Special Experimental Environment for Gen. IV Reactors with Graphite Reflector

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ABSTRACT

Nowadays, there is an increasing demand for new SMR reactors with a wide range of applications, often classified as a new generation IV. reactors. Unfortunately, there is no operating nuclear reactor meeting the characteristics of Gen. IV reactors by its technical design and features. Generation IV nuclear reactors are intensively developed worldwide, including in the Czech Republic. At least two general Gen. IV thermal neutron reactor concepts use graphite as a moderator or reflector, as do many concepts from the very popular small modular reactors. To support research activities linked with the development of these reactors, an appropriate experimental environment and resources simulating conditions expected in Gen. IV reactors with graphite are needed. The calculated data confirm the results obtained during previous research. The experiment at LR-0 with a graphite reflector gives better results of neutron flux distribution in the reflector due to the extra graphite reflector layer and central graphite plugs. Besides, the core arrangement is included in a set of experiments supporting the research of reactor cores with graphite reflectors. The main reason for this article is to support the development of a new functional sample of neutron instrumentation for Gen. IV reactors.

1 INTRODUCTION

Several designs of advanced reactors, which are under development, consider using graphite either as a moderator or a reflector. These designs include Molten Salt Reactors, Very High-Temperature Reactors with TRISO fuel, etc. [1] Graphite is again becoming more and more popular material in nuclear technology. Advanced reactors are often very complex concepts, and their reactor cores create a harsh and challenging environment regarding corrosiveness, high temperature, or moving TRISO fuel for any instrumentation and measurements. The conditions in these reactor cores often do not allow the use of in-core neutron instrumentation to measure a neutron flux and reconstruct a neutron power distribution. Hence, an ex-core neutron flux measurement should provide a precise and confident response to the neutron flux in the reactor core to reconstruct the power distribution and perform safety functions.

Thus, this article focuses on the simulation of ex-core neutron measurement and power distribution reconstruction in a unique experimental environment with a graphite reflector simulating the neutron environment of advanced Gen. IV reactors. Based on the previous research [2], the new experiment was performed at the LR-0 experimental reactor to verify prior results. The experimental core was then included in a set of various core arrangements with the graphite that can be used as support for experimental research of graphite reactor concepts.

The results in this paper support the research and development (R&D) of a new ex-core neutron flux instrumentation apparatus for a graphite-moderated nuclear reactor [3]. The output of the project will be closely linked to the R&D project for a small modular molten salt-cooled reactor. The main goal is to find the correct position of the ex-core detectors in the graphite reflector in order to reconstruct the neutron flux distribution and reactor power.

2 EXPERIMENT WITH GRAPHITE REFLECTOR

Previous experimentally verified reactor core arrangements in [2] did not provide a correct thickness of the radial graphite reflector, so the results were not satisfactory. They, therefore, did not truly simulate the desired specific environment of Gen. IV reactors with graphite reflectors. The apparent disadvantage of the obtained results was a noticeable effect of the centre holes in graphite blocks, which slightly disturbed the neutron distribution in the graphite reflector, and the reflector peak was difficult to recognise. Also, the thickness of the radial graphite reflector was quite small. Hence, based on the results of the previous research [2], another experiment was designed with the same reactor core arrangement but with a double thickness of the graphite reflector. The experimental core arrangement with the double-layered graphite reflector was created to clarify the previously chosen ex-core detector position.

2.1 Experimental reactor LR-0

The experimental arrangement was assembled at the LR-0, which is a zero-power, light water moderated, pool-type reactor operated at atmospheric pressure and room temperature in the Research Centre Řež in Czechia. The reactor supports the research and development of VVER-1000 and VVER-440 nuclear reactors. It is also used for creating benchmarks, activation experiments, and verification of microscopic cross-sections. [4-7] LR-0 is operated with shortened VVER-1000 fuel, and the criticality is reached by the change of the moderator level or control rod position in combination with various concentration of boric acid in the moderator. The continuous nominal power of LR-0 is 1 kW with thermal neutron flux ≈ 10^{13} m^{-2} s^{-1}.

2.2 Experimental core arrangement

The experimental reactor core used for the following research in this article is based on previous experiments and reference reactor cores evaluated by a team of experts [4-7]. The Research Centre Řež has provided the experimental data to validate created models. One of these experimental reactor cores was modified this time, and the double-layered graphite reflector was installed into the LR-0 reactor core. Moreover, the graphite plug in central graphite holes was used to ensure the higher homogeneity of the graphite reflector to reach more consistent results. The experimental core arrangement is shown in Figure 1.

The two-row experiment (Figure 1) serves as a complement to the previous reactor setups [2, 4-7]. It most authentically simulates a thick graphite reflector in the radial direction, in which the properties of graphite as a reflector can be better observed. The reactor core consists of six shortened VVER-1000 fuel assemblies with 3.28%, 3.29%, and 3.30% enrichment of ^{235}U. The central module is empty and filled with dry air. Since only 12 graphite modules were available, it was only possible to create the two-row graphite reflector on one side. The criticality of the experiment was achieved by changing the moderator level, and the critical level of the moderator H_{cr} was 46.963 ± 0.048 cm for this arrangement.

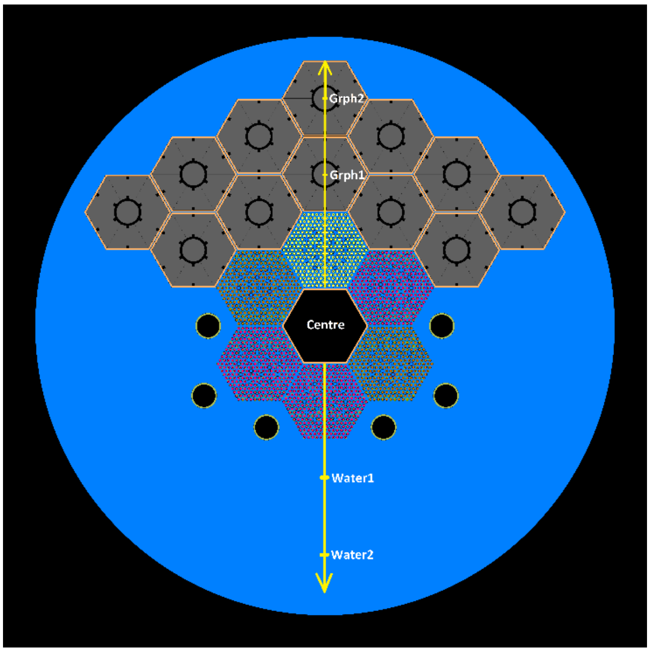

Figure 1: LR-0 reactor experimental core arrangement with double-layered graphite reflector. Model created in Serpent code. Colours in model: blue = light water, grey = graphite, black = void, purple, yellow and orange = fuel with 3.28 %, 3.29 % and 3.30 % enrich. of ^{235}U

2.3 Model and calculations

The criticality calculations and neutronic analyses were performed in Monte Carlo code Serpent 2.1.31 [8] with the nuclear data library ENDF/B-VII.1 [9]. In criticality calculations, the neutron transport was simulated with 50 000 neutrons per cycle and 10 000 active cycles (100 inactive cycles). Analyses of the neutron spectrum in the core centre ran with 500 000 neutrons per cycle in 50 000 active cycles with 100 inactive cycles because of a very fine energy group structure. The energy group structure includes 640 groups with a total energy span of 10^{-10} MeV to 20 MeV. This group structure has 45 energy groups per energy decade below 1 MeV and a group width of 100 keV above 1 MeV [10]. This fine structure was used to calculate the neutron spectrum in 5 predefined positions, two in graphite, two in water and one in the centre of the core, see Figure 1. The radial neutron spectrum course was investigated with the predefined 7-group CASMO energy structure. The energy structure was chosen to consider the microscopic cross-section of the graphite, which is smooth in the desired thermal energy. The calculations were performed with 200 000 neutrons in 50 000 histories with 100 inactive cycles. The uncertainty of the calculated neutron spectra varies from 3 to 5%.

3 NEUTRON FLUX DISTIBUTION

The position of the ex-core detectors in the graphite reflector could be adapted to particular requirements such as a temperature limit or maximal value of neutron flux. However, the optimal position of the ex-core detectors, in terms of good neutron flux response, is in the reflector peak. The results of the neutron flux distribution gained from [2] were slightly disturbed by air gaps located in the middle of graphite modules. Hence, the neutron flux distribution and neutron spectra were recalculated in the new reactor core arrangement with the double-layered graphite reflector to compare the results with previous data.

3.1 Neutron spectra

Firstly, the neutron spectra were calculated in different positions to investigate the influence of the two-row graphite reflector on neutron behaviour in this core arrangement. The results are shown in Figure 2. Scoring detectors are located in different positions across the core and reflector, as shown in Figure 1 (positions are named *Centre*, *Water1, Water2, Grph1 and Grph2*). One detector is in the middle of the reactor core in the dry experimental module (*Centre*), two detectors are placed in the first and second row of the graphite (*Grph1, Grph2*), and the last two detectors are located at the same distance from the centre of the core as the detectors in the graphite, but mirrored to the detectors in the reflector (*Water1, Water2*). Figure 2 shows neutron spectra in these scoring positions in the core. The goal was to compare the different levels of neutron thermalisation. According to the assumptions, the highest share of thermalised neutrons was detected in the more distant position in the moderator. However, one can notice that the thermalisation of the neutrons located in the second row of the graphite reflector is also high. Moreover, at the same time, the share of fast neutrons is the lowest compared to the neutron spectra in the water moderator and the central position. On the other hand, Figure 2 shows only the percentage of neutron energies at a given point. The Figure 2 shows that the highest fraction of thermal neutrons is at the *Water2* position. On the other hand, relative to the position, the total neutron flux at that position is very small, see Figure 4.

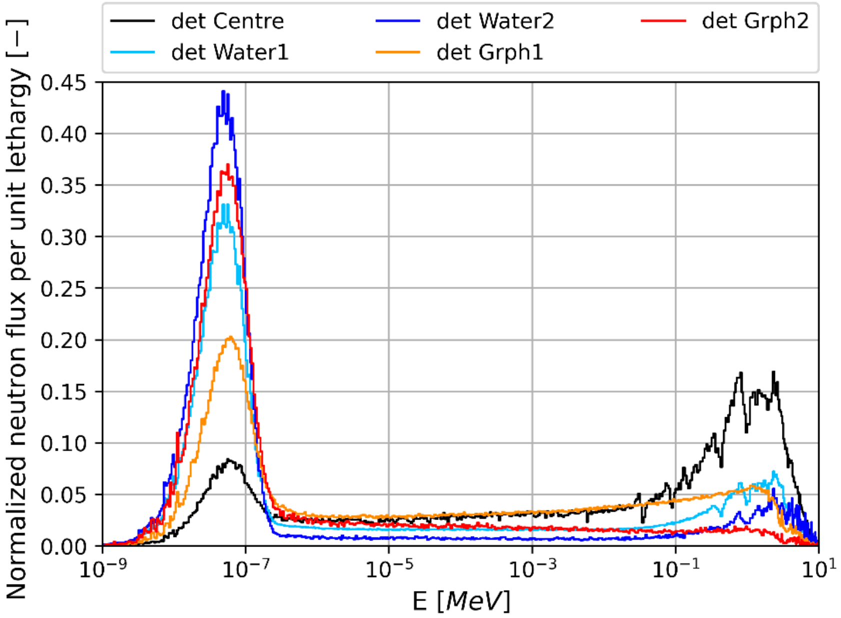

Figure 2: Neutron spectra in different positions of the reactor core with two-row graphite. Positions *Centre*, *Water1, Water2, Grph1 and Grph2* shows Figure 1.

3.2 Neutron flux distribution

Then, the neutron flux distribution was investigated to verify previous results [2]. Referring to Figure 1, the two directions were examined from the reactor core, i.e., the neutron distribution in the graphite reflector and the neutron distribution in the opposite direction in the water moderator (the same positions *Centre*, *Water1, Water2, Grph1 and Grph2)*. The results are shown in Figure 3 and Figure 4. Figure 3 shows neutron distribution in the graphite reflector. Compared to the data from previous experiments without central graphite plugs and with only one-row graphite reflector, the calculated neutron flux profile is smoother, and its shape corresponds with the assumptions. The reflector peak is now more visible, and it is possible to confirm earlier conclusions regarding the proper ex-core detector position. One can notice that the course of the flux shows periodically recurring peaks in the curve corresponding to the lower thermal energies which are caused by small air gaps in graphite geometry located in the peak area (see Figure 1) and also by the construction material of the graphite modules, which is made of pure aluminium. The thermal neutron flux in the graphite reflector is comparatively flattered compared to the water moderator (Figure 4), and the properties of graphite are well demonstrated. Figure 4 presents the neutron flux profile from the fuel assemblies to the moderator and water reflector. There is a very sharp peak of the thermalised neutrons, which is dropping steeply (see Figure 4). The parasitic neutron absorption of the water is very significant.

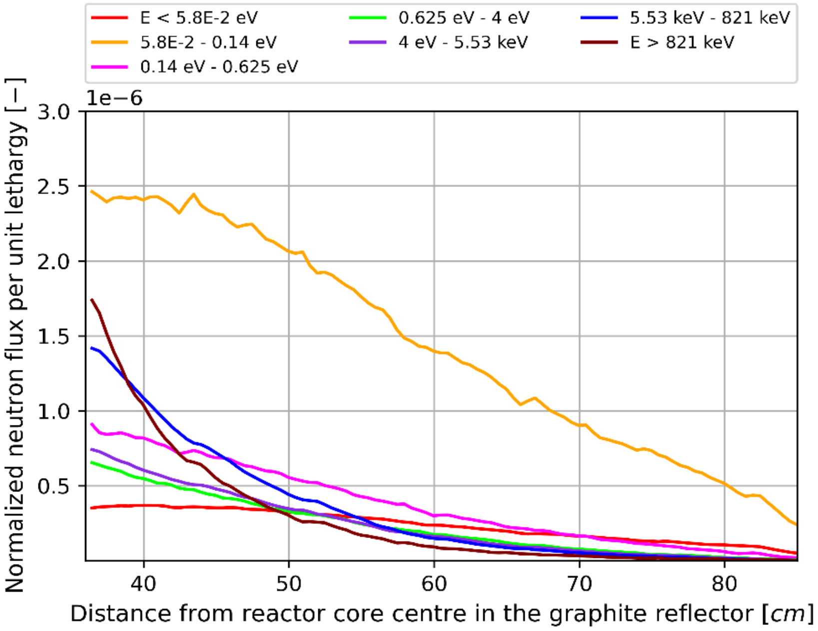

Figure 3: Neutron flux profile in the two-row graphite reflector, the 7-group structure. The position of scoring detectors is shown in Figure 1.

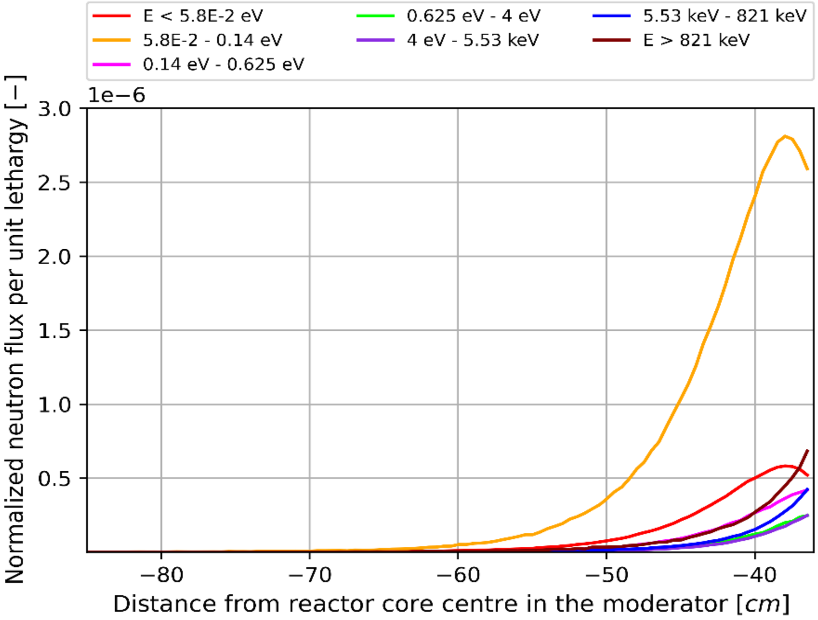

Figure 4: Neutron flux profile in the moderator, the 7-group structure. The position of scoring detectors is shown in Figure 1 The scoring detectors are in the opposite directions to the scoring detectors in two-row graphite reflector.

4 CONCLUSIONS

In order to support research activities related to the development of Gen. IV reactors, it is necessary to have an experimental environment that simulates as closely as possible the conditions that can be expected in a Gen. IV reactor with a graphite reflector or SMR. The LR-0 reactor core with a two-row graphite reflector presented above is included in the LR-0 reactor graphite core engineering package for Gen. IV purposes. The suggested technical solution contains variants of experimentally verified and computationally validated graphite environments in the form of five graphite prisms placed in the LR-0 reactor core in different shape and size modifications. These core arrangements have been used to create a utility model.

The obtained results from calculations and the presented experimental arrangement will be further used to verify various neutronic parameters and detection apparatuses that are being developed for measurements in the graphite reflector. The composition and configuration of the graphite prisms allow the detector to be placed in any position in the module, so it is possible to test not only the response of the detectors to the neutron flux density in the reactor core but also to optimise the position of the neutron flux detectors in the reflector of a given reactor concept.

ACKNOWLEDGMENTS

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