does not currently allow clear conclusions to be drawn regarding the physics characteristics of a reactor based on U-free fuel. More information is needed on the FTCs, as well as on the void coefficients for void fractions larger than 90%. It is for this reason that this benchmark was recently proposed as an international exercise in the framework of the OECD/NEA "Working Party on Plutonium Recycling" (WPPR), [10]. A broader participation would help to reduce the remaining uncertainties in the results.

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