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The Lead-Based VENUS-F Facility: Status of the FREYA Project

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Abstract. The GUINEVERE project in the 6th European Framework Program (FP6) [1] aimed to check the methods for sub-criticality monitoring. To execute the project, the water-moderated thermal VENUS facility was modified into the lead fast VENUS-F facility in the period 2007–2010. To prove the reliability of the reactivity monitoring methods, first of all a critical reference configuration was assembled and characterized by measurements of criticality, power distribution, and spectral indexes. These experiments were communicated for benchmarking at ISRD-14 [2]. The Monte Carlo MCNP 5-1.60 code with the JEFF 3.1.2 data library is used to perform simulations of the VENUS-F core, in particular to obtain Calculated-to-Experimental ratios (C/E) for fission rates and spectral indices. A sensitivity study is performed focusing on the impact of global and local parameters on C/E. In most cases C/E is close to unity within the uncertainties. Only a few exceptions were found, e.g. for the F28/F25 spectral index [3]. In order to investigate the discrepancies, a new measurement campaign with the same critical configuration was included in the currently ongoing FREYA project in FP7 [4]. The facility status, experimental plans, and the sensitivity study are presented in this paper.

1. Introduction

The GUINEVERE (Generator of Uninterrupted Intense NEutrons at the lead VEnus REactor) Project [1] was launched in 2006 within the framework of the FP6 IP-EUROTRANS program, devoted to feasibility studies for Accelerator Driven Systems envisaged in partitioning and transmutation strategies. This project mainly focused on the validation of a methodology for on-line reactivity monitoring of a sub-critical system. To execute the project, the water-moderated thermal VENUS facility was modified into the lead fast VENUS-F facility with solid components in the period 2007-2010. After the modification of the facility, the GUINEVERE project started with measurements in 2011 at the fast critical reference configuration called CR0. This core was loaded with enriched uranium and solid lead and had a solid lead reflector.

First, the operational parameters of the CR0 core were experimentally determined and evaluated in order to obtain the core certificate for full operation of the critical facility. These results were presented in [5]. Then, core characterisation parameters including spectral indices and radial and axial fission

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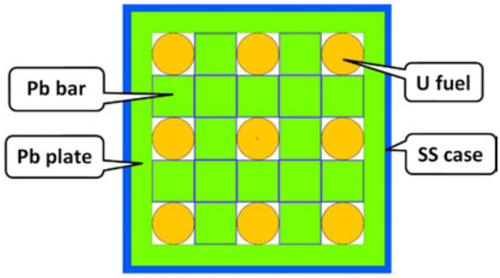

Figure 1. Cross section of a FA for the first VENUS-F core showing the cylindrical fuel rodlets and the square lead rodlets.

rate distributions were measured. The list of the measured parameters was presented for benchmarking in [2].

The Monte Carlo MCNP 5-1.60 code with the JEFF 3.1.2 data library is used to perform simulations of the VENUS-F core, in particular to obtain Calculated-to-Experimental ratios (C/E). A sensitivity study is performed focusing on the impact of global and local parameters on C/E. These studies include the influence of the air gaps between assemblies, the VENUS-F barite concrete bunker, and the impurities in the reflector zone. The results of this sensitivity analyses are presented in this paper.

In most cases C/E is close to unity within the uncertainties. Only a few exceptions were found, e.g. the F28/F25 spectral index (i.e. the ratio of the 238U to 235U fission rates) [3]. To check the discrepancies and to carry out additional experiments, a new measurement campaign with the same VENUS-F critical configuration CR0 was included in the currently ongoing FP7 FREYA project [4]. The facility status, experimental plans, and the sensitivity study are presented in this paper.

2. CR0 VENUS-F Critical Configuration

After the modifications that finished in 2010, the VENUS-F fast zero power reactor was installed in a cylindrical vessel of approximately 80 cm in radius and 140 cm in height. A 12×12 grid surrounded by a 30 mm stainless steel casing can receive up to 144 elements of $8 \times 8\,\text{cm}^2$ in section, which currently can be fuel assemblies, lead assemblies or specific elements for accommodating detectors or absorbent rods. The remaining space in the vessel is filled with semi-circular lead plates, which act as an outer radial neutron reflector. In addition, the core is reflected by top and bottom 40 cm-thick lead reflectors. Each fuel assembly (FA) consists of a 5×5 pattern filled with 9 fuel rodlets and 16 lead bars surrounded by lead plates (see Fig. 1). The fuel is 30 wt.% enriched metallic uranium provided by CEA (France).

After investigations of reactivity monitoring methods in different sub-critical VENUS-F cores coupled with the GENEPI-3C accelerator, in December 2013 the VENUS-F core was returned to the initial CR0 critical configuration. This configuration is shown in Fig. 2. 97 FAs are arranged in a pseudo-cylindrical core. Among them, six are actually safety rods (SR) made of boron-carbide with fuel followers with the absorbent part retracted from the core in normal operation. At the core periphery two boron-carbide control rods (CR) are used to adjust the reactivity. They can be moved from 0 mm (fully inserted inside the core) to 600 mm (fully pulled out). The special FAs with small holes are placed in positions E-1, E-2 and E-3 in the core. They are used for axial traverse and spectrum indes measurements with small fission chambers.

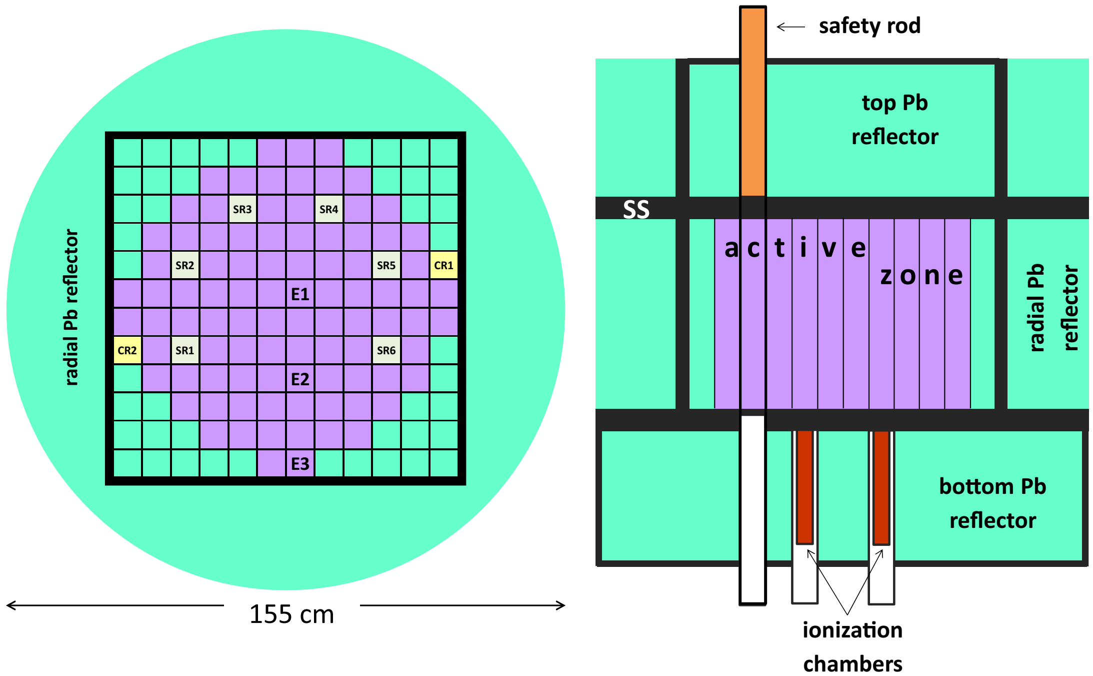

Figure 2. The CR0 VENUS-F critical configuration: horizontal cut (left) and vertical cut (right).

3. VENUS-F Sensitivity Study

In order to understand the VENUS-F design features for the validation of the critical core experiments [2], a sensitivity study [6] is performed on the VENUS-F CR0 critical core design. Some typical VENUS-F parameters are identified that can influence the results of the core characterisation experiments.

In this section, the results from the measurement campaign on the first VENUS-F critical core are compared to calculational results obtained with MCNP. Therefore the VENUS-F core was modelled in MCNP [7], and simulations were made with MCNP 5.160 [8] using the JEFF3.1.2 library [9].

3.1 Inter-assembly Air Gap

In a first stage, design parameters that influence the global parameter k_{eff} are investigated. Besides the well-known parameters such as fuel composition and impurities in the lead material, the air gap between the VENUS-F fuel assemblies inside the 12 × 12 grid is also an important parameter.

By design, an air gap of 0.7 mm is foreseen between the assemblies. To have a first estimation of the importance of this inter-assembly air gap, the thickness of the stainless steel casing is reduced to increase the gap. A change from 0.7 mm to 1 mm corresponds to a decrease of 126 +/−10 pcm. This change does not represent reality as the stainless steel casing thickness is well known, however it shows the importance of the air gap. In reality, the inter-assembly air gap could be slightly higher than 0.7 mm at certain positions in the 12 × 12 grid due to an inclination of the fuel assemblies, as there is 0.3 mm space between the outer assembly and the stainless steel casing of the 12 × 12 grid. This inclination effect is complex to model in neutronic codes.

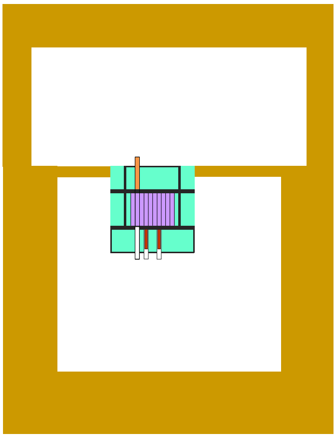

Figure 3. The VENUS-F reactor surrounded by the barite concrete bunker.

3.2 Concrete VENUS-F Bunker

The barite VENUS-F bunker (Fig. 3) acts as a reflector and thermalizing element for neutrons. Therefore a clear effect on the neutron spectra at the border of the VENUS-F core is noticed. Also inside the outer fuel assemblies, the neutron spectra are slightly modified, leading to an increase in k_{eff} of about 156 ± 10 pcm.

3.3 Impurities in the Top Lead Reflector

The VENUS-F top lead reflector contains Sb impurities. It leads to a decrease in k_{eff} of 162 ± 10 pcm. The effect of Sb can be illustrated on comparison of measured and calculated axial traverses using fissile isotopes. Figure 4(a) shows the axial traverse of a U-235 fission chamber inside the E1 experimental assembly. The simulations with and without Sb in the top Pb reflector considerably differ in the region above the active zone, where the Sb impurity is present. The calculation that takes the Sb impurity into account agrees very well with the experimental data.

3.4 Bottom Reflector Structures

In position E1, the profile of the axial traverse with fissile isotopes shows a flat behaviour in the bottom reflector (see Fig. 4(b)), contrary to the E2 and E3 profile. This flattening is due to the presence of the four ionisation chambers in the bottom reflector. The ionisation chambers contain a PEEK (polyether ether ketone) insulator block, which is a strongly thermalizing material for neutrons.

Figure 4(b) shows the simulations of the influence of the ionisation chambers' position on the axial traverse for Pu-239 in the E1 position. In the "Top 1" position, the ionisation chambers (with a length of about 37 cm) are located against the fuel grid support plate, completely inside the bottom reflector of 40 cm. The "Top 2" position corresponds to an 11 cm lower position, the "Middle Position" is 23 cm lower, and the "Bottom Position" is 46 cm lower located.

One can conclude that the effect of the position of the ionisation chambers on the Pu-239 traverse in E1 is significant, although the effect on k_{eff} between highest and lowest position is only 80 ± 10 pcm.

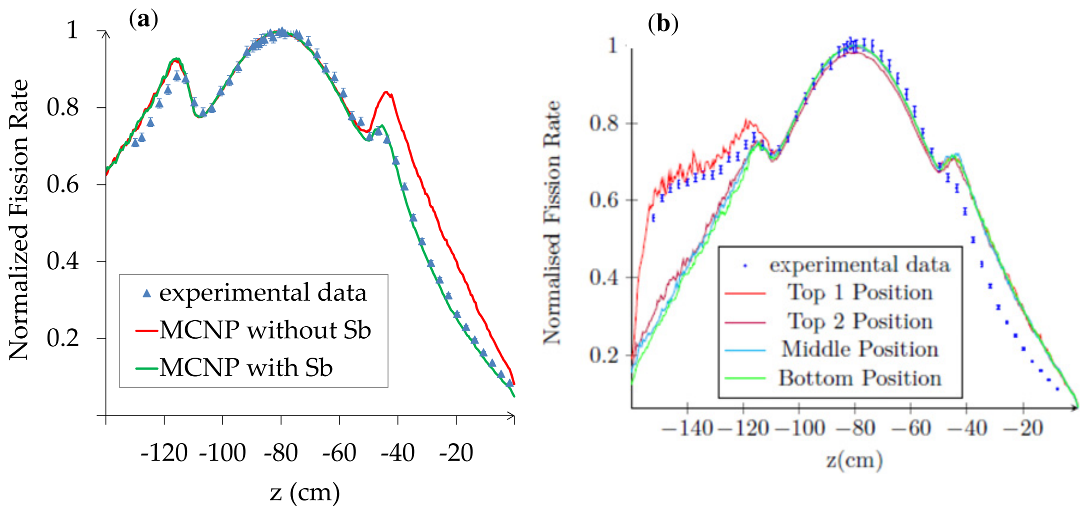

Figure 4. Axial traverses through the VENUS-F CR0 core at position E1. The centre height of the core is at z about −80 cm, the top of the core corresponds to z = 0 cm. a) U-235 fission rate for various amount of Sb impurities. b) Pu-239 fission rates for different heights of the ionisation chambers in the bottom reflector.

4. Recent Experiments in the CR0 Core

The measurements in 2011 at the first fast VENUS-F critical reference configuration CR0 were reported for benchmarking at ISRD-14 [2]. These include facility operational parameters such as safety and control rods worth and core characterisation parameters such as spectral indices, and radial and axial fission rate distributions. Since that time the analysis of these measurements were accomplished and C/E results are ready to be published [3]. In most cases C/E is close to unity within the uncertainties. Only a few exceptions were found, e.g. the F28/F25 spectral index. In order to study the discrepancies, a new measurement campaign in the same critical core configuration was executed in the period December 2013 – January 2014. This campaign consisted of CR worth calibrations, spectrum index (especially F28/F25) measurements with fission chambers and with foils, both in the same positions as in 2011 as in new positions, and additional axial traverses in position E-3.

4.1 Calibration of the Control Rods

In 2011 the control rod calibrations were performed applying the stable period method. Since the “critical” position for the control rods was around 400 mm, only half of the curves (the upper part) were measured. The lower parts of the curves were obtained by extrapolation. The CR worth values obtained with deterministic and Monte Carlo computer codes are not in a good agreement between each other, nor with the experimental extrapolated values. Particularly noticeable differences between the results of the calculations was observed for the estimations of the so-called “shadow effect of the CRs”: the sum of the separate worths of CR1 and CR2 often is not equal the worth of CR1 and CR2 moving together. For this reason new CR calibrations were performed in December 2013. The measurements of the sub-criticality evolution due to the CRs movement were carried out applying the MSM method with the Am-Be external neutron source. This method gave the possibility to measure all points of the CR curves and to measure the worth of both CRs moving together and separately. The analysis of these measurements are ongoing.

Table 1. Fission chambers and positions used for the fission rate ratio measurements.

	Positions		
Deposit	**E-1**	**E-2**	**E-3**
U-234	+		
U-235	+	+	+
U-238	+	+	+
Np-237	+	+	
Pu-239	+	+	
Pu-240	+	+	
Pu-242	+	+	

+ Measurement performed.

4.2 Axial Traverses Measurements

For the axial traverses, fission chambers (FCs) with U-235, U-238, Np-237 and Pu-239 deposits were used in 2011. All FCs were placed in the positions E-1 and E-2 (Fig. 2), but for the E-3 position only one FC with Pu-239 was applied.

Taking into account the design features presented in chapter 3, in general the calculation predict quite well the experimental fission rate distributions. But the difference between calculation and experimental values for Pu-239 axial fission rate distribution in position E-3 in some points was several times more than the uncertainties.

To solve these C/E problems, additional measurements with FCs in position E-3 were executed. The analyses are ongoing.

4.3 Foils Irradiation for Spectrum Index and Radial Traverse

Uranium foils were irradiated in 2011for the determination of the radial U-235 fission rate distribution and the C28/F25 spectrum index. The experimental fission rate distribution is in agreement with the calculated distribution within the uncertainties, except in the last FA on the fuel-reflector border. Therefore new experiments were performed focusing on this region. The experimental results obtained in 2011 were confirmed. Concerning the C28/F25 spectrum index, new measurements were performed with foils around the core centrum, to verify a possible dependence of the spectrum index on the surrounding material (fuel, Pb). No effect was observed within the uncertainties. Moreover the results are in good agreement with the calculations.

4.4 Fission Rates Ratios Obtained with Fission Chambers

The spectral indices as fission rate ratios of Pu-239 and U-238 to U-235 and of Pu-240, Pu-242, U-234 and Np-237 to U-235 were measured in 2011 using fission chambers at several positions in the CR0 critical core (see Table 1).

These measurements were also simulated with Monte Carlo calculations. In general good C/E agreement was found, however in some cases discrepant values were observed. In particular for the F28/F25 fission rate ratios obtained in all positions (E-1, E-2 and E-3) C/E was not good. Therefore in January 2014 these measurements were repeated for two positions (E-2 and E-3) and in addition the F37/F25, F40/F25 and F49/F25 fission rate ratios in position E-3 were measured. In general the new measurements showed the same results as the ones in 2011 and correspondently the same C/E values.

5. Conclusions

The first characterization measurements at the fast lead critical CR0 core of the VENUS-F facility carried out in 2011 communicated for benchmarking at ISRD-14. These include measurements of criticality, control rod worth, axial and radial fission rate distributions and spectrum indices.

The Monte Carlo MCNP 5-1.60 code with the JEFF 3.1.2 data library is used to perform simulations of the VENUS-F core, in particular to obtain Calculated-to-Experimental ratios (C/E). A sensitivity study is performed focusing on the influence of different parameters, such as the concrete of the reactor bunker, the bottom reflector structure, air gaps, Sb impurities in the Pb of the top reflector and the PEEK insulator of the ionization chambers.

In general a good agreement between the experiments and the calculations was found, however for some measurements this was not the case. Therefore new experiments have been recently performed. The analyses of these experiments are currently ongoing.

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