Modeling of FREYA Fast Critical Experiments with the Serpent Monte Carlo Code

Originally published:

May 2017

Annals of Nuclear Energy 108(2017), 239-252

DOI: https://doi.org/10.1016/j.anucene.2017.04.045

Modeling of FREYA Fast Critical Experiments with the Serpent Monte Carlo Code

E. Fridman[1], A. Kochetkov[2], A. Krása[2]

[1]Helmholtz-Zentrum Dresden-Rossendorf,
Bautzner Landstraße 400, 01328 Dresden, Germany

[2]SCK•CEN, Belgian Nuclear Research Centre,
Boeretang 200, 2400 Mol, Belgium

Keywords:
Serpent, Monte Carlo, FREYA, VENUS-F, critical experiments, lead fast reactor

Abstract

The FP7 EURATOM project FREYA has been executed between 2011 and 2016 with the aim of supporting the design of fast lead-cooled reactor systems such as MYRRHA and ALFRED. During the project, a number of critical experiments were conducted in the VENUS-F facility located at SCK•CEN, Mol, Belgium.

The Monte Carlo code Serpent was one of the codes applied for the characterization of the critical VENUS-F cores. Four critical configurations were modeled with Serpent, namely the reference critical core, the clean MYRRHA mock-up, the full MYRRHA mock-up, and the critical core with the ALFRED island.

This paper briefly presents the VENUS-F facility, provides a detailed description of the aforementioned critical VENUS-F cores, and compares the numerical results calculated by Serpent to the available experimental data. The compared parameters include keff, point kinetics parameters, fission rate ratios of important actinides to that of U235 (spectral indices), axial and radial distribution of fission rates, and lead void reactivity effect.

The reported results show generally good agreement between the calculated and experimental values. Nevertheless, the paper also reveals some noteworthy issues requiring further attention. This includes the systematic overprediction of reactivity and systematic underestimation of the U238 to U235 fission rate ratio.

1. Introduction

Fast Reactor Experiments for hybrid Applications (FREYA) (Kochetkov et al., 2013) has been a five-year collaborative project co-funded by European Commission within the Euratom 7th Framework Programme (FP7). The project led by the Belgian Nuclear Research Centre (SCK•CEN) and executed between 2011 and 2016 has been launched to support the design and licensing of sub-critical and critical lead-cooled fast spectrum systems which can potentially be used for transmutation of nuclear waste. The supported transmutation systems included Multi-purpose hYbrid Research Reactor for High-tech Applications (MYRRHA) (Engelen et al., 2015) and Advanced Lead-cooled Fast Reactor (LFR) European Demonstrator (ALFRED) (Grasso et al., 2014). While ALFRED is a “traditional” critical fast reactor, MYRRHA is being designed to operate in both critical and sub-critical (accelerator driven) modes.

In the framework of the FREYA project, a number of sub-critical and critical experiments were conducted at the VENUS-F facility within four technical work packages (WP):

- WP1: On-line reactivity monitoring methodologies in Accelerator Driven Systems (ADS)
- WP2: Sub-critical configurations for design and licensing of MYRRHA
- WP3: Critical configurations for design and licensing of MYRRHA
- WP4: Critical configurations for LFR

One of the main objectives of FREYA was the investigation and validation of reactivity monitoring techniques in sub-critical cores (e.g. Uyttenhove et al., 2012, 2014; Maria et al., 2014; Lecouey et al., 2015; Lehaut et al., 2015). The availability of the measured data in combination with the detailed information on experimental setups provides a very good opportunity for the benchmarking of neutronic computational tools. Therefore, substantial efforts were also dedicated to the code validation tasks.

During the FREYA project the MCNP5 code (X-5 Monte Carlo Team, 2003) was used at SCK•CEN as the main tool for design, characterization, and safety calculations of the VENUS-F cores. In addition to MCNP, the continuous-energy Monte Carlo reactor physics code Serpent 2 (Leppänen et al., 2015) was also used in the project. The purpose of the current study is to benchmark the Serpent code against the measured data obtained within the FREYA project and to investigate the Serpent applicability to the modeling and characterization of critical VENUS-F cores.

The paper has the following structure. Section 2 describes the VENUS-F facility and the relevant critical VENUS-F cores. Section 3 focuses on the verification of Serpent against the

MCNP5 code. The comparison of the Serpent results to experimental data is presented in Section 4. Section 5 summarizes the paper.

2. VENUS-F facility and critical cores

The VENUS facility was built at SCK•CEN, Mol, Belgium as a zero-power water-moderated thermal critical reactor. A number of LWR[1]-related experiments conducted in the VENUS reactor served as a basis for the well-known international benchmarks including VENUS-1 and VENUS-3 (OECD/NEA, 2000a) benchmarks for prediction of neutron embrittlement in the reactor pressure vessel, and VENUS-2 MOX core benchmarks (OECD/NEA, 2000b, 2004). Due to the increasing interest in lead-based fast reactor systems in Europe and the corresponding demand for integral experiments, in 2007-2010 VENUS was converted into the VENUS-F fast neutron facility with solid lead core components (Kochetkov et al., 2012).

A general view of the VENUS-F facility is presented in Fig. 1. The VENUS-F core comprises of 12×12 square lattice with the lattice pitch of 8.07 cm. The active core height is 60 cm. In the radial direction, the core is surrounded by square stainless steel casing and cylindrical lead reflector which fills the reactor vessel having a radius of about 80 cm. In the axial direction, the core is reflected by top and bottom lead reflectors of 40 cm each.

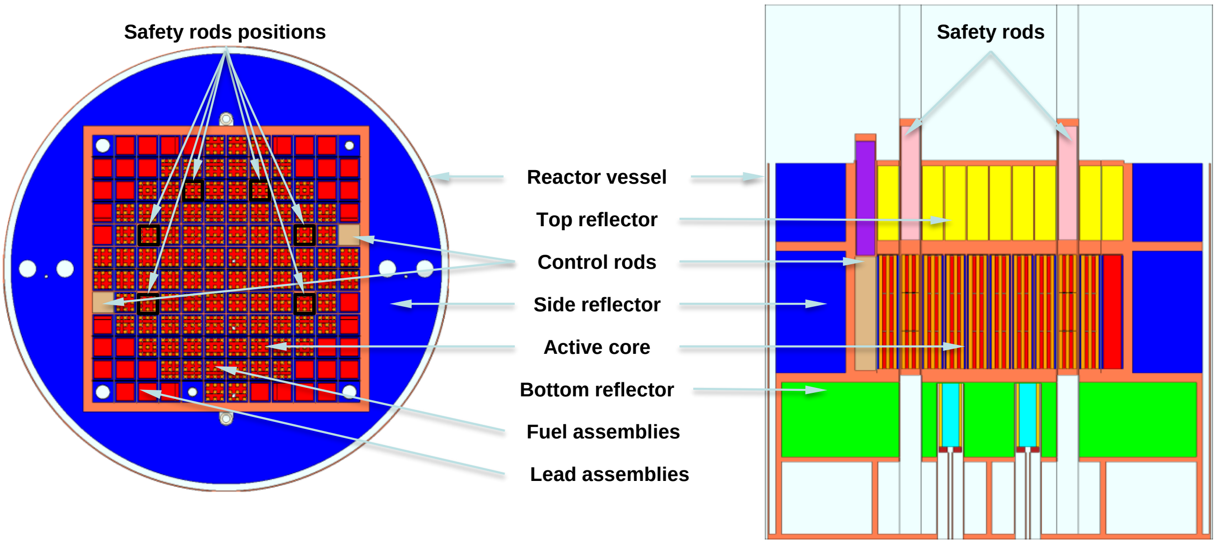
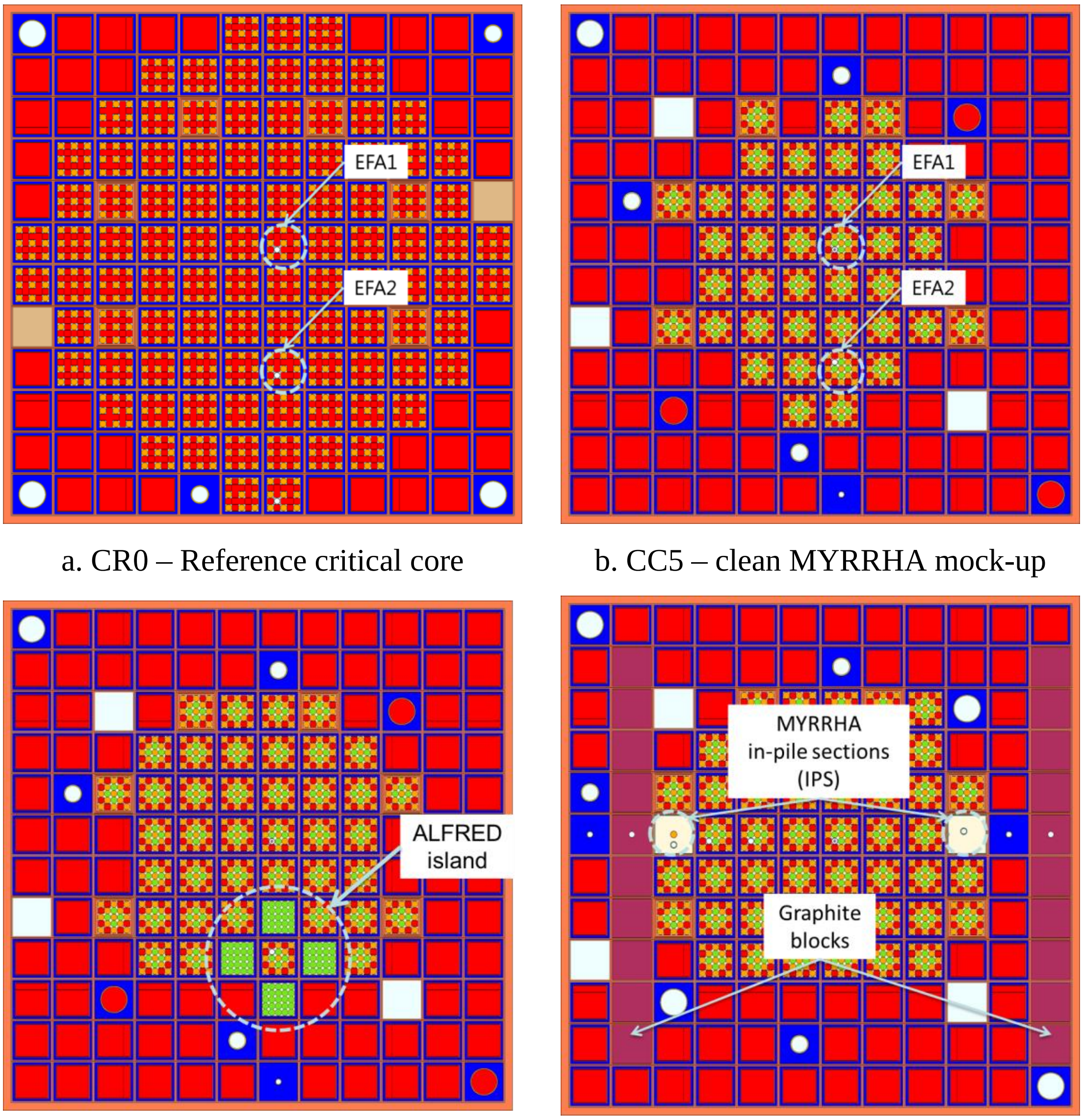


Fig. 1. Radial and axial view of VENUS-F

The safety shutdown system includes six boron carbide safety rods located above the movable fuel assemblies as depicted in Fig. 1. When inserted, the safety rods are pushing the

[1] LWR – Light Water Reactor

corresponding fuel assemblies out of the active core in the direction of the bottom reflector. During the operation, the reactivity can be adjusted with the help of two control rods located at the core periphery (Fig. 1).



a. CR0 – Reference critical core

b. CC5 – clean MYRRHA mock-up

c. CC6 – CC5 core with ALFRED island

d. CC8 – full MYRRHA mock-up

Fig. 2. Active cores layouts

The lead-based system supported by the FREYA project (i.e. MYRRHA and ALFRED) have being designed to operate primarily with Pu-based Mixed Oxide Fuel (MOX). However, due to the unavailability of Pu MOX, 30 wt.% enriched uranium was used as a fissile driver throughout the entire experimental campaign. Within WP1, WP3, and WP4 of the FREYA project several critical VENUS-F cores were investigated. The current paper focuses on the following configurations:

– CR0 – reference critical core (Fig. 2a)

– CC5 – “clean” MYRRHA core mock-up (Fig. 2b)

– CC6 – Modified CC5 core with ALFRED island (Fig. 2c)

– CC8 – “full” MYRRHA core mock-up (Fig. 2d)

All VENUS-F cores utilize 5×5 fuel assemblies (FAs) with square lattice array as shown in Fig 3. The FAs in the CR0 core comprise of 9 metallic uranium rods and 16 lead blocks (Fig. 3a). In FAs of the CC5, CC6, and CC8 cores 8 lead blocks were replaced by 4 Al_2O_3 and 4 additional metallic uranium rods (Fig. 3b) in order to mimic the behavior of oxide fuel. In some FA a single uranium rod was replaced by a stainless steel instrumental guide tube (Fig. 3c and Fig. 3d) to allow for in-core measurements. These FA are referred to as experimental FA (EFA). The reference critical CR0 was loaded with 97 FAs. Due to the higher number of fuel rods per FA, the CC5, CC6, and CC8 cores required a lower amount of FAs to attain criticality. These cores were loaded with 41, 41, and 47 FAs respectively (Fig. 2). The remaining non-fuel positions in the CR0 and CC5 cores contained solid lead (Fig. 4a) and experimental assemblies (Fig. 4b and Fig. 4c).

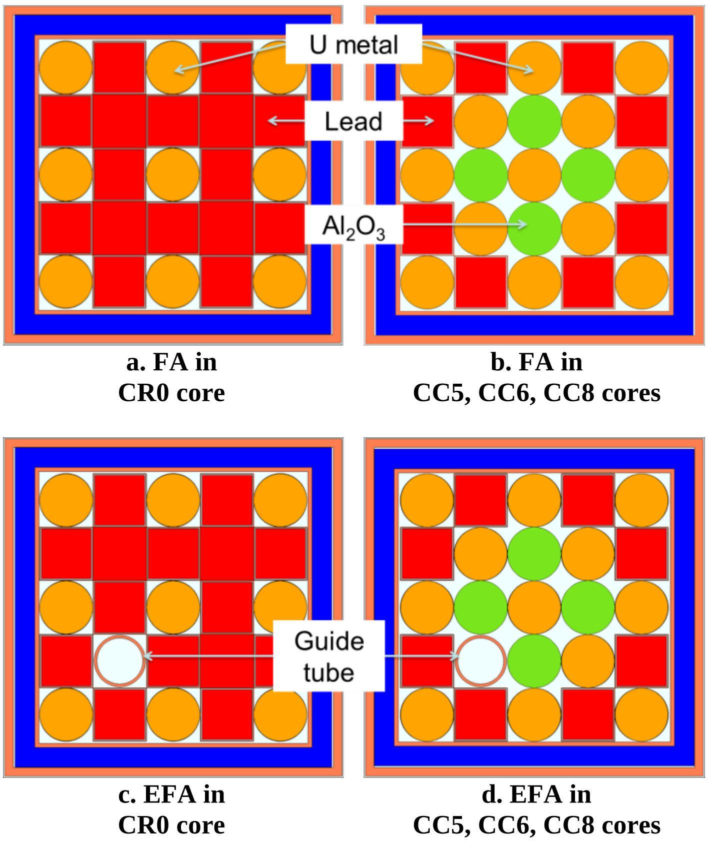
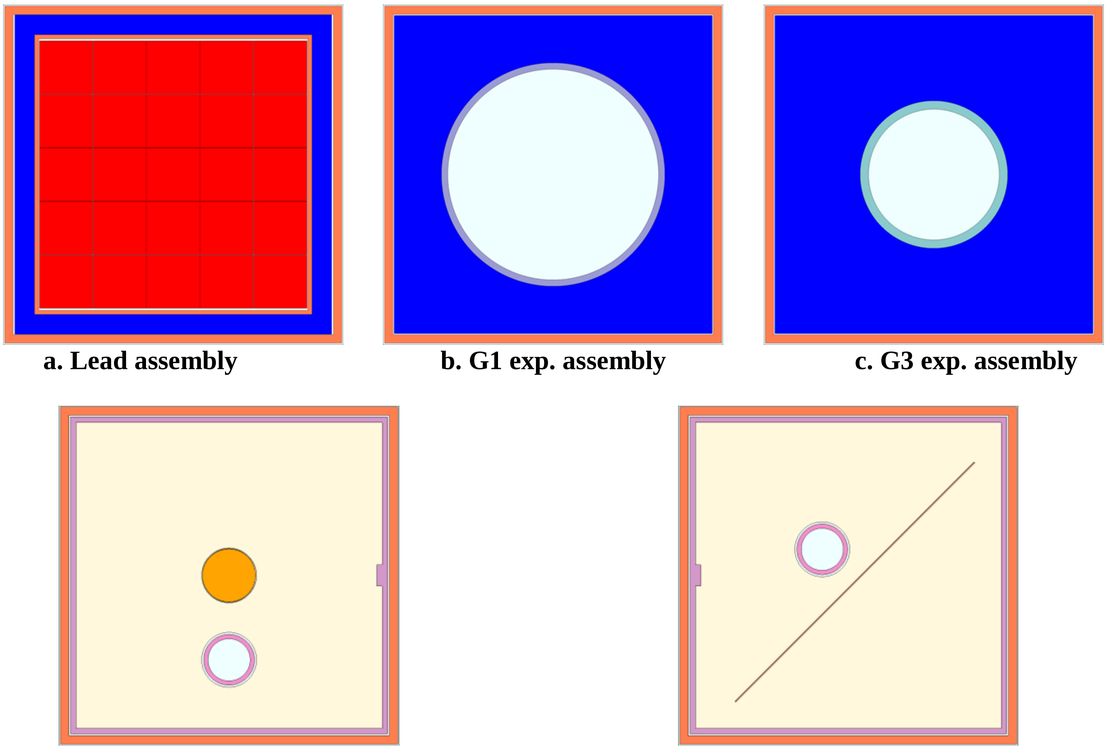


Fig. 3. VENUS-F fuel assembly layouts



a. Lead assembly b. G1 exp. assembly c. G3 exp. assembly

d. MYRRHA IPS mockup with U rod (IPS1) e. MYRRHA IPS mockup with U foils (IPS2)

Fig. 4. VENUS-F non-fuel assembly layouts

The CC6 and CC8 cores had somewhat more complex configurations. In the CC6 core, one peripheral FA was surrounded by four ALFRED Inert Assembly (AIA) containing Al_2O_3 rods. This so-called “ALFRED island” was introduced in order to simulate spectral conditions of the ALFRED core (Fig. 2c).

The CC8 core included graphite blocks simulating MYRRHA BeO reflector and two mockups of MYRRHA thermal In-Pile Sections (IPSs) dedicated to the production of Mo-99 in enriched uranium targets (Figs. 2d-2e). Both IPS assemblies are fabricated from polyethylene (PE) blocks surrounded by Cd layer and inserted into a stainless steel casing. The presence of enriched uranium in IPS1 is simulated with the help of 30 wt.% uranium rod (Fig. 4d) while in IPS2 aluminum-wrapped 93 wt.% uranium foils were used (Fig. 4e). Both IPS assemblies included aluminum tubes used as experimental guide tubes for the measurement equipment.

3. Verification of Serpent against MCNP

Serpent inputs used in the study were derived from a very detailed MCNP model of the VENUS-F CR0 core developed at SCK•CEN and provided to the project partners. The MCNP model features fully resolved representation of fuel assemblies, control and safety rods, experimental channels, as well as internal and peripheral core structures.

As the first step in the application of Serpent in the FREYA project, the consistency of the MCNP and Serpent models of the VENUS-F CR0 core was examined by comparing various parameters calculated by the codes including integral values, neutron flux spectra, and radial power distribution.

The full core MCNP5 and Serpent calculations were performed using identical JEFF-3.1 based ACE format cross section library. Both codes were executed with a total of half a billion active neutron histories (i.e. 1000 active cycles, 200 skipped cycles, and half a million neutron histories per cycle). The obtained 1σ uncertainty on k-eff was in the range of 2-3 pcm. In the FREYA framework, all calculations were performed using Serpent v. 2.1.22.

The integral core parameters including reactivity (ρ), total control rod worth, effective prompt neutron generation time (Λ_{eff}), and effective delayed neutron fraction (β_{eff}) are compared in Table 1. The reactivity and total control rod worth values predicted by MCNP5 and Serpent show an excellent agreement of 13 and 10 pcm respectively. The values of Λ_{eff} and β_{eff} calculated using the iterated fission probability (IFP) approach (Kiedrowski et al., 2011; Leppänen et al., 2014) are also very close and agree within 1σ.

The representative fuel neutron flux spectrum in the energy range from 1keV to 10MeV is shown in Fig. 5 (top). The flux spectra calculated by MCNP5 and Serpent typically agree within 2σ with the maximum discrepancy being less than 0.4% (Fig. 5, bottom).

The normalized radial power distribution calculated by Serpent is presented in Fig. 6a. As shown in Fig. 6b., the MCNP5 and Serpent results are in a very good agreement with the average difference of 0.04% and the maximum difference not exceeding 0.12%.

In summary, the current section presents and compares various neutronic parameters of the VENUS-F CR0 core predicted with the MCNP5 and Serpent codes. In general, a very good agreement between the codes was observed. This provides a confidence in the consistency of the MCNP5 and Serpent setups used for the modeling of the VENUS-F CR0 core. The developed Serpent model of the CR0 core served as a basis for generating inputs for the follow-up VENUS-F cores including CC5, CC6, and CC8.

Table 1: Comparison of integral parameters, Serpent vs. MCNP

	MCNP	Serpent	Difference
ρ, pcm	483±3	496±2	13
Total control rod worth, pcm	795±4	785±3	10
Λ_{eff}, nsec	401.8±0.8	401.4±0.5	0.4
β_{eff}, pcm	728±2	731±1	3

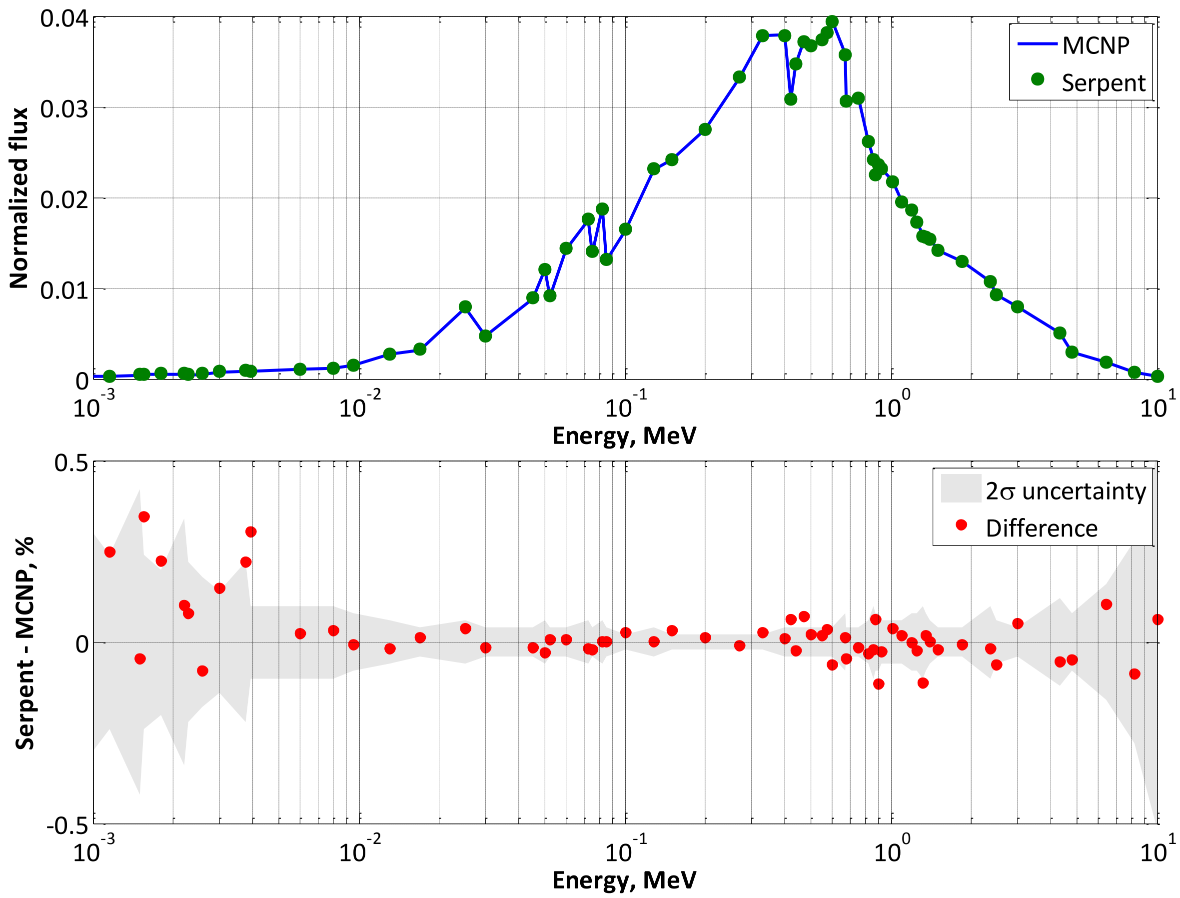
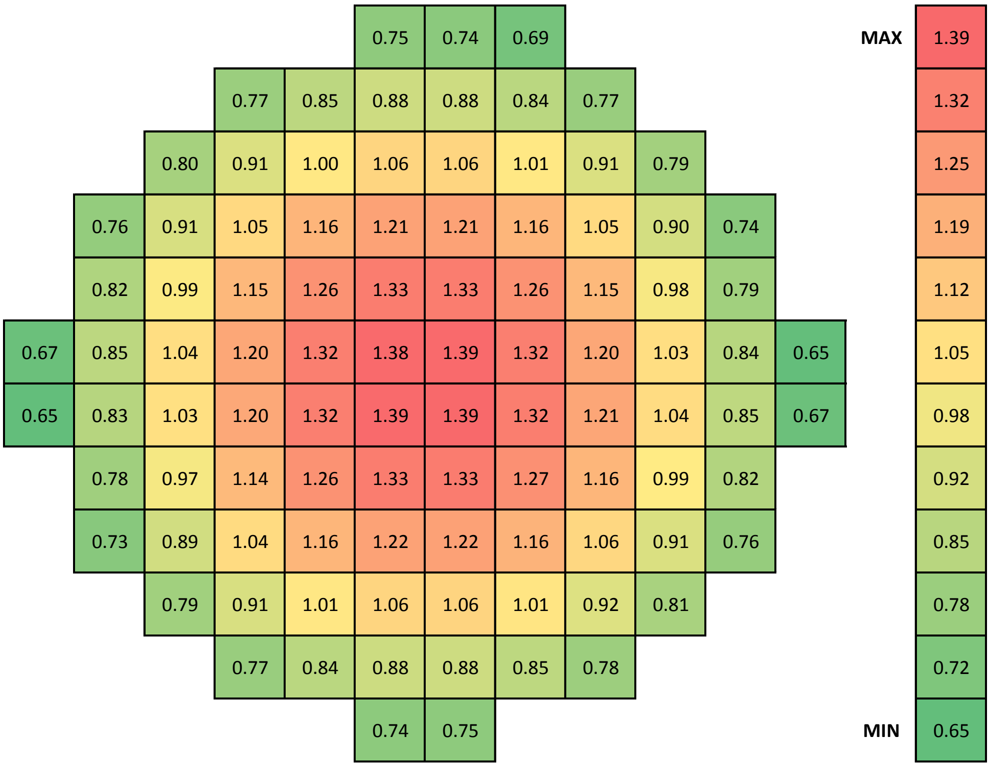
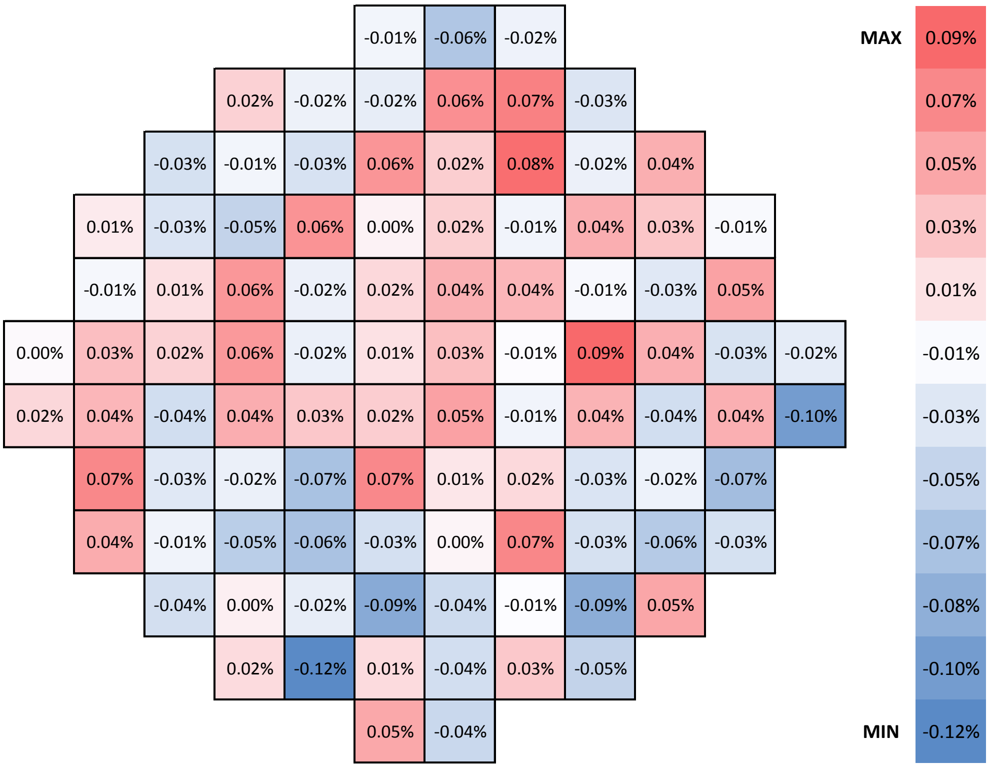


Fig. 5. Comparison of representative neutron flux spectra in the fuel region, Serpent vs. MCNP



a. Normalized radial power distribution, Serpent



b. Difference in normalized radial power distribution

Fig. 6. Comparison of normalized radial power distribution, Serpent vs. MCNP

4. Comparison of calculated and experimental data

4.1 Compared parameters

In the framework of the FREYA project, a number of experiments conducted in critical VENUS-F cores were simulated with the Serpent code. In this section, selected measured parameters are compared to those calculated by Serpent. The considered integral and local parameters include:

- Core reactivity (ρ),
- Effective delayed neutron fraction (β-eff) and prompt neutron generation time (Λ_{eff}),
- Spectral indices (SI) – fission rate ratios of important actinides to that of U235,
- Axial and radial traverses – axial and radial fission rate distributions obtained with fission chambers containing different actinide deposits,
- Lead void reactivity effect (LVRE).

The aforementioned parameters were measured in different cores as summarized in Table 2.

Table 2: List of compared parameters

Core / **Parameter**	**CR0**	**CC5**	**CC6**	**CC8**
Reactivity	+	+	+	+
β_{eff} and Λ_{eff}	+			
Spectral indices	+	+	+	+
Axial traverses	+	+		
Radial traverses		+		+
LVRE			+	

4.2 Reactivity

The reactivity values calculated by Serpent for the critical VENUS-F cores are shown in Table 4. Serpent systematically overestimates the reactivity by several hundred pcm with the largest difference of 812 pcm observed in the CC6 case. However, it is worth noting that the Serpent results are consistent with those of MCNP exhibiting a similar trend of a systematic reactivity overestimation. For example, as shown in Table 1, both MCNP and Serpent overpredict the reactivity of the CR0 core by about 500 pcm. Furthermore, the repeating MCNP calculations with alternative nuclear data libraries (i.e. ENDF/B-VII.0, JEFF-3.2, and JENDL-4.0) retains the difference within about 200 and 1000 pcm (Bécares et al., 2016).

Table 3: Reactivity of the critical VENUS-F cores calculated by Serpent

Core	ρ, pcm
CR0	496±2
CC5	763±3
CC6	812±2
CC8	186±1

There are several possible reasons (or a combination of reasons) for the systematic overestimation of reactivity including uncertainty in physical dimensions, material specifications, etc. The one that can be particularly mentioned is the uncertainties in nuclear data. Some recent studies involving fast spectrum lead cooled systems (Alhassan et al., 2015; Aufiero et al., 2016) demonstrated a noticeable sensitivity of k_{eff} to cross section uncertainties of lead isotopes, and in particular to that of Pb208. The quantification of the impact of nuclear data uncertainties on the MC reactivity estimates requires a systematic sensitivity and uncertainty study. This, however, falls beyond the scope of this paper and is planned for the future.

4.3 Kinetic parameters

The measurement of the kinetic parameters including β_{eff} and Λ_{eff} were conducted in the critical CR0 core using the Rossi-Alpha technique as described in details in (Doligez et al., 2015). As mentioned in Section 4, the Monte Carlo estimates of β_{eff} and Λ_{eff} were calculated by Serpent using the IFP method.

The measured and calculated values compared in Table 3 show an excellent agreement. The difference is about 1 pcm for β_{eff} and 9 nsec for Λ_{eff} which is well within 1σ uncertainty. These results provide an additional confirmation of the consistency of the IFP method implemented in Serpent for the calculation of adjoint-weighted reactor point kinetics parameters.

Table 4: Comparison of kinetic parameters of CR0 core, Serpent vs. experiment

	Experiment	Serpent	Difference
β_{eff}, pcm	730±11	731±1	1
Λ_{eff}, nsec	410.0±40.0	401.4±0.5	8.6

4.4 Spectral indices

The fission rates measurements were conducted in all critical VENUS-F cores. The fission rates were obtained by means of small-sized Fission Chambers (FC) containing actinide deposits with the mass ranging from 20 to 200 μg which were calibrated in the standard neutron field of the BR1 reactor at SCK•CEN (Wagemans et al., 2012). The FC with U235, U238, Pu239, Pu240, Pu242, Np237, and Am242 deposits were used. The fission rates were primarily measured within the guide tubes of the EFAs (CR0, CC5, CC6, and CC8). In the CC8 core, the measurements were also performed within the IPS and graphite reflector assemblies. The considered SIs are denoted as shown in Table 5.

Table 5: Considered SIs

SI	Fission rate ratio		SI	Fission rate ratio
F28/F25	U238 to U235		**F40/F25**	Pu240 to U235
F28/F25	Np237 to U235		**F42/F25**	Pu242 to U235
F49/F25	Pu239 to U235		**F51/F25**	Am241 to U235

In Serpent calculations, the fission reaction rates were tallied within small cuboids of 2×1×1 cm placed in accordance with the actual measurement positions. In order to obtain a reasonable statistical uncertainty for the calculated reaction rates, a relatively large number of neutron histories was used (i.e. 8000 active cycles, 200 skipped cycles, and a million neutron histories per cycle).

The experimental and calculated SIs are compared as a relative difference between the calculated and measured values (C/E-1) in Table 5. The spread of all C/E-1 along with the representative experimental and statistical uncertainties is shown in Fig. 7. The obtained results can be summarized as follows:

- Serpent systematically underestimates the F28/F25 indices by about 7 to 16% which is more than 2σ from the experimental values. It is worth mentioning that the F28/F25 results obtained with MCNP and several alternative nuclear data libraries exhibit a similar trend as well (Kochetkov et al., 2016a, 2016b). Up to now, the reason for such systematic underprediction by the codes remains unclear. In order to resolve this issue, some further steps will be taken in the framework of the FREYA follow-up project MYRTE (SCK•CEN, 2016). These includes, for example, re-evaluation of the effective mass of the U238 deposits as well as performing additional SI measurements using activation foils instead of the FCs. Additionally to new experimental activities, the sensitivity of the F28/F25 indices to the nuclear data uncertainties should also be studied.

- Serpent predicts well the F49/F25 indices while the measured and calculated values agree within 1 to 2σ.
- The SIs of Np237 and fertile Pu isotopes are typically calculated within 2σ with a slight tendency to under-prediction of the experimental values. In two cases (i.e. F37/F25 in EFA1 of CR0 and F42/F25 in EFA1 of CC5) the difference is slightly higher than 2σ.
- The values of F51/F25 measured in the CC5 and CC8 cores are significantly underestimated by Serpent by about 7 and 10% respectively. It should be noted, however, that the experimental value of F51/F25 measured in the CC8 core is associated with a large experimental uncertainty of 10%.

Table 6: C/E-1 values (%) for SI measured in CR0, CC5, CC6, and CC8 cores

Core	Position	SI					
		F28/F25	F49/F25	F40/F25	F42/F25	F37/F25	F51/F25
CR0	EFA1	-15.2±2.9*,†	-3.0±2.4	**-0.1±4.2**	**-3.4±4.2**	-6.1±3.0	-
	EFA2	-15.3±2.8	**-2.5±2.9**	**-2.7±4.0**	**0.3±4.1**	-5.6±2.8	-
CC5	EFA1	-9.4±2.1	**0.2±2.1**	-4.2±2.1	-6.3±2.5	-3.3±2.5	-6.6±2.3
	EFA2	-10.0±2.2	3.3±2.2	-	-	**0.0±2.8**	-
CC6	EFA2	-10.2±2.5	**-0.1±2.4**	-	-	-4.4±2.9	-
CC8	EFA1	-7.5±3.3	**0.7±3.3**	-4.8±3.1	-5.8±3.7	**-3.0±3.6**	**-9.9±10.0**
	EFA2	**-1.5±3.4**	-	-	-	-	-
	EFA3	-7.4±3.3	**-0.5±3.9**	-	-	-	-
	IPS1	-10.4±3.2	-4.2±3.3	-	-	-	-
	IPS2	-16.2±3.2	-4.2±3.4	-	-	-	-
	C-12	-8.5±3.6	-4.3±4.1	-	-	-	-

* value ± uncertainty

† Values shown in **green** are < 1σ, in black are within 1-2σ, and in red are > 2σ

It should be noted that the F28/F25 results for the in-pile sections of the CC8 core were initially presented in (Kochetkov et al., 2016b) where the reported difference between the measured and calculated values was about 70%. As compared to (Kochetkov et al., 2016b) the current F28/F25 results show significant improvement while the C/E-1 values reduced to 10%-16%. This improvement can be solely attributed to the accounting for the U235 impurities present in the U238 deposit at the level of about 0.04 wt.%. As shown in Fig. 8 the IPS regions are characterized by very thermal neutron flux spectra. Therefore, the U238 fission chambers located in these thermal regions are very sensitive to even tiny amounts of

U235 (Fig. 9). This is in contrast to "typical" fast spectrum regions such as EFA1 (Fig. 8) where the effect of the U235 impurities is significantly less pronounced (Fig. 9).

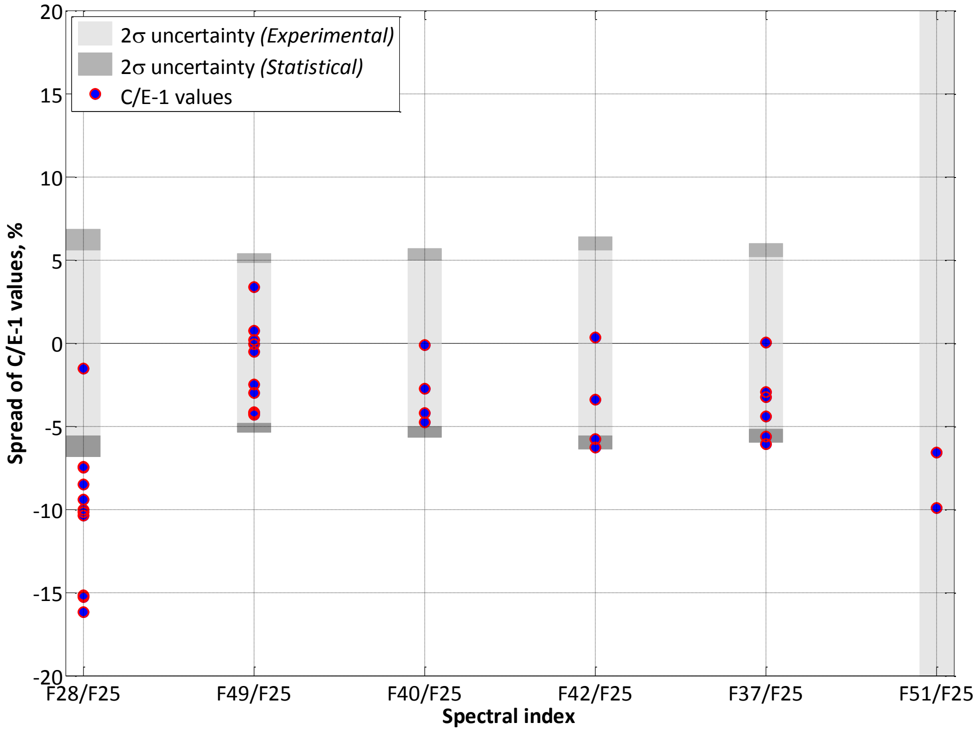


Fig. 7. Spread of the C/E-1 values for SI from the CR0, CC5, CC6, and CC8 cores combined

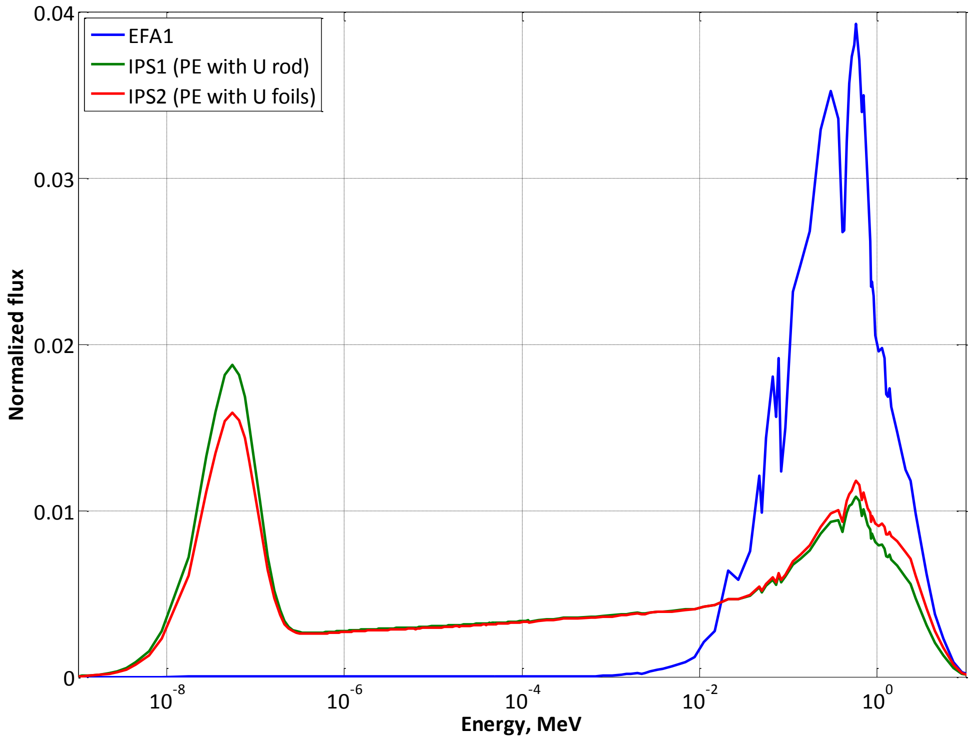


Fig. 8. Neutron flux spectra in EFA1, IPS1, and IPS2 of the CC8 core

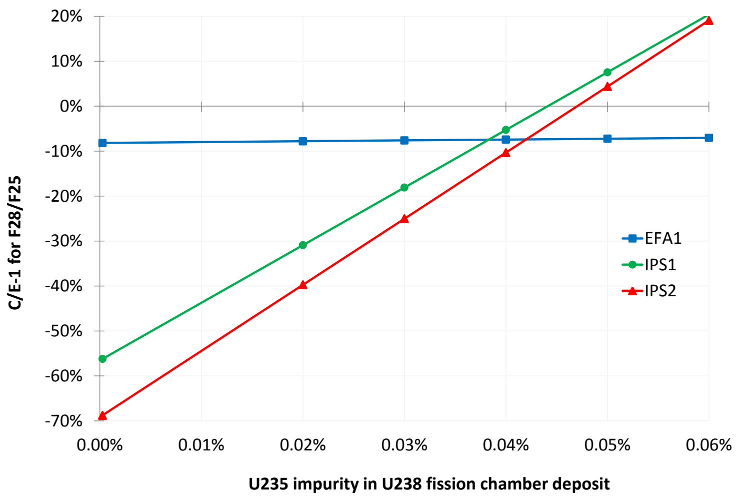


Fig. 9. C/E-1 for F28/F25 vs. U235 impurity in U238 fission chamber, the CC8 core

4.5 Axial traverses

The FREYA experiments included the measurements of the axial distribution of fission rates referred to as axial traverses. In this section, the axial traverses measured in the CR0 and CC5 cores are presented and compared with those calculated by Serpent. In both cores, the axial traverses were measured along the guide tubes of the EFA1 and EFA2 (Fig. 2) using small FC with fissile (i.e. U235, Pu239) and fertile (i.e. U238, Np237) deposits. In the EFA1 and EFA2 of the CR0 and in the EFA1 of the CC5 core the measurements started in the bottom reflector. In the EFA2 of the CC5 core, the measurements covered the active core and top reflector only.

The fission rates were evaluated by Serpent using the collision-based mesh tally with the axial resolution of 2 cm. The measurements were performed with the U238 deposit containing 0.24 wt.% of U235. This impurity was taken into account in the Serpent calculations.

The experimental and calculated axial traverses normalized to the maximum value at the core mid-plane are compared in Figs. 10-11 and Figs. 12-13 for the CR0 and CC5 cores respectively. It can be observed that in the active core regions the axial traverses of the fissile isotopes calculated by Serpent are in a reasonable agreement with the measured data. However, non-negligible differences are visible in the reflectors, particularly in the bottom part. On the other hand, the calculated axial traverses of fertile isotopes closely resemble the experimental curves in both the active core and reflector regions.

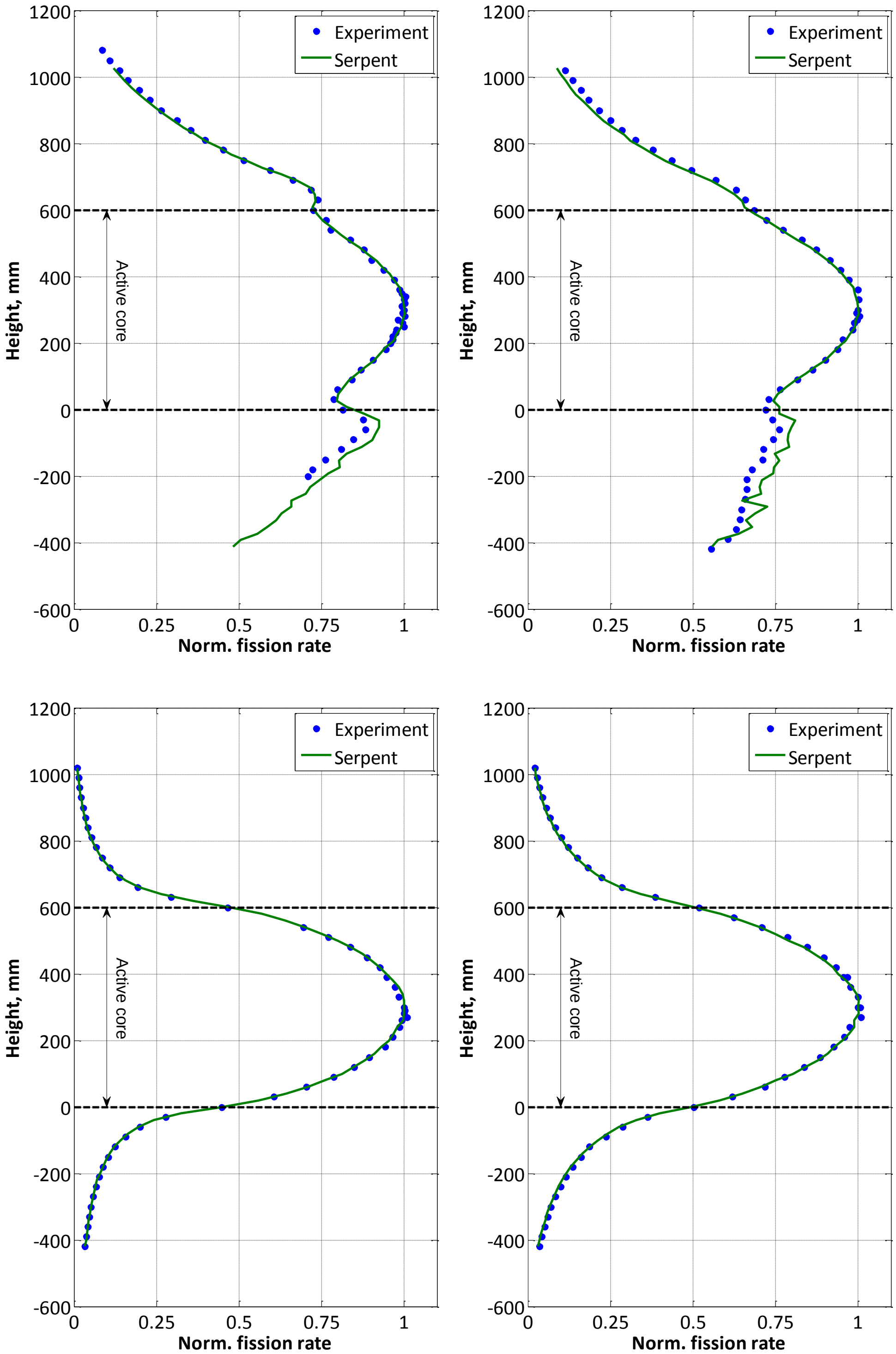


Fig. 10. Axial traverses in EFA1 of CR0 core.
Top-left: U235; top-right: Pu239; bottom-left: U238; bottom-right: Np237

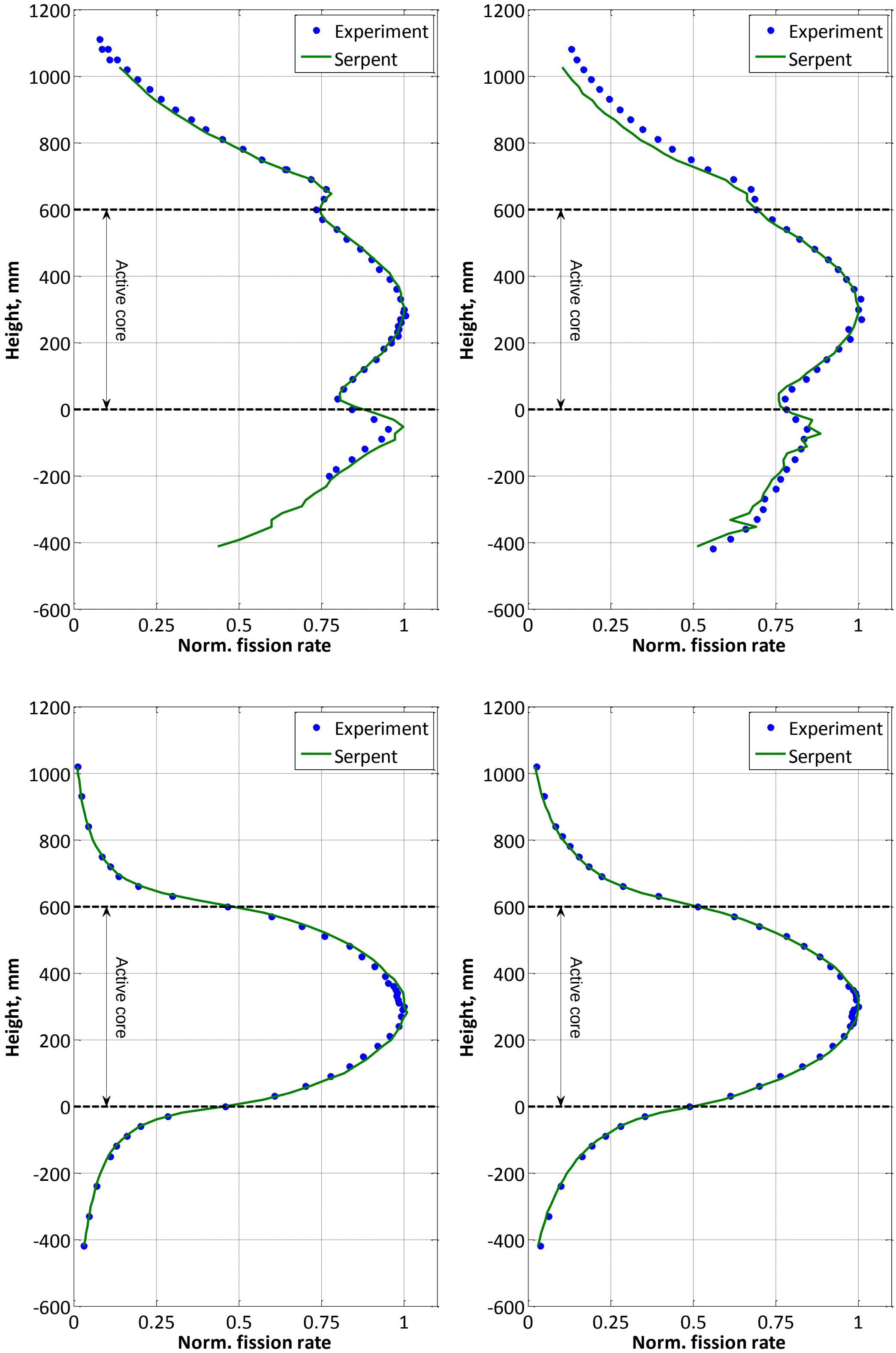


Fig. 11. Axial traverses in EFA2 of CR0 core.

Top-left: U235; top-right: Pu239; bottom-left: U238; bottom-right: Np237

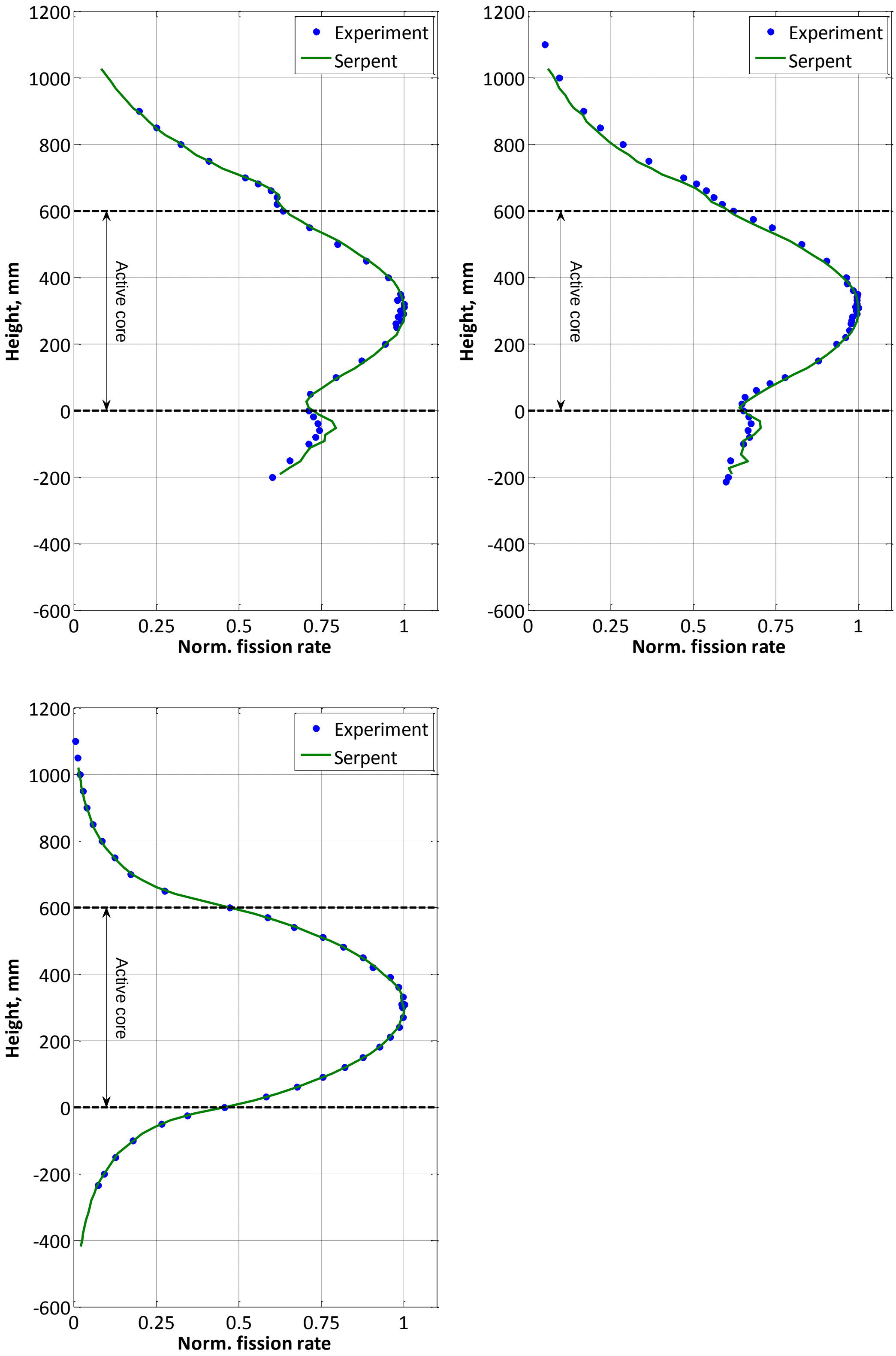


Fig. 12. Axial traverses in EFA1 of CC5 core.

Top-left: U235; top-right: Pu239; bottom-left: Np237

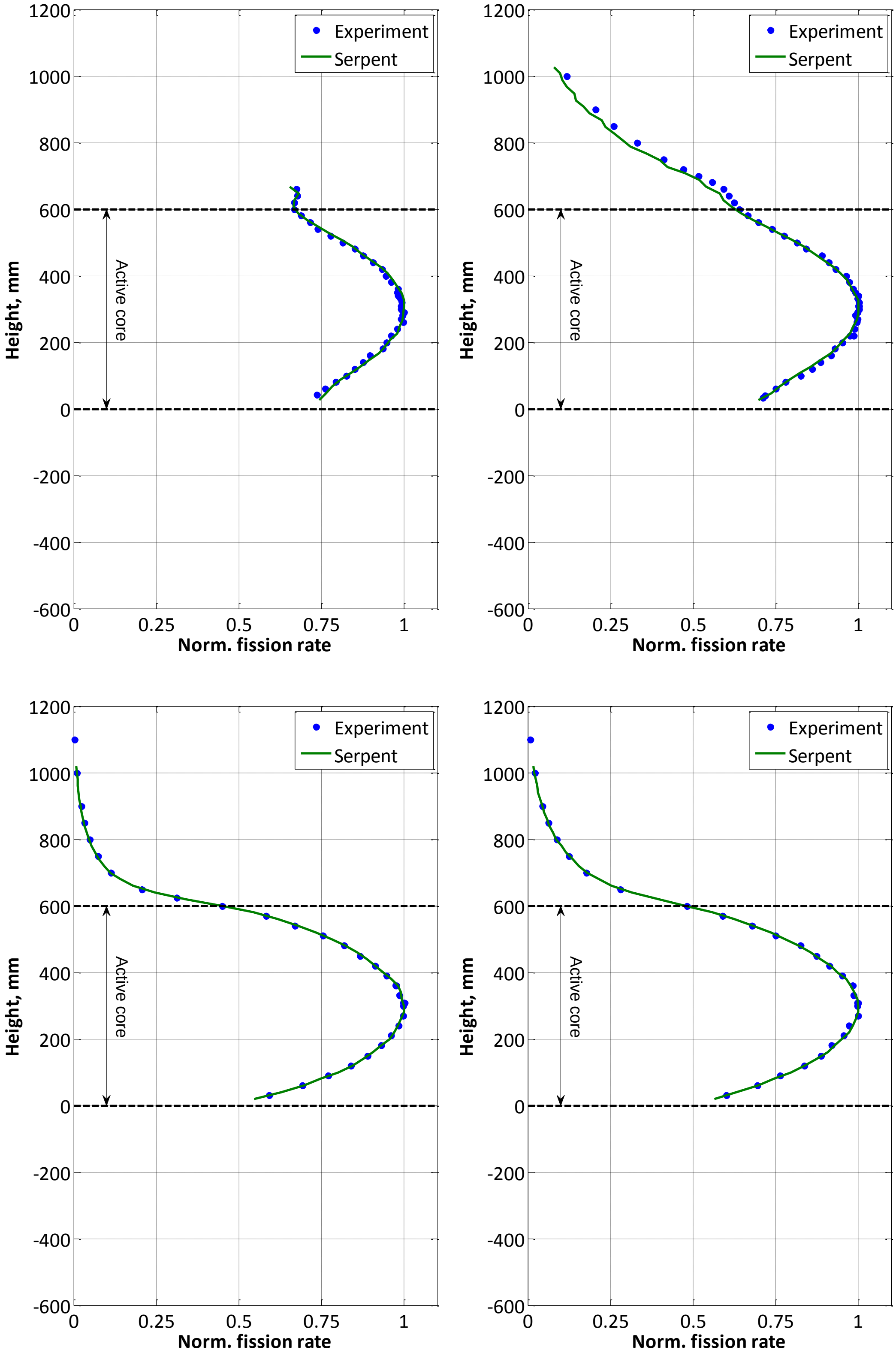
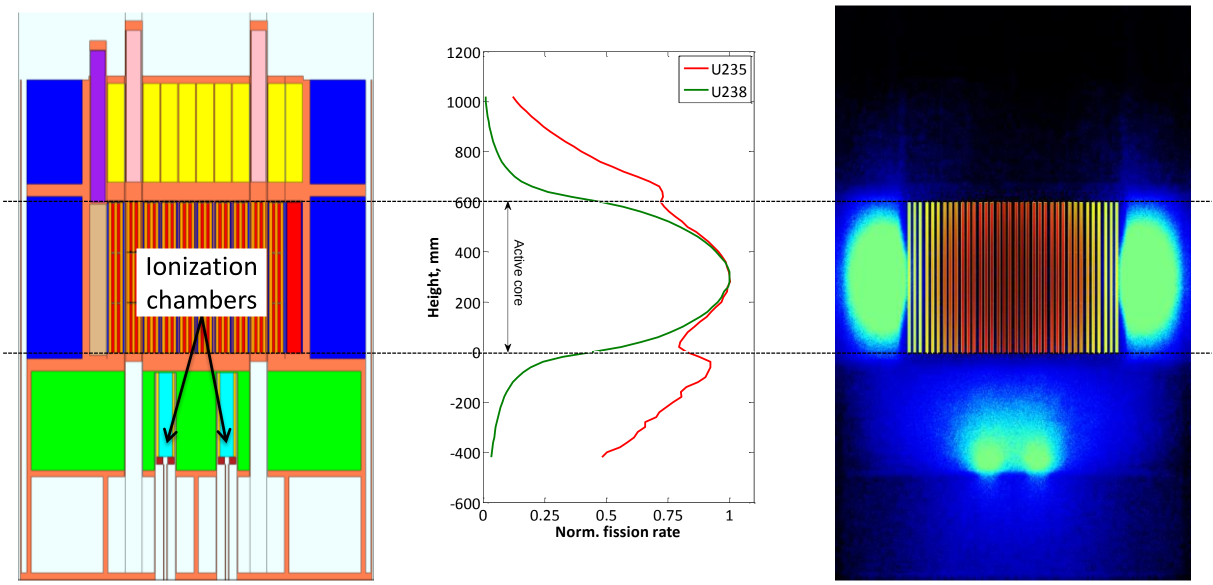


Fig. 13. Axial traverses in EFA2 of CC5 core.

Top-left: U235; top-right: Pu239; bottom-left: U238; bottom-right: Np237

The presented results reveal that the axial traverses of the fissile and fertile isotopes have noticeably different axial profiles. While fertile isotopes have practically symmetric cosine shapes, the fissile isotopes are characterized by asymmetric shapes with a secondary peak located close to the active core/bottom reflector interface. This “abnormal” behavior can be explained with the help of Fig. 14. The VENUS facility contains four ionization chambers located in the bottom reflector (Fig. 14a). The chambers are insulated with an organic polymer polyether ether ketone (PEEK). The chemical formula of PEEK is $(C_{19}H_{12}O_3)_n$. The PEEK insulator acts as a neutron moderator and produces thermal flux spots clearly visible in Fig. 14c. The presence of thermal neutrons in the bottom reflector increases the fission rates and alters the axial traverses of the fissile isotopes but does not affect the fertile isotopes having threshold fission cross sections. These results emphasize the importance of the detailed modeling not just of the active core but also of the peripheral structures and instrumentation.



a. Axial core layout (X-Z) b. Axial traverses c. Thermal flux map

Fig. 14. Effect of the ionization chambers on axial traverses

4.6 Radial traverses

This section presents the results of the radial traverse measurements conducted in the CC5 and CC8 cores with the U235 FC. The experimental and calculated radial traverses together with the locations of the experimental channels are shown in Fig. 15 and Fig. 16 for the CC5 and CC8 cores respectively. In the CC5 case, the experimental radial traverse of U235 is generally well represented by Serpent (Fig. 15). The exception is the radial reflector region where some slight differences can be observed. The experimental and calculated radial traverses of U235 in the CC8 core are in a reasonable agreement as well (Fig. 16). As compared to the CC5 core, the U235 radial traverse in CC8 has a considerably different shape with two major peaks located in the IPS channels and resulting from neutron moderation in PE.

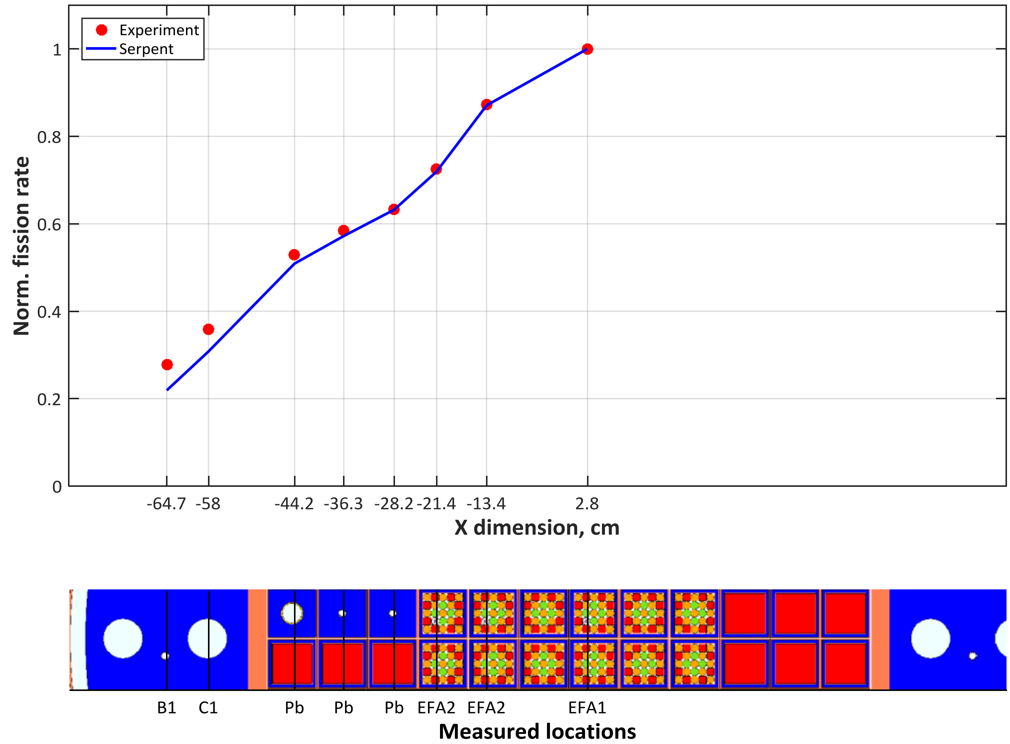


Fig. 15. U235 radial traverse in the CC5 core

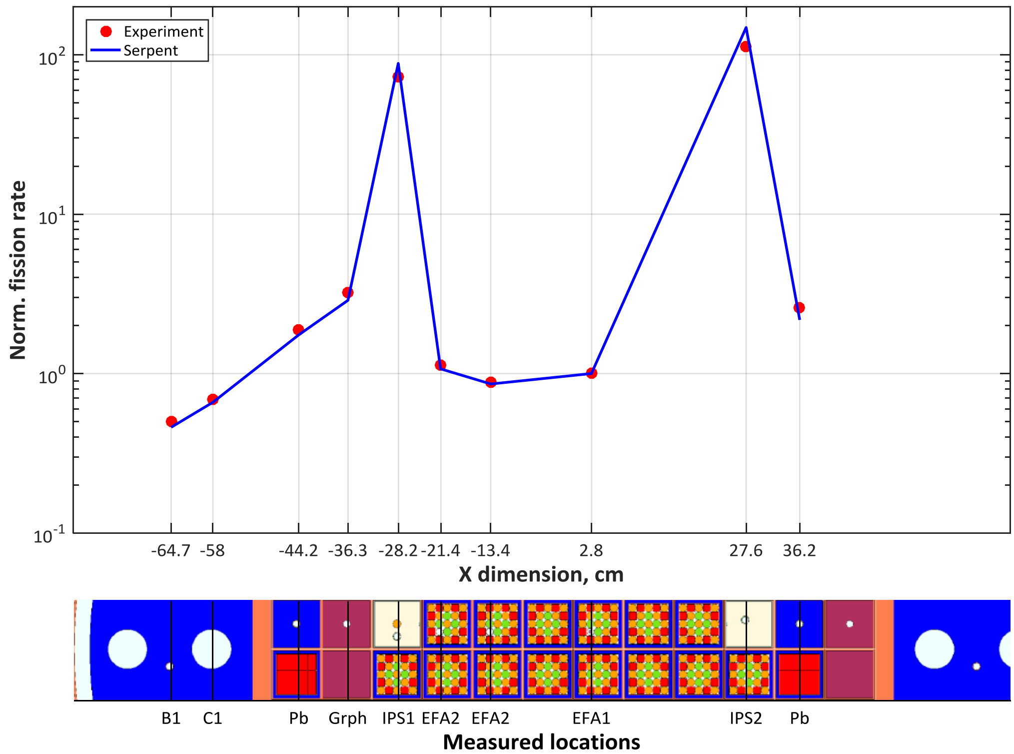


Fig. 16. U235 radial traverse in the CC8 core

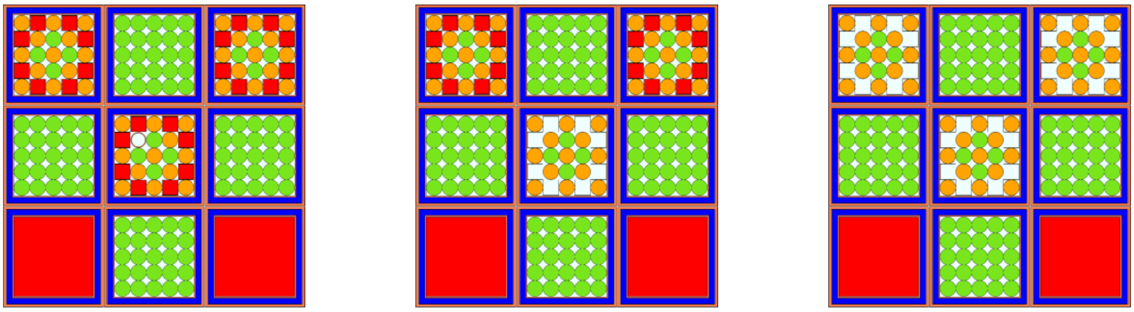
4.7 Lead void reactivity effect

The Lead Void Reactivity Effect (LVRE) measurements were performed in the CC6 core. The "voiding" was achieved by removing lead rods from the FAs located in the ALFRED island. Two different voiding scenarios were considered as shown in Fig. 17:

- Case A: Removing lead rods from the central FA (Fig. 17b)
- Case B: Removing lead rods from the central and two peripheral FAs (Fig. 17c)

The reference and the voided cores were brought to criticality by the movement of the CR. The corresponding critical CR heights in combination with the CR calibration curves were used for the evaluation of the experimental LVRE. The MC estimates of the LVRE were obtained as the difference in reactivity between the reference (Fig. 17a) and the voided states.

The experimental and calculated values of the LVRE, compared in the form of C/E-1 in Table 7, agree well within 1σ for both voiding scenarios. It is worth mentioning that in Case A the combined experimental and statistical uncertainty is more than twofold higher than in Case B due to a significantly lower magnitude of the LVRE.



a. Reference　　b. Void Case A　　b. Void Case B

Fig. 17. Modification of the ALFRED island for the estimation of lead void reactivity in CC6 core

Table 7: C/E-1 for lead void reactivity effect in CC6 core

	C/E-1, %
Case A	-4.4±8.3
Case B	0.7±3.8

5. Summary and conclusions

In the framework of the FREYA project, various critical experiments were conducted in the VENUS-F facility at SCK•CEN to support the design and licensing of fast lead-based reactor systems such as MYRRHA and ALFRED.

During the project, the Monte Carlo code Serpent was one of the codes used for the characterization of the critical VENUS-F core configurations. Four cores were modeled with Serpent, namely the reference critical core, the clean MYRRHA mock-up, the full MYRRHA mock-up, and the critical core with the ALFRED island. Very detailed Serpent models with the fully heterogeneous representation of the core and peripheral structures and instrumentation were used in the analyses.

In this paper, a number of parameters calculated by Serpent including core reactivity, point kinetics parameters, axial and radial traverses, spectral indices, and lead void reactivity effect were compared to the available experimental data. In general, a reasonably good agreement between the calculated and experimental values was observed. The reported results suggest that Serpent is an efficient and reliable tool for the modeling of the critical VENUS-F cores.

Nevertheless, the study also revealed a number of noteworthy issues requiring further attention. This includes the systematic overestimation of reactivity and systematic underestimation of the U238 to U235 fission rate ratio (F28/F25 spectral index). These inconsistencies are not specific for Serpent, other MC codes show similar trend regardless to the nuclear data library applied. In order to address these issues, some further activities are planned for the near future. This includes, for example, investigation of the k_{eff} sensitivity to uncertainties in nuclear data of lead isotopes, and in particular to that of Pb208 using a recent Serpent version with sensitivity/perturbation calculation capabilities (Aufiero et al., 2015). In addition the experimental values of F28/F25 will be reassessed by reevaluation of the effective masses of the U238 FCs and performing additional measurements of F28/F25 using alternative techniques (i.e. activation foils). Some of these experimental activities will be conducted in the framework of the on-going project MYRTE, the follow-up project of FREYA.

Acknowledgment

This work was supported by the 7th Framework Program of the European Commission (EURATOM) through the FREYA Project under the contract FP7-2010-269665.

References

Alhassan, E., Sjöstrand, H., Helgesson, P., Koning, A.J., Österlund, M., Pomp, S., Rochman, D., 2015. Uncertainty and correlation analysis of lead nuclear data on reactor parameters for the European Lead Cooled Training Reactor. Annals of Nuclear Energy 75, pp. 26–37.

Aufiero, M., Bidaud, A., Hursin, M., Leppänen, J., Palmiotti, G., Pelloni, S., Rubiolo, P., 2015. A collision history-based approach to sensitivity/perturbation calculations in the continuous energy Monte Carlo code SERPENT. Annals of Nuclear Energy 85, pp. 245–258.

Aufiero, M., Martin, M., Fratoni, M., Fridman, E., Lorenzi, S., 2016. Analysis of the coolant density reactivity coefficient in LFRs and SFRs via Monte Carlo perturbation/sensitivity, in Proc.: PHYSOR 2016, Sun Valley, ID, USA.

Bécares, V., Fridman, E., Fabrizio, V., Krása, A., Villamarín, D., Carta, M., Kochetkov, A., Firpo, G., Gabrielli, F., 2016. MYRRHA Critical Mock-up Characterization, FREYA deliverable D3.2.

Doligez, X., Billebaud, A., Chabod, S., Chevret, T., Fourmentel, D., Krasa, A., Kochetkov, A., Lecolley, F.R., Lecouey, J.L., Lehaut, G., Marie, N., Mellier, F., Vittiglio, G., Wagemans, J., 2015. Effective delayed neutron fraction measurement in the critical VENUS-F reactor using noise techniques, in Proc.: 2015 4th International Conference on Advancements in Nuclear Instrumentation Measurement Methods and Their Applications, ANIMMA 2015, Lisbon, Portugal.

Engelen, J., Aït Abderrahim, H., Baeten, P., De Bruyn, D., Leysen, P., 2015. MYRRHA: Preliminary front-end engineering design. International Journal of Hydrogen Energy 40, pp. 15137–15147.

Grasso, G., Petrovich, C., Mattioli, D., Artioli, C., Sciora, P., Gugiu, D., Bandini, G., Bubelis, E., Mikityuk, K., 2014. The core design of ALFRED, a demonstrator for the European lead-cooled reactors. Nuclear Engineering and Design 278, pp. 287–301.

Kiedrowski, B.C., Brown, F.B., Wilson, P.P.H., 2011. Adjoint-weighted tallies for k-eigenvalue calculations with continuous-energy Monte Carlo. Nuclear Science and Engineering 168, pp. 226–241.

Kochetkov, A., Baeten, P., Billebaud, A., Chabod, S., Doligez, X., Lecolley, F.R., Lecouey, J.L., Lehaut, G., Marie, N., Mellier, F., Thyébault, H.E., Uyttenhove, W., Vittiglio, G., Wagemans, J., Ban, G., Dessagne, P., Kerveno, M., Mercatali, L., 2013. Current progress and future plans of the FREYA Project, in Proc.: International Workshop on Technology and Components of Accelerator Driven Systems (TCADS) OECD Nuclear Energy Agency, Technology and Components of Accelerator-Driven Systems Second International Workshop Proceedings 21-23 May 2013, Nantes, France.

Kochetkov, A., Krása, A., Baeten, P., Vittiglio, G., Wagemans, J., Bécares, V., Bianchini, G., Fabrizio, V., Carta, M., Firpo, G., Fridman, E., Sarotto, M., 2016a. Analysis of C/E results of fission rate ratio measurements in several fast lead VENUS-F cores, in Proc.: ND2016, Bruges, Belgium.

Kochetkov, A., Krása, A., Vittiglio, G., Wagemans, J., Bianchini, A.G., Fabrizio, V., Carta, M., Firpo, G., Fridman, E., Sarotto, M., Bécares, V., 2016b. Spectrum Index and Minor Actinide Fission Rate Measurements in Several Fast Lead Critical Cores in the Zero Power Venus-F Reactor, in Proc.: PHYSOR 2016, Sun Valley, ID, USA.

Kochetkov, A., Wagemans, J., Vittiglio, G., 2012. VENUS-F: A first fast lead critical core for benchmarking. Journal of ASTM International 9, pp. 1–7.

Lecouey, J.L., Marie, N., Ban, G., Bianchini, G., Billebaud, A., Carta, M., Chabod, S., Fabrizio, V., Kochetkov, A., Lecolley, F.R., Lehaut, G., Mellier, F., Thyébault, H.E., Uyttenhove, W., Van Grieken, C., Vittiglio, G., 2015. Estimate of the reactivity of the VENUS-F subcritical configuration using a Monte Carlo MSM method. Annals of Nuclear Energy 83, pp. 65–75.

Lehaut, G., Lecouey, J.L., Marie, N., Baeten, P., Bécares, V., Billebaud, A., Chabod, S., Chevret, T., Doligez, X., Kochetkov, A., Krasa, A., Lecolley, F.-R., Mellier, F., Uyttenhove, W., Villamarin, D., Vittiglio, G., Wagemans, J., 2015. Study of space-energy effects in subcritical reactor within a time-dependent multi-group 1- dimensional diffusion approach, in Proc.: ICAPP 2015, Nice, France.

Leppänen, J., Aufiero, M., Fridman, E., Rachamin, R., van der Marck, S., 2014. Calculation of effective point kinetics parameters in the Serpent 2 Monte Carlo code. Annals of Nuclear Energy 65, pp. 272–279.

Leppänen, J., Pusa, M., Viitanen, T., Valtavirta, V., Kaltiaisenaho, T., 2015. The Serpent Monte Carlo code: Status, development and applications in 2013. Annals of Nuclear Energy 82, pp. 142–150.

Maria, S. Di, Y.Romanets, P.Teles, P.Vaz, G.Mila, S.Argirò, Beolé, S., Maserab, M., A.Kochetkov, P.Baeten, W.Uyttenhove, G.Vittiglio, J.Wagemans, A.Billebaud, M. Osipenko, 2014. Area and Prompt Decay Constant Techniques for Reactivity Assessment in Deep Subcritical Configuration : A Case Study within the Framework of the FREYA Project, in Proc.: 13. Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, Seoul, Republic of Korea.

OECD/NEA, 2004. Benchmark on the Three-dimensional VENUS-2 MOX Core Measurements, NEA/NSC/DOC(2003)5, Paris, France.

OECD/NEA, 2000a. Prediction of neutron embrittlement in the reactor pressure vessel: VENUS-1 and VENUS-3 benchmarks, ISBN 92-64-17637-3, Paris, France.

OECD/NEA, 2000b. Benchmark on the Venus-2 MOX core measurements, NEA/NSC/DOC(2000)7, Paris, France.

SCK•CEN, 2016. MYRTE - MYRRHA Research and Transmutation Endeavour [WWW Document]. http://myrte.sckcen.be/en

Uyttenhove, W., Lathouwers, D., Kloosterman, J.-L., van der Hagen, T.H.J.J., Van den Eynde, G., Baeten, P., 2014. Methodology for modal analysis at pulsed neutron source experiments in accelerator-driven systems. Annals of Nuclear Energy 72, pp. 286–297.

Uyttenhove, W., Van Den Eynde, G., Baeten, P., Kochetkov, A., Vittiglio, G., Wagemans, J., Lathouwers, D., Kloosterman, J.-L., Van Der Hagen, T.J.H.H., Wols, F., Billebaud, A., Chabod, S., Thybault, H.-E., Lecouey, J.-L., Ban, G., Lecolley, F.-R., Marie, N., Steckmeyer, J.-C., Dessagne, P., Kerveno, M., Mellier, F., 2012. Detector positioning for the initial subcriticality level determination in accelerator-driven systems, in Proc.: PHYSOR 2012.