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ORIGINAL PAPER

Assessment of the control rods shadow effect in the VENUS-F core

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Abstract. The partitioning and transmutation (P&T) of spent nuclear fuel is an important field of present development of nuclear energy technologies. One of the possible ways to carry out the P&T process is to use the accelerator driven systems (ADS). This technology has been developed within the EURATOM Framework Programmes for several years now. Current research in this field is carried out within the scope of 7th FP project FREYA. Important parts of the project are experiments performed in the GUINEVERE facility devoted to characterising the subcritical core kinetics and development of reactivity monitoring techniques. The present paper considers the effects of control rods use on the core reactivity. In order to carry out the evaluation of the experimental results, it is important to have detailed core characteristics at hand and to take into consideration the differences in the effect of control rods acting separately or together (the so-called shadow effect) on both the reactivity value and the measured neutron flux. Also any core asymmetry should be revealed. This goal was achieved by both MCNP simulations and the experimental results. However, in the case of experimental results, the need for calculating respective correction factors was unavoidable.

Key words: accelerator driven systems (ADS) • control rod • FREYA • GUINEVERE • reactivity

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Introduction

One of the key aspects of nuclear energy development is partitioning and transmutation (P&T) of the nuclear waste with three major benefits of the process: reduced amount of waste intended for final storage, reduced time of storage and better use of the nuclear fuel. Growing interest in P&T research could have been, therefore, observed world-widely over the last decades. This is caused by the fact that, if partial transmutation is possible in light water reactors by reusing the plutonium from the spent fuel, fully closed fuel cycle can be achieved only with new reactor designs.

There are several solutions considered for that purpose. First possibility is using fast reactors for actinide burning due to their more advantageous burning-to-production ratio of minor actinides in comparison with the reactors working in the thermal neutron spectra. Another solution is using a subcritical reactor, so-called accelerator driven system (ADS). Coupling the subcritical reactor with a proton accelerator and spallation neutron source makes it possible to have the reactor operate in a subcritical state and makes its distance to super-prompt-criticality independent from the fuel isotopic composition. It is important, because minor actinides have smaller delayed neutron fraction than compounds of classic uranium and MOX fuels, which limits the content of minor actinides in the critical reactor fuel. As a result, using ADS also reduces the needed share of dedicated actinide burners in the total installed power in nuclear power plants (from about 35% when using critical fast reactors to about 10%) [1]. As long as dedicated actinide burners are expected to be more expensive than the classic water reactors, this can be an important advantage.

The FP7-FREYA project

The project Fast Reactor Experiments for hYbrid Applications (FREYA) was started in 2011 within the 7th Framework Programme of EURATOM. It has 16 institutes as participants with SCK-CEN playing the leading role. Several aspects of actinide burners development are studied within the project, the most important being the variety of reactivity monitoring techniques for ADS and design and licensing aspects for MYRRHA.

The MYRRHA reactor (Multi-purpose hYbrid Research Reactor for High-tech Applications) will be a semi-industrial scale reactor with 50–100 MW thermal output and is scheduled to be operational in 2025 [2]. It will be the first ADS to use the spallation source and 600 MeV proton accelerator. What is important, it will be capable of operating in both subcritical and critical modes (without using external neutron source). Both these types of actinide burners are therefore investigated by the FREYA project.

Reactivity monitoring techniques are one of the key aspects of future ADS safety. For that reason, an extensive experimental program is run, where different proposed methods are being tested. All experiments are done using the VENUS-F reactor and GENEPI-3 accelerator at SCK-CEN site in Mol, Belgium.

The VENUS-F facility

The VENUS (Vulcan experimental nuclear study) reactor is located at SCK-CEN in Mol, Belgium. It has been operational since 1964, at first as a water-moderated thermal reactor. It went through several modernisation programs, last started in 2008 within the GUINEVERE project [3]. The aim was to change the reactor into a fast spectrum device and couple it with the GENEPI-3 accelerator and D-T neutron source. Since then, the reactor has been known as VENUS-F and became the world's first scale model of a subcritical reactor with a total lead core driven by a particle accelerator [3]. The accelerator can be run in continuous, pulsed and beam trips (continuous with short, periodical beam interruptions) modes.

The reactor itself is a zero-power facility using metallic highly enriched (30% ^{235}U) uranium fuel in a solid lead matrix. Inside a cylindrical, stainless steel casing, there is a 12 × 12 square grid, which can be filled with fuel assemblies, lead assemblies

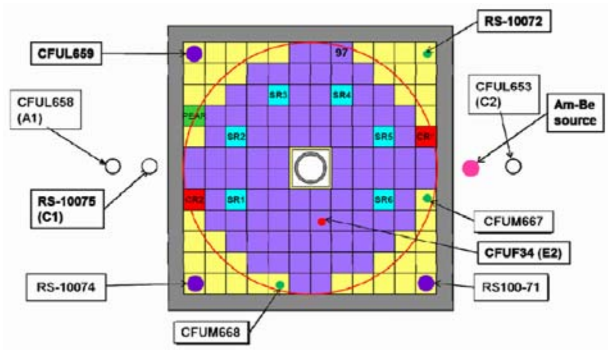

Fig. 1. VENUS-F SC1 core cross section.

and assemblies housing detectors or control (CR) and safety rods (SR). Depending on number of the fuel assemblies used, it can be operated in both critical and subcritical states with wide range of k_{eff} from 0.85 to 0.99. In the subcritical mode, the accelerator beam line and the tritium target are placed in the centre of the core. There are two control rods for smaller changes of reactivity and six safety rods.

The following study considers the critical configuration and the subcritical configuration SC1 with k_{eff} = 0.97. The cross section of the core in SC1 configuration with neutron detectors position is shown in the Fig. 1. The main goal of the study was to evaluate the effects of the control rod movement on the reactivity and the neutron flux and spectrum.

The control rods used in the VENUS-F core are placed at the perimeter of the core. There are two rods placed on the opposite sides of the core (see Fig. 1). The absorber part of the control rod assembly consists of a block made of boron carbide (B_4C), using natural boron as the neutron absorber. The height of the absorber part is 60.96 cm, which equals the height of the active fuel. It is followed by the void follower part. The whole control rod assembly is surrounded by stainless steel cladding. During the reactor operation, both control rods can be inserted in the core separately or together by moving whole respective assemblies [4].

Methodology

In the simulation part of the study, all presented calculations were done with the use of MCNP5 code and JEFF 3.1 nuclear data libraries. The reactivity of the core was calculated using the KCODE card, which is the standard function in MCNP for k_{eff} calculation [5]. The calculations of the reactivity were performed for a variety of different control rod positions. Special attention was given to the central range of the control rods movement, where the change of reactivity is linear. The neutron flux spectra in the whole volume of absorber material were also calculated.

In the experimental part of the study, only the results from the subcritical configuration were investigated. The accelerator was run in the continuous mode and the source multiplication was used to determine reactivity. In this method, reactivity is given by the formula [6]:

Table 1. Results of reactivity calculations in CRs' extreme positions

Description		Reactivity	Uncertainty	Loss of reaction	Uncertainty
		[pcm]		[pcm]	
Subcritical core	0, 0	–2922	12	–	–
	CR1	–3315	11	393	16
	CR2	–3325	11	403	16
	CR1 + CR2	–	–	796	23
	CR1&CR2	–3732	11	810	16
Critical core	0, 0	628	11	–	–
	CR1	281	13	347	17
	CR2	266	11	362	16
	CR1 + CR2	–	–	709	23
	CR1&CR2	–82	11	710	16

(1) $$\rho = \left(\frac{C_0}{C}\right)\rho_0$$

where C and C_0 are detector count rates normalised to source intensity, in the current and the reference state, and ρ_0 is the reference reactivity. It is important to notice that this method allows us only to measure relative changes of reactivity, not the reactivity itself. Therefore, the reference point count rates from CR position 479.3 mm was used, which is the point where criticality was achieved in the critical state. For the reference reactivity respective value calculated by MCNP was used.

Calculation results

The results of the first calculation show the reactivity values (see Table 1) in different CR positions. In each case, the rods were fully extracted or inserted to a depth of 60 cm. For the rod that was not inserted, the space in core was filled with lead. Then the k_{eff} was recalculated for each case. The loss of the reactivity for both rods inserted (CR1&CR2) was compared with the sum of the reactivity losses obtained for situation, when each of them was inserted separately (CR1 + CR2). It can be clearly seen that the differences are, in both cores, smaller than the respective uncertainties. Thus, the shadow effect is not visible. Also the values for both separately inserted rods fit within the range of uncertainties.

The rod worth in the VENUS-F core is rather small and more accurate method of the shadow effect analysis was needed. It is based on the analysis of the linear part of the slope (see Fig. 2) showing the relation between the rod insertion depth and the respective reactivity. In this method, the calculation of k_{eff} was done for several positions of the control rods between 20 and 47 cm depth. After obtaining the reactivity values for each position, the linear regression was used for the purpose of evaluation of the slope (see Fig. 3). Since the lines represent almost equal values of reactivity for the 20-cm depth, the reactivity at this position as well as the position were assumed to be zero and the slope of the lines was calculated again (see Fig. 4). This time for comparison of the rod worth of CR inserted separately

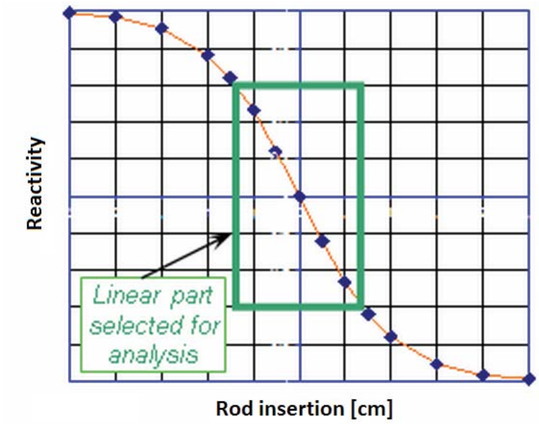

Fig. 2. Idealised curve of control rod integral worth.

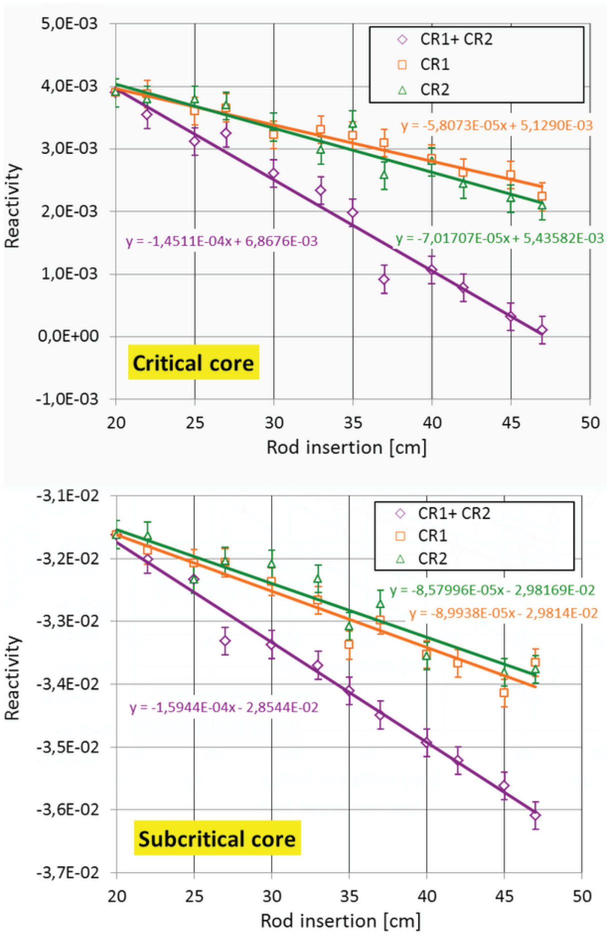

Fig. 3. Linear parts of the control rod integral worth curves for critical and subcritical core.

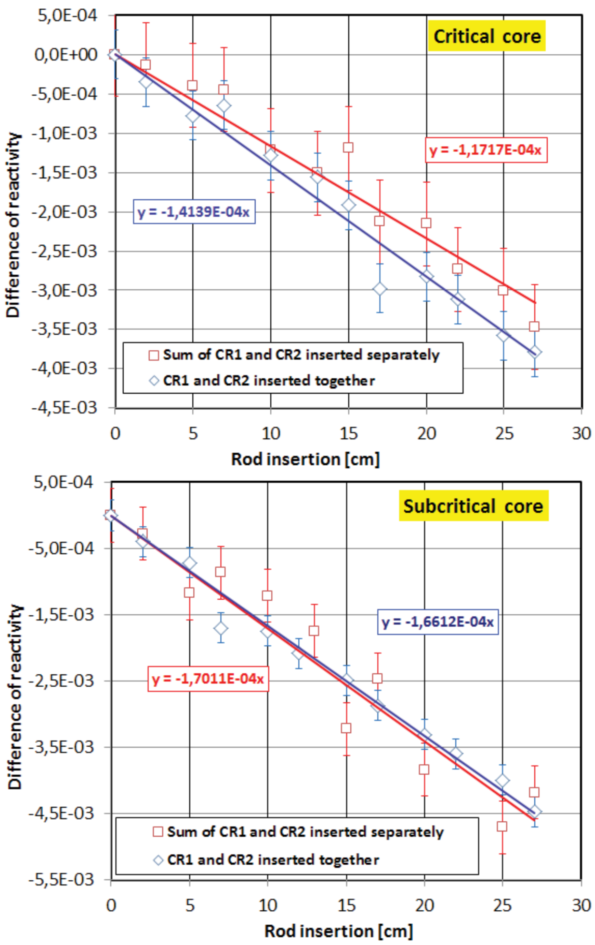

Fig. 4. Comparison of slopes for separate and common insertion of control rods CR1 and CR2.

and together. Results of the comparison of respective values are presented in Table 2.

It can be observed that the uncertainties for the lines crossing point 0.0 are lower, also due to the fact that only one parameter instead of two was evaluated by regression. As before, a significant shadow effect cannot be seen for the subcritical core, while for critical the difference is more evident. Also the difference between CR1 and CR2 worth is more significant in the critical core.

The calculated values of the neutron flux density in control rod material were also adopted for the assessment of the shadow effect. It was assumed that the comparison of the flux spectrum in the absorber is equivalent to that of reactivity, since the material composition of both CRs is identical. Additionally, this approach can provide us with the answer whether both rods can be regarded as interchangeable and if the system is symmetrical. The neutron fluxes in full volumes of both rods fully submerged at the same time are presented in Fig. 5.

Comparison of the spectra of neutron fluxes in rods CR1 and CR2, for both systems, subcritical and critical, shows a high degree of similarity (difference in k_{eff} affects only the values and not the shape of the respective spectra). Small, but significant difference between the rods is visible for both core configurations, particularly in the 0.1–0.3 MeV region. It is even more evident in case of the graph, where the ratio of both fluxes and its deviation from unity is visible (see Fig. 6). Summarised flux (in arbitrary units), for the entire volume of neutron absorbent in the assembly and the entire energy spectrum, differs by 3.2% for critical and 3.5% for subcritical configuration. For the critical core and for higher energy part of the neutron spectrum there is slight decrease of the flux ratio. For the subcritical configuration, similar effect is observed. The evaluated dependence of the flux ratio Φ_{CR1}/Φ_{CR2} on energy E is for subcritical core:

(2) $$\Phi_{CR1}/\Phi_{CR2} = -0.00868 \cdot \ln E + 0.944$$

and for critical core:

(3) $$\Phi_{CR1}/\Phi_{CR2} = -0.01004 \cdot \ln E + 0.951$$

Experimental results

The impact of the control rods position on the core reactivity was then assessed using the experimental data, which aimed at verification of the results of calculations. The main goal was to evaluate the experimental worth of control rods, acting separately and together, and to compare the results with calculations. In the experiments, the subcritical core configuration was used and the control rods were placed in variable static positions. In case of the experiments with the use of both control

Table 2. Results of the reactivity slope calculations

Description	Critical core		Subcritical core	
	Slope	Uncertainty	Slope	Uncertainty
	[pcm/cm]		[pcm/cm]	
CR1 moved from 20 to 47 cm, CR2 = 20 cm	–5.81	0.37	–8.99	0.76
CR2 moved from 20 to 47 cm, CR1 = 20 cm	–7.02	0.64	–8.58	0.91
Difference of slopes: CR1–CR2	1.21	0.74	–0.41	1.19
CR1 with CR2 moved from 20 to 47 cm	–14.51	0.81	–15.94	0.58
Sum of slopes for CR1 and CR2 inserted separately	–12.82	0.74	–17.57	1.19
CR1 with CR2 moved from 20 to 47 cm (reactivity assumed = 0 at 20 cm)	–14.14	0.42	–16.61	0.57
Sum of slopes for CR1 and CR2 inserted separately (reactivity assumed = 0 at 20 cm)	–11.72	0.45	–17.01	0.84

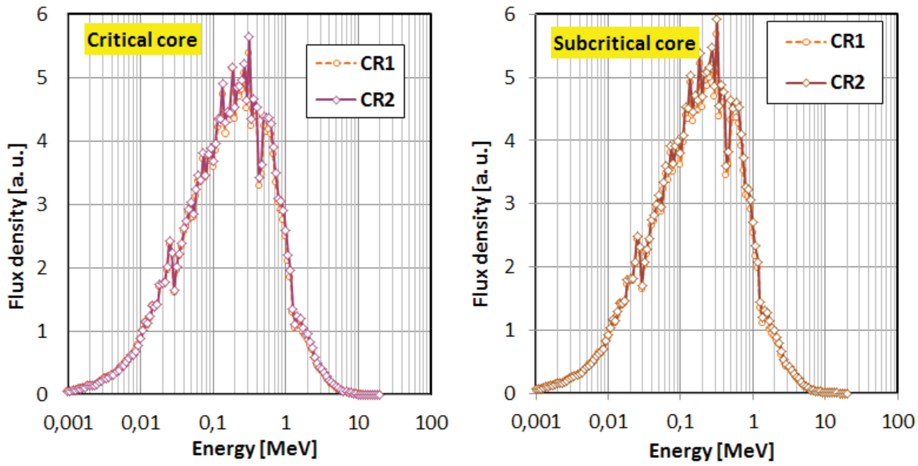

Fig. 5. Calculated neutron spectra in the whole volume of the CR1 and CR2 rods.

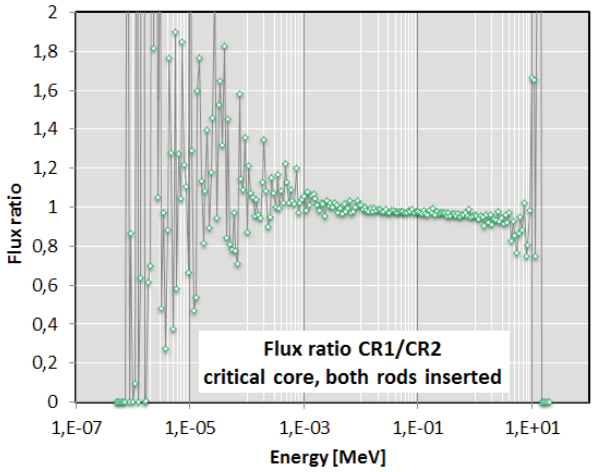

Fig. 6. Ratio of the calculated neutron spectra in the whole volume of the CR1 and CR2 rods in critical core.

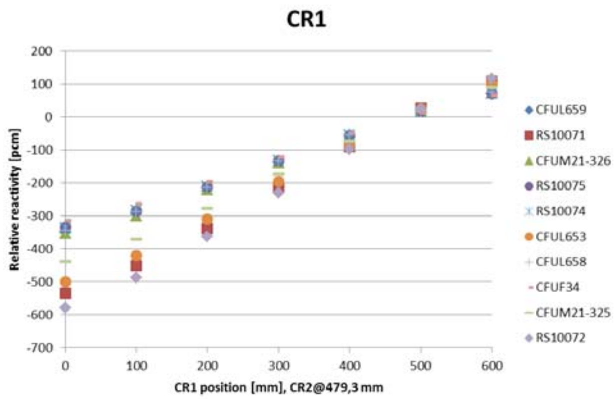

Fig. 8. Reactivity values from different detectors for CR1 moving from 600 to 0 mm with a step of 100 mm and CR2 fixed.

rods, they were moved from 0 to 600 mm with 60 mm step. When only one rod was moved, it was done in 100 mm steps, with the second rod fixed at 479.3 mm position. The neutron detectors configuration is shown in the Fig. 1. The 479.3 mm point was used as the reference to obtain reactivity values for every other CRs' position. The reactivity values in relation to this point are shown in the Figs. 7–9. A separate value was obtained for every single detector. The rod worth measured by every detector was also calculated (see Table 3).

Huge dispersion of the results can be observed dependently on the position of the detector, especially the detectors placed close to the moving control rods are showing significantly bigger registered reactivity change due to bigger neutron flux changes near the control rod. It can also be observed that the detectors placed further from the core are indicating slightly increased reactivity changes. It is caused by the fact that the source multiplication method is derived from the point kinetic model and does not take spatial effects, like the changing flux distribution over the core, into account. It suggests

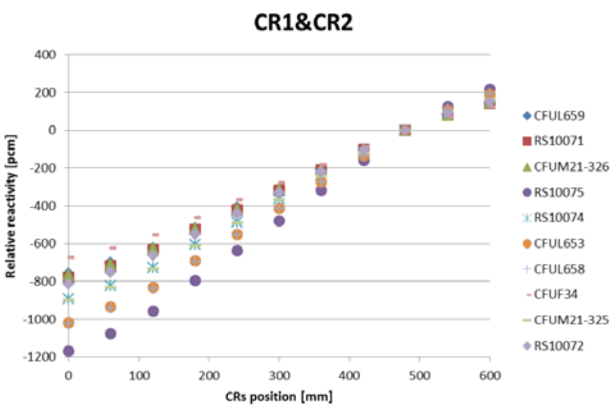

Fig. 7. Reactivity values from different detectors for both control rods moving from 600 to 0 mm with a step of 60 mm.

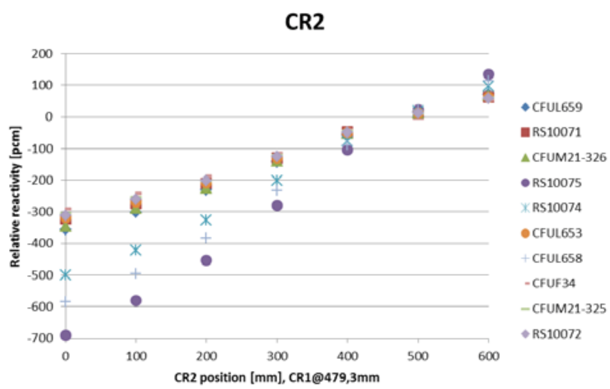

Fig. 9. Reactivity values from different detectors for CR2 moving from 600 to 0 mm with a step of 100 mm and CR1 fixed.

Table 3. Calculated rod worth for CRs moved separately and together

Detector	Rod worth			
	CR1 600 to 0 mm CR2@479.3 mm	CR2 600 to 0 mm CR1@479.3 mm	Sum of CR1 + CR2	CR1&CR2 600 to 0 mm
CFUL659	**420(12)**	428(12)	849(17)	**900(21)**
RS10071	643(11)	**385(10)**	1028(15)	**920(26)**
CFUM668	**428(11)**	415(12)	843(16)	**911(23)**
RS10075	**408(10)**	824(16)	1232(19)	1386(29)
RS10074	**409(11)**	598(14)	1007(18)	1057(26)
CFUL653	600(14)	**381(11)**	981(18)	1205(25)
CFUL658	**419(11)**	697(15)	1116(19)	1214(31)
CFUF34	380(13)	345(12)	726(117)	798(25)
CFUM667	529(15)	**367(11)**	896(19)	1066(22)
RS10072	696(16)	**370(11)**	1066(19)	964(26)

that the MSM (modified source multiplication) method should be used instead of simple source multiplication method and the correction factors need to be calculated. Reactivity in MSM method is given by [7]:

$$\rho = f_{\text{corr}}\left(\frac{C_0}{C}\right)\rho_0 \tag{4}$$

where f_{corr} is the correction factor for each detector.

Calculation of all needed correction factors means a huge calculation effort. It is however possible to select the detectors with the correction factors close to unity and use only these values to calculate the rod worth. Those values are bolded in the Table 3. It should be noticed that dependently on the used control rod those would be different detectors. In case of a single rod movement the most accurate results are given by the detectors placed on the other side of the core. There is no single detector that gives reliable results without the correction factor in all three cases considered. CFUM668 is the closest one. However, using only selected detectors for each case would allow us to assess first estimation of the rod worth.

The summary of the experimental results, along with the comparison of them and the calculations is shown in Table 4. Both sets of results show similar values of single rod worth. However, it should be noticed that in experiments the difference between both rods is more visible. It can suggest that the core is not symmetrical. Moreover, in experiment CR1 shows bigger rod worth than CR2, while in MCNP calculations they are practically equal. However, in detailed calculation analysis of a single rod movement, in the range between 20 and 47 cm, the slopes suggest slightly bigger worth of CR1, like in experiment. However, one must keep in mind that non-symmetrical detector positions can also be a factor in this matter. Most evident difference applies to both rods inserted together. The experimental value is significantly bigger and showing negative shadow effect of ca. 100 pcm. What should also be pointed is the fact that in the compared calculation results for single rod movement, the second rod was fully extracted (or inserted by 20 cm, which corresponds to CR position of 400 mm), while in experiments it was at 479.3 mm. Due to this fact, the experimental results for single control rods could be affected by shadow effect from the second, partially inserted rod. It is therefore disputable if they should be considered as accurate single control rod worth assessments.

Table 4. Comparison of experimental and calculation results of rod worth (subcritical core) [pcm]

	Experiment	MCNP
CR1 600 to 0 mm	417(12)	393(16)
CR2 600 to 0 mm	375(12)	403(16)
Sum of CR1 + CR2	792(23)	796(23)
CR1&CR2 600 to 0 mm	910(17)	810(16)

Summary and conclusions

The main goal of this study was to achieve the VENUS-F core characteristics needed for further experiments regarding the core reactivity measurements and validation of the results. The MCNP simulation results revealed small negative shadowing effect in the critical core, while in subcritical core no evident shadow effect was observed. Moreover, no strong core asymmetry was revealed. Those observations apply for both evaluation methods – for rods moved between their extreme positions and for detailed analysis of the central movement region, where relation between depth and reactivity is linear. Even if the difference in the neutron spectrum in both rods can be observed, its influence on rod worth is rather insignificant and only in the critical core difference between estimated rod worth for CR1 and CR2 is slightly bigger than uncertainties.

The experimental results are showing very similar values of single rod worth to calculations and almost identical for sum of separately used rods. However in this case, small asymmetry can be observed with CR1 giving bigger value. Moreover, experimental results are showing presence of negative shadow effect of about 100 pcm for both rods inserted. However, these results can be only considered preliminary due to the fact that huge dispersion of the results was observed dependently on detector position. It was revealed that control rods insertion strongly affects neutron flux in their proximity and therefore also results given by detectors placed in this area. It should be possible to get rid of that effect by using the MSM method and it will be the next step in our evaluation of the experimental data. However, it requires significant amount of additional MCNP calculations. It is worth to notice that mentioned effect of the control rod's influence on the detector results causes detectors to show reactivity values bigger than the actual ones, so it can be expected that final results will be closer to the simulation results. Moreover, it reveals that there is need for extensive analysis of flux spatial distribution and its changes with rod insertion in different parts of the core for future ADS reactivity monitoring system.

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References

1. OECD Nuclear Energy Agency. (2002). *Accelerator Driven Systems (ADS) and Fast Reactors (FR) in advanced nuclear fuel cycles: A comparative study*. Paris, France.
2. OECD Nuclear Energy Agency. (2009). *Independent evaluation of the MYRRHA project: Report by an international team of experts*. Paris, France.
3. Billebaud, A., Baeten, P., Aït Abderrahim, H., Ban, G., Baylac, M., Bergmans, G., Bondoux, D., Bouvier, J., Chabod, S., De Conto, J. M., Dessagne, P., Gaudiot, G., Gautier, J. M., Granget, G., Heitz, G., Kerveno, M., Kochetkov, A., Laune, B., Lecolley, F. R., Lecouey, J. L., Marie, N., Mellier, F., Merrer, Y., Nuttin, A., Reynet, D., Steckmeyer, J. C., Uyttenhove, W., Vandeplassche, D., Vermeersch, F., & Vittiglio, G. (2009). *The GUINEVERE Project for Accelerator Driven System Physics,* International Conference GLOBAL 2009 "The Nuclear Fuel Cycle: Sustainable Options & Industrial Perspectives". Paris, France.
4. Mellier, F. (2009). *Status of core design*. In 2nd EUROTRANS ECATS Progress Meeting, 28–29 January 2009. Aix-en-Provence, France.
5. X-5 Monte Carlo Team. (2003). *MCNP–A General Monte Carlo N-Particle Transport Code, Version 5 – Volume II: User's guide*. Los Alamos National Laboratory. (LA-CP-03-0245).
6. Tsuji, M., Suzuki, N., & Shimazu, Y. (2003). Subcriticality measurement by neutron source multiplication method with a fundamental mode extraction. *J. Nucl. Sci. Technol.*, *40*(3), 158–169.
7. Endo, T., Yamamoto, A., & Yamane, Y. (2011). Detected-neutron multiplication factor measured by neutron source multiplication method. *Ann. Nucl. Energy*, *38*(11), 2417–2427.