Analysis of C/E results of fission rate ratio measurements in several fast lead VENUS-F cores

Anatoly Kochetkov[1,a], Antonín Krása[1], Peter Baeten[1], Guido Vittiglio[1], Jan Wagemans[1], Vicente Bécares[2], Giancarlo Bianchini[3], Valentina Fabrizio[3], Mario Carta[3], Gabriele Firpo[4], Emil Fridman[5], and Massimo Sarotto[6]

[1] Belgian Nuclear Research Centre SCK•CEN, Advanced Nuclear Systems Institute, 2400 Mol, Belgium
[2] CIEMAT, Madrid, Nuclear Fission Division, Spain
[3] ENEA CASACCIA, Energy and Sustainable Economic Development, Roma, Italy
[4] ANSALDO NUCLEARE, S.p.A, Genova, Italy
[5] HZDR, Helmholtz-Zentrum Dresden-Rossendorf, Germany
[6] ENEA UTFISSM-PRONOC, Energy and Sustainable Economic Development, Saluggia (VC), Italy

Abstract. During the GUINEVERE FP6 European project (2006–2011), the zero-power VENUS water-moderated reactor was modified into VENUS-F, a mock-up of a lead cooled fast spectrum system with solid components that can be operated in both critical and subcritical mode. The Fast Reactor Experiments for hybrid Applications (FREYA) FP7 project was launched in 2011 to support the designs of the MYRRHA Accelerator Driven System (ADS) and the ALFRED Lead Fast Reactor (LFR). Three VENUS-F critical core configurations, simulating the complex MYRRHA core design and one configuration devoted to the LFR ALFRED core conditions were investigated in 2015. The MYRRHA related cores simulated step by step design peculiarities like the BeO reflector and in pile sections. For all of these cores the fuel assemblies were of a simple design consisting of 30% enriched metallic uranium, lead rodlets to simulate the coolant and Al_2O_3 rodlets to simulate the oxide fuel. Fission rate ratios of minor actinides such as Np-237, Am-241 as well as Pu-239, Pu-240, Pu-242 and U-238 to U-235 were measured in these VENUS-F critical assemblies with small fission chambers in specially designed locations, to determine the spectral indices in the different neutron spectrum conditions. The measurements have been analyzed using advanced computational tools including deterministic and stochastic codes and different nuclear data sets like JEFF-3.1, JEFF-3.2, ENDF/B7.1 and JENDL-4.0. The analysis of the C/E discrepancies will help to improve the nuclear data in the specific energy region of fast neutron reactor spectra.

1. Introduction

The EU FP7 project FREYA [1] (Fast Reactor Experiments for hYbrid Applications) was recently (March 2016) finalized. During the last two years of this project, four critical VENUS-F reactor cores were investigated. These zero power cores represented the features of the lead cooled fast core designs of the ADS MYRRHA [2] and LFR ALFRED [3]. The composition of the fuel assemblies (FA) for these cores consisted of enriched metallic uranium, lead and Al_2O_3 rodlets to simulate the oxide fuel of MYRRHA and ALFRED.

Some Minor Actinide (MA) cross sections are not very well known yet in the fast energy region, especially for lead cooled fast systems. For this reason, several MA fission rate ratios have been measured with small size (4 mm diameter) Fission Chambers (FC) placed in channels that are present in some assemblies in various positions of the investigated cores. To validate the reliability of neutron spectrum calculations, the standard spectral indices as F28/F25 and F49/F25 were measured as well.

The first analysis of the measurements have been carried out with deterministic (ERANOS [4]) and stochastic (MCNP [5], Serpent [6]) codes. In all these calculations the JEFF-3.1 [7] data set was used. The results were recently presented in the PHYSOR conference (May 2016, [8]). It was pointed out there that the only acceptable C/E (calculation to experiment) results were obtained for the F49/F25 fission rate ratios. For all the others indices the C/E results are out of the uncertainty limits. In the conclusions of this paper it was proposed to investigate the disagreement between experiment and calculation for the threshold fission rate ratios and especially for the standard F28/F25 index with following actions:

- performing the calculations with other data sets such JEFF-3.2, ENDF/B7.1, JENDL-4.0;
- measuring and estimating the influence of the impurities in the deposits for all fission chambers.

In this paper the measurements have been analyzed using deterministic and stochastic codes and different nuclear data sets like JEFF-3.1, JEFF-3.2, ENDF/B7.1, and JENDL-4.0. Furthermore, the U-235 content in the U-238 fission chamber deposits was measured in the standard neutron fields of the BR-1 reactor [9].

The C/E (calculation to experiment) and C/C (calculation to calculation) results are presented and discussed in this paper.

[a] e-mail: anatoly.kochetkov@sckcen.be

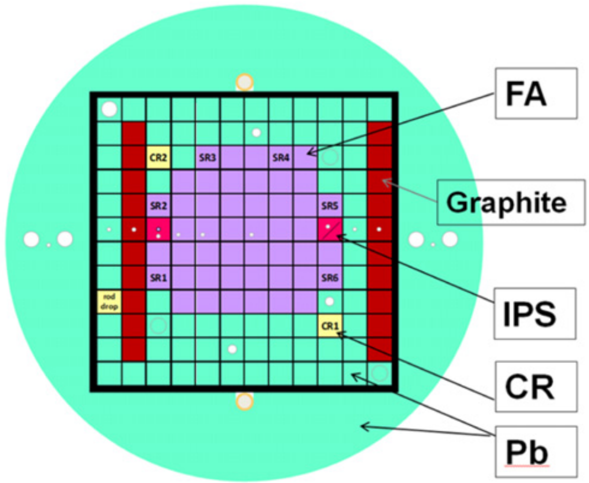

Figure 1. VENUS-F CC8 core to simulate reflector and IPS of MYRRHA.

2. Core configuration and detectors

In 2011 the zero-power water-moderated VENUS reactor, that was extensively used for benchmarking in the past, was modified into VENUS-F. This system has a 12 × 12 grid surrounded with a stainless steel casing, in which square assemblies (8 × 8 cm^2) fit. This grid can be filled with fuel, reflector (lead) or other assemblies and with 6 safety and 2 control rods as well. The safety rods consist of an absorbing material (B4C with natural boron), with a fuel follower (with the same pattern as in the core). When a safety rod is up, its fuel follower is at the height of the core, thereby eliminating core perturbations. Some special assemblies with axial detector channels are also present. Around the core there are 40 cm top and bottom lead reflectors, as well as a radial lead reflector around the casing, filling the whole 160 cm diameter of the existing VENUS vessel.

Three VENUS-F critical configurations simulating complex MYRRHA core designs and one configuration devoted to the ALFRED core conditions were investigated in 2015. The MYRRHA related cores simulated step by step the design peculiarities like the reflector and In Pile Sections (IPS) and are called CC5, CC7 and CC8 (see details for all cores in [8] and Fig. 1 for the last core). The VENUS-F core with the ALFRED island is called CC6. In all these cores, the Fuel Assemblies (FA) contained 30% enriched metallic uranium, lead rodlets to simulate the coolant and Al_2O_3 rodlets for oxide fuel simulation (Fig. 2, left).

3. Detectors used

For the measurements of the spectrum indices and the MA fission rate ratios, small FCs with 4 mm outer diameter and small deposit mass (20–200 μg) were used. FCs with the following deposits were used for the measurements: U-235, U-238, Pu-239, Pu-240, Pu-242, Np-237 and Am-241. For the measurements these FCs were placed in specific Experimental Fuel Assemblies (EFA, see Fig. 2) that have a special stainless steel guiding tube instead of the standard FA element in the 5 × 5 FA structure or in reflector assemblies with appropriate holes (see Fig. 1) in the middle plane of the core. In the CC6 and CC7 cores the measurements were performed only in one specific position and not with all FCs while in the CC5 and CC8 cores many positions along the core radius and all available FCs were used.

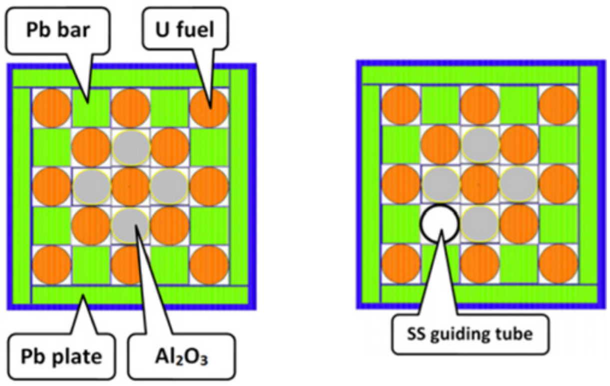

Figure 2. Left: fuel assembly; Right: experimental fuel assembly.

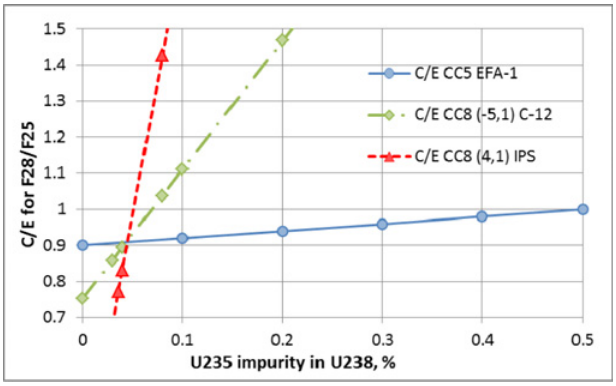

Figure 3. C/E for F28/F25 depending of the U-235 content in the U-238 deposit of the FC. The calculated results obtained with MCNP and JEFF-3.1 data were used.

Even tiny amounts of U-235 that are usually present as an impurity in U-238 fission chamber deposits should be taken into account, especially when analysing partly thermalized neutron spectra like in the investigated cores nearby graphite and polythene (see Fig. 3). To cheverifyck the available certificate data of U-235 impurities in the U-238 deposits of the FCs, they were placed in a standard neutron field of the BR1 reactor to measure the real U-235 content. We observed that the U-235 content in the U-238 deposits that were used for the spectral index measurements is about 0.04%. This is in good agreement with the certificate (0.036%).

4. Analysis of the results

4.1. Computational tools

The spectral indices were calculated using the following computational tools including both deterministic and stochastic codes and recent nuclear data sets.

ERANOS (European Reactor ANalysis Optimized System) is a deterministic nuclear code that allows solving the transport equation. This is a modular system with several functions to analyze reactivity, fluxes, burn-up

Table 1. C/E results obtained with JEFF-3.1 and with different codes.

	C/E results : CC8 core, EFA-1 position, JEFF-3.1 data						Experiment uncert. ±%
	MCNP 6.1.1	**SERPENT**	**ERANOS**	**averaged**	st dev %	Max-Min %	
F28/F25	0.903	0.907	0.960	**0.923**	**2.8**	**6.2**	**2.0**
F49/F25	0.991	1.007	1.013	**1.004**	0.9	**2.2**	**2.1**
F37/F25	0.929	0.970	0.994	**0.964**	**2.8**	**6.7**	**2.4**
F40/F25	0.932	0.952	0.914	**0.933**	1.7	**4.1**	**2.1**
F42/F25	0.914	0.943	0.970	**0.942**	2.4	**6.0**	**2.5**
F51/F25	0.878	0.901	0.931	**0.903**	2.4	**5.9**	**2.3**

Table 2. C/E results obtained with MCNP 6.1.1 and different data sets.

	C/E results: CC8 core, EFA-1 position, **MCNP 6.1.1 code**							Exp. unc.
Index \ Data	ENDF/B-VII.0	JEFF-3.2	JENDL-4.0	JEFF-3.1	average	st dev %	Max-Min %	±%
F28/F25	0.914	0.914	0.923	0.903	**0.914**	0.8	**2.2**	**2.0**
F49/F25	0.987	0.979	1.002	0.991	**0.990**	0.8	**2.3**	**2.1**
F37/F25	0.957	0.912	0.967	0.929	**0.941**	2.3	**5.8**	**2.4**
F40/F25	0.924	0.942	0.909	0.932	**0.927**	1.3	**3.5**	**2.1**
F42/F25	0.877	0.898	0.914	0.914	**0.901**	1.7	**4.1**	**2.5**
F51/F25	0.879	0.846	0.902	0.878	**0.876**	2.3	**6.4**	**2.3**

and reaction rates of a nuclear system for 1D, 2D and 3D geometries. JEFF 3.1 was chosen as reference data library. The analysis has been carried out for the VENUS XYZ model with a 49 energy group structure. Once the different cross section sets are obtained by an ECCO [10] calculation, a specific cell code, the TGV-VARIANT [11] module, has been used to evaluate the neutron fluxes. Then using different post-processing modules the reaction rates and spectral indices are analysed.

MCNP is a well-known general-purpose Monte Carlo N-Particle code that can be used for neutron, photon, electron, or coupled neutron/photon/electron transport. In the framework of the FREYA project, the MCNP code (version MCNP5 and MCNP 6.1.1) was widely used for detailed and complete simulations of the VENUS core neutronics.

Different nuclear data sets like JEFF-3.1, JEFF-3.2, ENDF/B7.1 and JENDL-4.0 were applied for the spectral index analysis here.

Serpent is a continuous-energy Monte-Carlo (MC) reactor physics code developed at VTT Technical Research Centre of Finland. Serpent runs significantly faster than other MC codes thanks to the use of the Woodcock delta-tracking in combination with a typical surface-to-surface ray-tracking for the free path length sampling, and the use of unionized energy grid for all point-wise reaction cross sections. All Serpent calculations considered here were performed employing the JEFF-3.1 library as well.

4.2. Results of the analysis

As it was presented in PHYSOR 2016 the tendency of all C/E results for all investigated cores (CC5, CC6, CC7 and CC8) in general were the same: acceptable agreement for the ‘fissile’ index F49/F25 but not for the ‘threshold’ indices. The present paper presents a re-analyses of the results that were obtained in the central position EFA-1 (1, 1) in the CC8 core only. These new calculations were accomplished with different data sets and with different codes (see Tables 1 and 2). The uncertainties on the results obtained with MCNP and with Serpent are <0.8%, the experimental uncertainties are <2.5%.

5. Discussion

Analysing the results from Tables 1 and 2 someone can state that:

– in general all C/E discrepancies on the minor actinides and Pu minor isotopes fission spectral indices are in the range of the possible results using current evaluated files, meanwhile F28/F25 index need a deeper investigation,
– in most of the C/E averaging the standard deviations are less than experimental uncertainties, especially when ERANOS results omitted. The fact that the presence of the deterministic code worsen the deviation values can be explained with simplifications of the core geometry of the input file of ERANOS comparing with MCNP one,
– almost all of C/C Max-Min values are higher than the experimental uncertainties. Thus the experimental results are valid for nuclear data and codes improvement,
– almost all C/E results are essentially less than 1. This fact can’t explain with wrong reference fission rate (F25), since first the C/E for the index F49/F25 is OK and second F25 was measured several times with three different FCs. But it could be explained with not appropriate calculation of the soft part of the neutron spectrum.

6. Conclusions

The first steps to solve the C/E differences observed for the spectral indices presented at PHYSOR 2016 have been accomplished:

– the U-235 impurities in the U-238 FCs were verified with measurements in the BR1 reactor. The results are in agreement with the certificate.
– different nuclear data sets (JEFF-3.1, JEFF-3.2, ENDF/B7.1 and JENDL-4.0) were applied for the spectral index analysis. In general, the C/E problems remain. But in the same cases several significant C/C differences were observed which needs further investigation.

To solve the remaining C/E differences for the threshold fission rate ratios, and especially for the standard F28/F25 index, following actions will be taken:

– measuring the F28/F25 index with foils in the same conditions as for the FCs (ongoing);
– verifying the effective masses of the deposits of the FCs in additional experiments and calculations.

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