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Neutron propagation experiments with a lead test section inserted in the core of the LR-0 reactor

Evžen Losa[a,*], Michal Košťál[a], Vojtěch Rypar[a], Bohumil Jánský[a], Evžen Novák[a], Giacomo Grasso[b], Massimo Sarotto[b], Francesco Lodi[b]

[a] Research Centre Rez (CVR), 250 68 Husinec-Rez 130, Czech Republic
[b] Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), v. Martiri di Monte Sole, 4, 40129 Bologna, Italy

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ABSTRACT

Validation of neutronic parameters for lead-cooled systems, by integral and local experiments, became of primary interest with advances in ALFRED lead cooled reactor demonstrator design. Notably, aiming at advancing the core design from the conceptual to the basic stage, the assessment of uncertainties coming from numerical simulation, with respect to real experiments, was of paramount importance to support the claims of outstanding safety demonstration meant for ALFRED. Among the required evidences, the assessment of the spatial distribution of the neutron flux and power in fuel pins required conceiving ad-hoc experiments, and disposing of state-of-the-art post-irradiation examination capabilities. For all these reasons, these experiments were one of the main focuses of the collaboration between the Research Centre Rez and ENEA. This paper presents the conception phase of the test and discusses some of the main results of the first phase of the experimental campaign, dealing with neutrons propagation, collected during its execution at the LR-0 research reactor (hence before the post-irradiation examination of the experimental pins placed in the lead test rig). The experimental work involved at first neutron spectrum measurements in the energy range from 0.1 to 10 MeV. Additionally, measurement of basic neutronic parameters of lead were performed, such as its reactivity worth, its effect on the neutron spectrum and its slowing-down properties. The comparison of calculations and experimental results shows good agreement. In case of calculation in benchmark model with different nuclear data libraries, the criticality is systematically over-predicted by approximately 150 pcm, which is, however, in the 1σ of the uncertainty interval. Neutron spectrum measurement shows only slight variations being around 10% most of the time.

1. Introduction

Efforts are being spent worldwide in the quest for advanced reactor systems to be deployed in the future, so as to provide a long-term and safe option for secure and sustainable energy (e.g., for Europe (European Commission, 2015)). In this framework, Generation IV (GIF, 2002) Fast Reactors (FRs) are in the spotlight of the most ambitious initiatives, as they are seen as the most promising option to fulfil the sustainability goals by fully exploiting the energy potential of the available resources and strongly reducing the burden of the management of the spent fuel.

Among the ongoing programs, at European level the Lead-cooled Fast Reactor (LFR) is quickly strengthening its technological bases so as to achieve the aimed maturity required for its deployment. The cornerstone for this advancing path is the construction and operation of a demonstration reactor: ALFRED (the Advanced Lead-cooled Fast Reactor European Demonstrator) (Alemberti et al., 2013). A pan European action was initiated in 2009 within the LEADER project (De Bruyn et al., 2013), co-funded within the 7th EURATOM Framework Programme. At the conclusion of this collaborative project, an international consortium was created, gathering all the main players of the initiative either as full members or through an associate partnership. The Fostering ALFRED Construction (FALCON) consortium (Alemberti et al., 2014) initiated all the supporting, managerial, infrastructural and technical actions required not only to bring the technology and the ALFRED design to maturity, but also to support Romania, the Eastern Europe region and the whole continent in embarking on this ambitious project.

Presently, FALCON initiated introductory dialogues with the Romanian National Commission for the Control of Nuclear Activities (CNCAN), as prelude to a pre-licensing phase expected to end with the design certification of ALFRED and an agreed experimental program for

* Corresponding author.
E-mail address: Evzen.Losa@cvrez.cz (E. Losa).

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the safety demonstration of the anticipated features of the system. Among the key steps planned, and being pursued, to substantiate the design that will be submitted to CNCAN, a thorough assessment was performed on the impact of uncertainties affecting the design.

Neutronic measurements including criticality and spectrum indices were done in past, utilizing the experimental facility VENUS (Kochetkov et al., 2016). Nuclear data and simulation uncertainties assumed still have a remarkable relevance, mostly due to the general lack of experimental reactors where to assess integral and local effects.

In this context, and for these reasons, a new campaign was proposed in collaboration with the neutron physics group around the LR-0 reactor at the Research Centre Rez (CVR), Gen-IV reactors being part of their investigation topics. Despite the thermal neutron spectrum of the sustaining core, the extreme flexibility of the LR-0 in arranging ad-hoc configurations and the advanced Post-Irradiation Examination (PIE) capabilities of the associated laboratory were identified as key factors for an experiment with lead to produce relevant results for the general validation of neutron simulation codes, with a specific focus on the stochastic transport code MCNP (Goorley et al., 2012) and a number of neutron cross-section libraries.

Within the limits of representativeness of a lead test section in a thermal reactor, the planned experiment here presented focuses on basic characteristics as reactivity worth, neutron propagation and neutron spectrum measurement, which are general quantities providing actual feedbacks on the correctness of nuclear data and simulation tools in describing the studied systems. It is expected indeed that all the chosen observables, despite the neutron spectrum of the LR-0 reactor which is of LWR type, will be very similar to the ones typical of an LFR. Therefore, the findings would help in developing methodologies and in nuclear data validation for LFRs.

2. Reactor arrangement

The experimental work was carried out at the zero-power research reactor LR-0, located at the Research Centre (CVR) in Řež. The main enabling feature for precise reactivity measurements – a key for this experiment to provide fidelity results – is the possibility of reaching criticality by moderator level change. This allows the reactivity effect of inserted materials to be retrieved by the difference in the moderator level in the reactor with and without material insertion.

The reactor design also allows a major flexibility in arranging different core configurations, each properly tailored to the goal aimed for the meant experiment. The reactor core, for this specific case, is made of six VVER-1000-type fuel assemblies with shorter active length (126 cm instead of 353 cm) and nominal enrichment of 3.3% (slight variations from nominal enrichment are accounted for each fuel assembly and are schematically noted in Fig. 1). The six fuel assemblies, in the hexagonal lattice defined by the lower core plate, form a ring around the dry experimental channel. A more detailed description of the used reactor and core configurations can be found in the NEA benchmark specification LR(0)-VVER-RESR-003 CRIT (NEA, 2016). The used reactor configuration is very well defined by previous experiments including neutron cross sections verification (Kostal et al., 2017a), reactivity (Kostal et al., 2016a), fission rates distribution characterization (Kostal et al., 2016b) and neutron spectra measurement in experimental channel used for integral experiments with material insertions (Kostal et al., 2015a) and (Kostal et al., 2017b).

The used lead test section is composed of a stainless-steel canister filled with pure (99.97 wt%) lead (Fig. 2). To allow the measurement of capture and fission densities (presently ongoing) for precise neutron propagation validation, the canister hosts six test fuel pins, in positions allowing their irradiation at different depths of the surrounding lead layer (central and right pictures in Fig. 2). The shape of the canister is also studied to allow the measurement of other neutronic characteristics as the neutron spectrum: indeed, the large central cavity in the test rig is used to host detectors for neutron spectrometry.

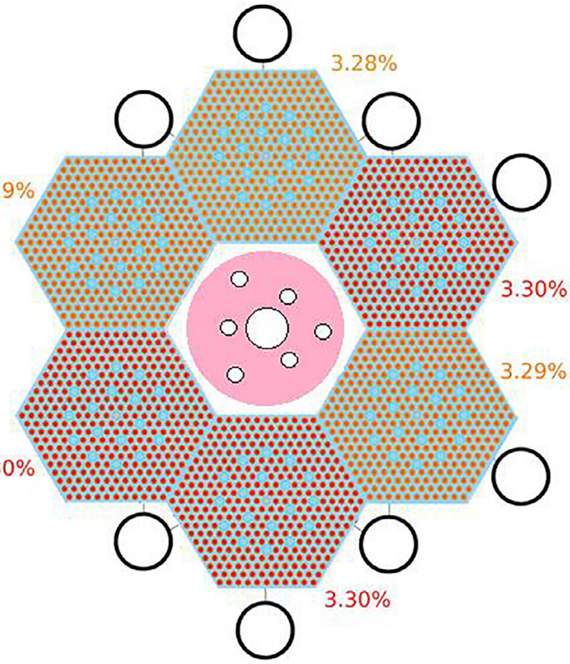

Fig. 1. Radial section of the core configuration used to host the lead test rig; variations in the enrichment are noted for each fuel assembly.

3. Methodology

3.1. Experimental arrangement

The actual arrangement adopted for the experiment is depicted in Fig. 3, where the main configurations assembling the lead test section and measured in the core are presented. The main outcomes of the performed critical experiments, reported in Table 1, are the critical moderator levels (H_{Cr}): as stated in Section 2, criticality of the reactor is reached indeed by moderator level adjustment. To appreciate the differential reactivity worth of each component of the lead test section, several cases were analysed, progressively introducing the lead test section components into the experimental channel. Case 1 refers to the initial configuration made only of the driver fuel assemblies (i.e., without the lead test section), here assumed as reference; Case 2 refers to the insertion of the empty steel canister (i.e., without lead filling); Case 3 is obtained by inserting in the empty channel the full arrangement – steel canister filled with lead; finally, Case 4 refers to the final configuration where the experimental fuel pins are also placed in the cavities of the lead test section as described at the end of Section 2. For comparison, proving the measurement stability in time, critical levels of experiments for cross section validations (NaF, As_2O_3) are also included. The reactivity variation attributed to 1 cm change in the moderator level is approximately 230 pcm (evaluated for the reference case of void experimental channel): through this the reactivity worth of each component of the lead test section can be calculated starting from the moderator level change between two compared cases.

The empty configuration, Case 1, is the reference one which has been used for integral neutron cross section measurements. These independent experiments are usually done with small activation foils or with larger capsules. Criticality results shown in Table 1 should be understood as an evidence of stability of critical moderator level measurement.

The reactivity of the system near the critical state, based on the critical moderator level, is described by Szatmary et al. (1985). A reactimeter derived from this theory and working on the basis of the inverse kinetics method was developed (Juricek, 2009) and implemented into an independent auxiliary computer system. This