RERTR 2012 — 34th International Meeting on
Reduced Enrichment for Research and Test Reactors

October 14-17, 2012
Warsaw Marriott Hotel
Warsaw, Poland

Neutronics Analysis of LEU Fuel Assemblies Based on UO_2 in Maria Reactor Core

Ł. Koszuk, T. Kulikowska, M. Łuszcz, Z. Marcinkowska
Nuclear Energy Department
National Centre for Nuclear Research,
ul. Andrzeja Sołtana 7, 05-400 Otwock, Świerk – Poland

ABSTRACT

Since 2005 in National Centre for Nuclear Research the works have been led on the fuel conversion from highly enriched uranium (HEU) with 36% of 235U to low enriched one (LEU) with 235U content below 20%.

After the previous tests with U_3Si_2 LTA the same test experiments are planned for the LTA based on low enrichment UO_2. Two LTA's are to be loaded in two sequential cycles on the core periphery and reloaded to the core central positions in the next cycles. For consecutive cycles the core characteristics substantial for reactor safe operation are calculated.

The present work includes the reactivity feedbacks and reactivity worth of control rods as well as scram reactivity. They are compared to their values for the present MARIA configuration with HEU assemblies. It is shown that the core characteristics with proposed LEU fuel give as safe reactor operation as that based on HEU fuel.

INTRODUCTION

An oxide fuel (UO2) with low enrichment has been proposed for use in MARIA research reactor as an alternative for the presently introduced silicide fuel (U3Si2). It is necessary to realize a test of the proposed fuel assemblies in the reactor, as it was done with the silicide fuel. The tests comprise the irradiation of two test fuel assemblies (LTA) in the reactor under regular reactor operation The tests have to be preceded by a set of neutron physics calculations of the reactor core behavior with two LTA's, including the prediction of core parameters responsible for its safety.

The core consists of tubular fuel assemblies (cf. Fig.1) placed in a matrix of beryllium blocks, which, during present analysis, had a configuration presented in Fig. 2. Beryllium blocks have vertical cylindrical channels used for reactor control and isotope irradiation.

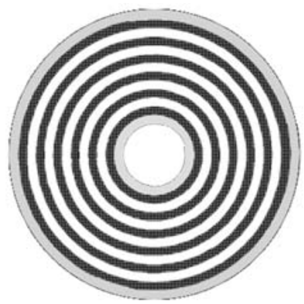

Fig. 1. MARIA fuel assembly transverse section.

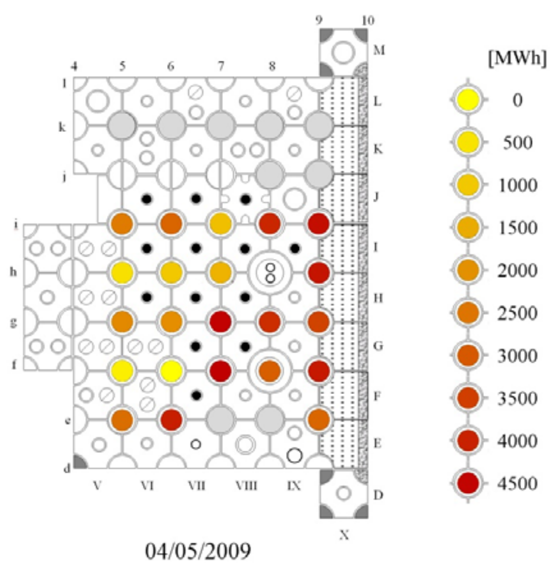

Fig. 2. Loading pattern of MARIA reactor used in the analysis.

In the figure, the capital letters and Roman numerals are used as coordinates of beryllium blocks, while small letters and Arabic numerals as coordinates of the fuel channels. The colors describe the burn-up level of particular assemblies. The positions not occupied by fuel assemblies are filled with graphite or beryllium plugs. Control and safety rod positions are marked by black circles. The presently used fuel assemblies with 36% 235U enrichment, as well as the LTA analyzed in the present paper, have the form shown in Fig. 1. The HEU and LEU assemblies differ in the thickness of layers of fuel meat and canning and in the fuel meat specification. The amount of 235U in LEU's is 485g as compared to 430g in HEU's. This is obtained by a respective increase of fuel density and fuel layer thickness.

For the above defined new type of fuel the test operation is foreseen. The test is to be carried out in the same way as it was done for the CERCA fuel in 2009. It means that two test assemblies (LTA's) will be loaded consecutively to the core periphery (position i5) and subsequently moved to the core center. The steps of that procedure are shown in Fig. 3. The two LTA's are numbered I and II.

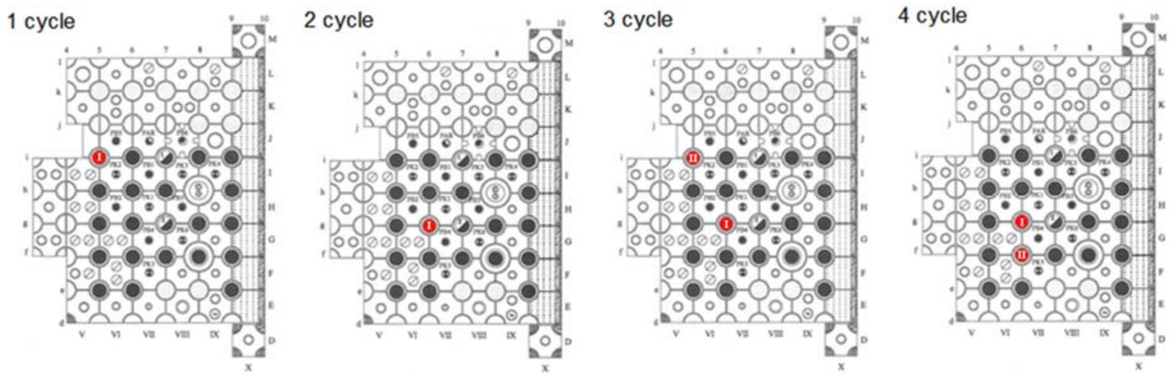

Fig. 3. Steps for the new LTA test experiment.

For such experimental test the neutron physics characteristics had to be calculated to prove the operational safety of the core. The results presented below show that the reactivity feedbacks, kinetics parameters and reactivity worth of control rods stay within the limits for the MARIA core working on HEU fuel. All calculations are carried out by the set of programs used as standard in MARIA reactor computational analysis, i.e., WIMS ANL [1] with its library and 3D REBUS [2] calculations with auxiliary programs [3].

REACTIVITY AND POWER DISTRIBUTION

It has been assumed that the calculations are to be carried out for the same reactor MARIA configuration as those for tests of CERCA fuel. The configuration of May 4, 2009, presented in Fig. 1, was used to calculate the reference HEU cycle, referred to as 'cycle 0'.

The reactivity values for that cycle, calculated and derived by the reactor staff from the control rod positions, are given in Fig. 4 showing the agreement within the experimental error.

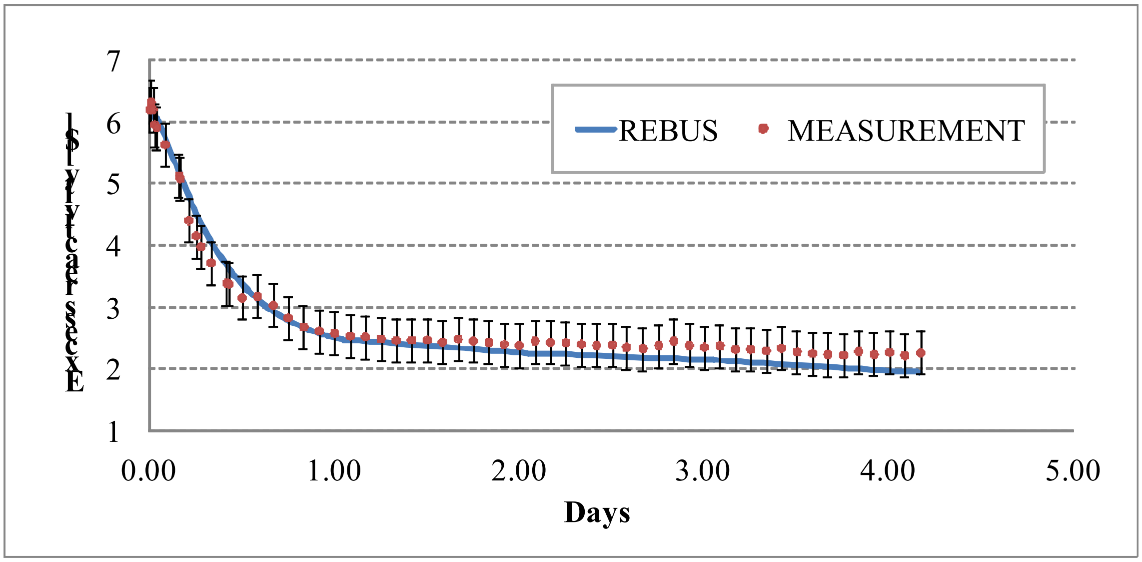

Fig. 4. Comparison of calculated and measured reactivity change in HEU cycle.

The predicted reactivity changes during 4 experimental cycles are shown in Fig. 5, where the slow reactivity decrease for subsequent cycles is seen due to normal HEU and LEU burnup.

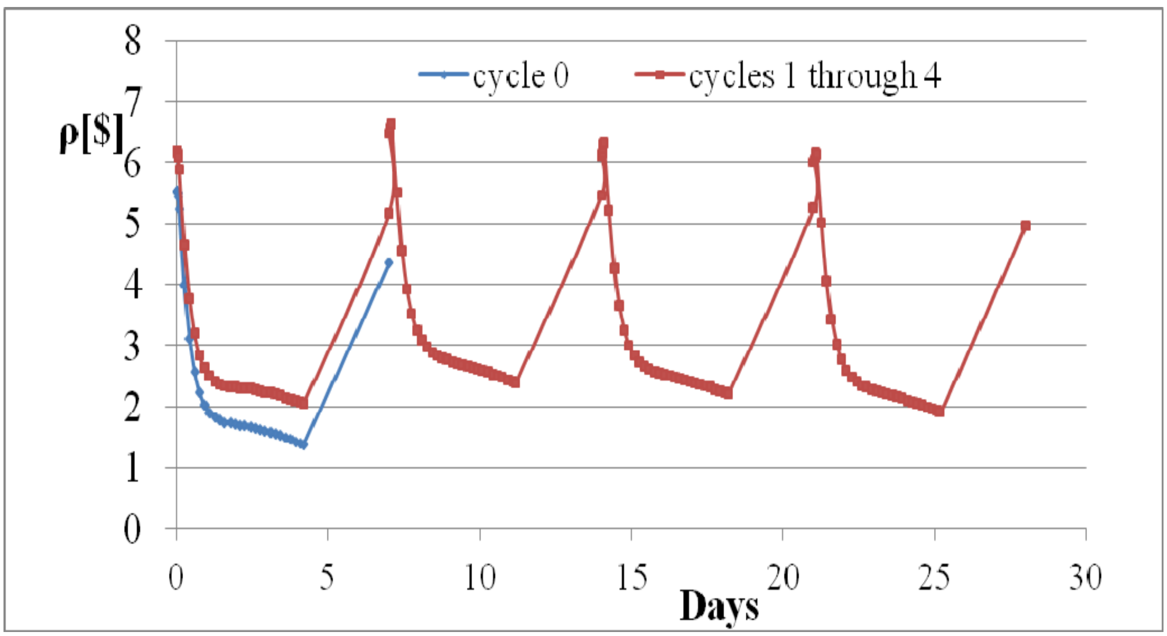

Fig. 5. Reactivity change predicted for 4 cycles.

The calculations assumed conservative, 1.0MW in the first cycle, limits on power density in LTA's and the general limit of 1.8MW in the most loaded assembly. The total reactor power was adjusted to satisfy those limits. For the first cycle it was 18MW. The calculated power density distribution in fuel assemblies is given in Fig. 6.

Cycle 1

BOC

5	6	7	8	9	
1.00	0.94	0.96	0.42	0.18	i
1.23	1.43	1.23		0.24	h
1.15	1.39	0.87	0.62	0.30	g
1.11	1.36	0.72	0.55	0.23	f
0.62	0.62			0.21	e

EOC

5	6	7	8	9	
0.98	0.94	0.96	0.43	0.18	i
1.22	1.43	1.24		0.24	h
1.15	1.38	0.88	0.63	0.31	g
1.10	1.33	0.73	0.56	0.23	f
0.61	0.62			0.21	e

Power scale [MW]

1.80	↔	2.09
1.50	↔	1.79
1.20	↔	1.49
0.90	↔	1.19
0.60	↔	0.89
0.30	↔	0.59
0.00	↔	0.29

Cycle 2

5	6	7	8	9	
0.75	0.89	0.92	0.41	0.18	i
1.19	1.41	1.22		0.23	h
1.16	1.73	0.89	0.63	0.30	g
1.13	1.38	0.74	0.56	0.23	f
0.62	0.63			0.21	e

5	6	7	8	9	
0.75	0.89	0.92	0.41	0.18	i
1.19	1.40	1.22		0.24	h
1.15	1.70	0.88	0.63	0.31	g
1.12	1.36	0.74	0.57	0.23	f
0.62	0.63			0.21	e

1.80	↔	2.09
1.50	↔	1.79
1.20	↔	1.49
0.90	↔	1.19
0.60	↔	0.89
0.30	↔	0.59
0.00	↔	0.29

Cycle 3

5	6	7	8	9	
1.00	0.91	0.93	0.41	0.18	i
1.22	1.41	1.21		0.23	h
1.14	1.68	0.86	0.61	0.29	g
1.10	1.33	0.71	0.54	0.22	f
0.60	0.60			0.20	e

5	6	7	8	9	
0.97	0.91	0.93	0.41	0.18	i
1.20	1.40	1.21		0.24	h
1.14	1.67	0.86	0.62	0.30	g
1.09	1.32	0.71	0.55	0.23	f
0.61	0.61			0.21	e

1.80	↔	2.09
1.50	↔	1.79
1.20	↔	1.49
0.90	↔	1.19
0.60	↔	0.89
0.30	↔	0.59
0.00	↔	0.29

Cycle 4

5	6	7	8	9	
0.74	0.87	0.90	0.40	0.17	i
1.18	1.38	1.20		0.23	h
1.15	1.71	0.87	0.62	0.30	g
1.14	1.50	0.74	0.56	0.23	f
0.64	0.64			0.21	e

5	6	7	8	9	
0.74	0.87	0.91	0.41	0.18	i
1.17	1.38	1.21		0.24	h
1.14	1.69	0.87	0.63	0.31	g
1.12	1.46	0.73	0.57	0.24	f
0.63	0.63			0.22	e

1.80	↔	2.09
1.50	↔	1.79
1.20	↔	1.49
0.90	↔	1.19
0.60	↔	0.89
0.30	↔	0.59
0.00	↔	0.29

Fig. 6. Power density distribution in 4 cycles for BOC and EOC.

REACTIVITY FEEDBACKS AND KINETICS PARAMETERS

The reactor response to the change of temperature was calculated separately for fuel assemblies, beryllium and graphite blocks. Such separation of the effects was necessary because MARIA reactor has one separate cooling system for fuel assemblies and another one for the pool water cooling beryllium and graphite blocks. Additionally, the water temperature coefficient was divided into the part caused by the change of neutronic properties of the medium, calculated by using different cross section values from the library, and the effect of density change, referred to as void coefficient. For BOC the core parameters after Xe stabilization (approximately one hour from reactor start-up) were chosen. The control rod positions were assumed as in the 0-th, HEU, cycle for that moment. For EOC the control rod 'out' positions have been assumed. The calculations were carried out for the following temperatures:

- 294°K, 400°K, 600°K in fuel assemblies and cooling water,
- 294°K, 400°K in fuel only,
- 294°K, 400°K in beryllium,
- 294°K, 333°K, in pool water,

with other materials at room temperature. The void coefficients for water were calculated for the operational conditions with 5% and 10% reduction of water density. The coefficients are shown in Tables 1 through 4.

Table 1. Temperature reactivity coefficients for BOC.

Coefficient [¢/C]	[°K]	HEU	LTA in i5	LTA in g6	LTA in i5 & g6	LTA in g6 & f6
FA	294-400	-2.2	-2.1	-2.0	-2.0	-2.0
	400-600	-2.0	-2.0	-1.9	-1.9	-1.9
	294-600	-2.1	-2.0	-1.9	-2.0	-1.9
Fuel	294-400	-0.1	-0.1	-0.2	-0.2	-0.2
Beryllium	294-400	1.0	1.0	1.0	1.0	1.0
Pool water	294-333	1.1	1.1	1.0	1.0	1.0

Table 2. Temperature reactivity coefficients for EOC.

coefficient [¢/C]	Zakres [°K],[%]	HEU	LTA in i5	LTA in g6	LTA in i5 & g6	LTA in g6 & f6
FA	294-400	-2.0	-2.0	-1.9	-1.8	-1.9
	400-600	-1.8	-1.8	-1.8	-1.7	-1.8
	294-600	-1.9	-1.9	-1.8	-1.8	-1.8
Fuel	294-400	-0.1	-0.1	-0.2	-0.2	-0.2
Beryllium.	294-400	1.1	1.1	1.0	1.0	1.0
Pool water	294-333	1.1	1.1	1.0	1.0	1.0

Table 3. Void coefficients at BOC.

cycle	HEU	LTA in i5	LTA in g6	LTA in i5 & g6	LTA in g6 & f6
0 – 5%	-10.1	-10.1	-10.7	-10.9	-11.1
5 – 10%	-11.3	-11.3	-11.8	-12.0	-12.2
0 – 10%	-10.7	-10.7	-11.2	-11.4	-11.6

Table 4. Void coefficients at EOC.

Cycle	HEU	LTA in i5	LTA in g6	LTA in i5 & g6	LTA in g6 & f6
0 – 5%	-7.5	-7.6	-8.1	-8.1	-8.2
5 – 10%	-8.5	-8.6	-9.1	-9.1	-9.2
0 – 10%	-8.0	-8.1	-8.6	-8.6	-8.7

The kinetics parameters, delayed neutron fractions, β, and generation times, λ, were calculated for operational conditions for BOC and EOC. They are given in Tables 5 and 6.

Table 5. Kinetics parameters for BOC.

coefficient	HEU	LTA in i5	LTA in g6	LTA in i5 & g6	LTA in g6 & f6
β_{eff}	7.02E-3	7.03E-3	7.04E-3	7.03E-3	7.04E-3
λ [μs]	144	143	140	141	140

Table 6. Kinetics parameters for EOC.

coefficient	HEU	LTA in i5	LTA in g6	LTA in i5 & g6	LTA in g6 & f6
β_{eff}	6.97E-3	6.98E-3	6.98E-3	6.98E-3	6.98E-3
λ [μs]	149	148	144	146	145

REACTIVITY WORTH OF CONTROL RODS

The control rod worth was calculated in operational conditions of the reactor and for room temperature for each of the 6 control rods, denoted by consecutive numbers*: PK1, PK2, PK3, PK4, PK5, PK6* and the automatic control rod, *PAR*. They were calculated with *PAR* half inserted and the other *PKn* in the 'out' position. The *PAR* worth was calculated as an average from the worth with other rods in the out position and the worth with other rods fully inserted.

The control rod worth calculated for room temperature had lower values and therefore they were taken as a final result, the conservative approach. It should be also remembered that the experimental worth of the rods is measured at room temperature.

The calculated control rod worth values are presented in Tables 7 and 8, for BOC and EOC, respectively. In Table 9 the control rod worth values calculated for operational conditions are compared with those obtained for the reactor in room temperature.

Table 7. Control rod worth, BOC [$].

CR	Position	Cycle 0	Cycle 1	Cycle 2	Cycle 3	Cycle 4
PK1	H7	3.62	3.55	3.69	3.64	3.64
PK2	I6	2.10	2.29	2.03	2.25	2.00
PK3	I8	1.06	1.05	0.99	1.00	0.97
PK4	I9	0.21	0.20	0.19	0.19	0.19
PK5	F7	1.42	1.33	1.36	1.30	1.42
PK6	G8	1.35	1.27	1.31	1.25	1.32
PAR	J7	0.75	0.80	0.70	0.76	0.69

Table. 8. Control rod worth, EOC [$].

CR	Position	Cycle 0	Cycle 1	Cycle 2	Cycle 3	Cycle 4
PK1	H7	3.73	3.67	3.77	3.73	3.75
PK2	I6	2.17	2.34	2.09	2.28	2.07
PK3	I8	1.10	1.09	1.03	1.03	1.02
PK4	I9	0.22	0.21	0.20	0.20	0.20
PK5	F7	1.44	1.36	1.41	1.35	1.45
PK6	G8	1.41	1.34	1.36	1.31	1.37
PAR	J7	0.79	0.83	0.73	0.78	0.72

Table 9. Control rod worth for cold and operational conditions.

CR/position		Cycle 0, BOC		Cycle 1, BOC		Cycle 0, EOC		Cycle 1, EOC	
		20°C	work	20°C	work	20°C	work	20°C	work
PK1	H7	3.62	3.72	3.55	3.65	3.73	3.84	3.67	3.55
PK2	I6	2.10	2.16	2.29	2.36	2.17	2.23	2.34	2.18
PK3	I8	1.06	1.10	1.05	1.09	1.10	1.15	1.09	0.91
PK4	I9	0.21	0.22	0.20	0.21	0.22	0.23	0.21	0.00
PK5	F7	1.42	1.47	1.33	1.37	1.44	1.48	1.36	1.17
PK6	G8	1.35	1.39	1.27	1.31	1.41	1.46	1.34	1.16
PAR	J7	0.75	0.78	0.80	0.83	0.79	0.82	0.83	0.86

An example of differential worth is given in Fig. 7 for the heaviest control rod, *PK1*. It can be seen that the curves for the reference HEU cycle is identical with those for cycle 1 and cycle 2.

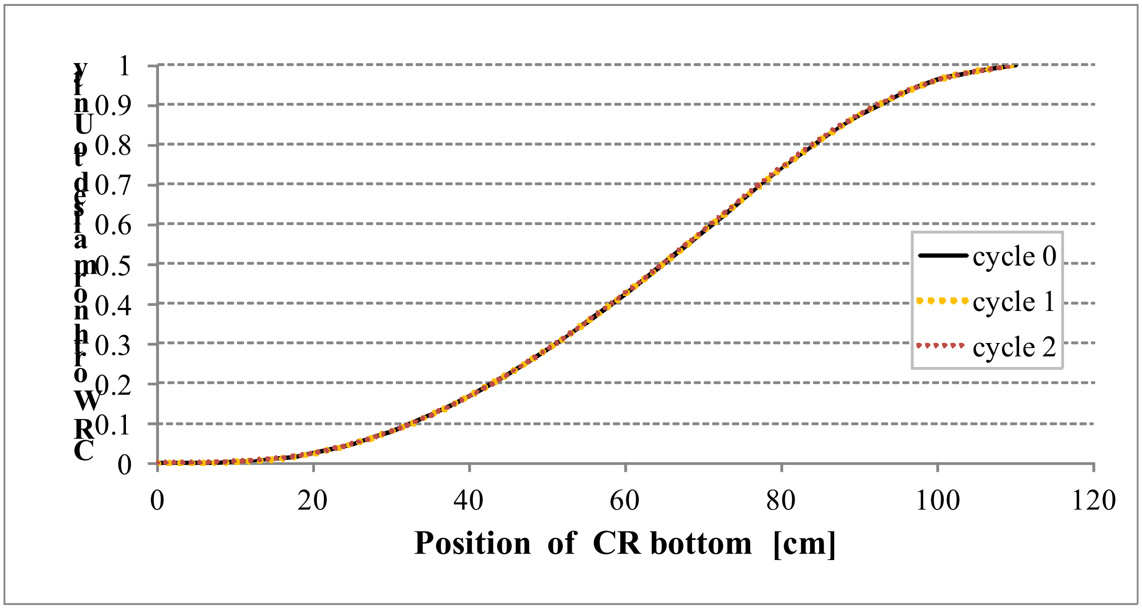

Fig. 7. Differential worth of *PK1*.

The last set of results gives the scram reactivity and is shown in Table 10 and Table 11.

Table 10. Scram reactivity, BOC [$].

Rods in	Stuck rod	HEU	LEU in i5	LEU in g6	LEU in i5 i g6	LEU in g6 i f6
PB+PK	-	21.59	21.69	21.47	21.79	21.28
PB+PK	PK1	18.72	18.82	18.43	18.75	18.33
PB	-	12.04	12.07	12.04	12.18	11.94
PB	PB2	8.01	7.98	7.87	7.93	7.84
PK	-	10.79	10.80	10.55	10.70	10.50
PK	PK1	6.98	7.04	6.65	6.83	6.67

Table 11. Scram reactivity, EOC [$].

Rods in	Stuck rod	HEU	LEU in i5	LEU in g6	LEU in i5 & g6	LEU in g6 & f6
PB+PK	-	22.35	21.69	22.09	22.36	21.99
PB+PK	PK1	19.37	18.82	18.98	19.25	18.94
PB	-	12.43	12.07	12.35	12.48	12.31
PB	PB2	8.28	7.98	8.11	8.16	8.10
PK	-	11.17	10.80	10.88	11.00	10.87
PK	PK1	7.23	7.04	6.90	7.04	6.91

SUMMARY

The goal of the presented analysis is to show that the MARIA core with LTA's introduced to the reactor core in a predefined way has reactivity characteristics as safe as the original HEU core. The goal has been achieved for the following reasons:

- The criterion on the limit on power density in newly loaded LTA is fulfilled if reactor power does not exceed 18MW,
- A weak influence of LTA's on basic safety parameters has been observed. In particular the temperature reactivity coefficients of fuel assembly are less negative by about 10% and Doppler coefficients are more negative. This stays in agreement with the previously obtained values for CERCA fuel assemblies as the discrepancies between the coefficients for the reference HEU cycle and cycles with LTA's are of the same order for both types of fuel. An example of comparison of temperature reactivity coefficients for cores with both types of LTA's is given in Table 12. The void coefficients are more negative when loaded LTA's are loaded,
- The control rod worth exhibit differences of few percent. This is valid also for the scram values. However the same has been observed for CERCA fuel case and in general those few percents have to be accepted as accuracy of calculations caused by different reactor core status. In particular the differences in control rod worth are observed between the BOC and EOC conditions,
- The differential reactivity worth of control rods is practically independent of the LTA substitution in the core.

Table 12. Temperature reactivity coefficients for BOC.

Coefficient [¢/C]	[°K]	Cycle 1		Cycle 4	
		silicide	oxide	silicide	oxide
FA	294-400	-2.3	-2.1	-2.1	-2.0
	400-600	-2.0	-2.0	-2.0	-1.9
	294-600	-2.1	-2.0	-2.0	-1.9
Fuel	294-400	-0.3	-0.1	-0.2	-0.2
Beryllium	294-400	0.8	1.0	1.0	1.0
Pool water	294-333	1.6	1.1	1.0	1.0

REFERENCES

1. Deen J.R., Woodruff W.L., Costescu C.I., Leopando L.S. (2004) WIMS-ANL user Manual, Rev.6. ANL/TD/TM-99-07.
2. Olson A.P. (2001) A User's Guide for the REBUS-PC Code. Version 1.4. ANL/RERTR/TM-32.
3. Andrzejewski K., Kulikowska T., Marcinkowska Z. (2009) (3.1) Report on Core Neutronics (SAR-5.2) and Core Reactivity Characteristics (SAR-5.3), Deliverable 3.1 under ANL Work Order 6J-00106-0003A.