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Possible Implementation of Ex-core Measurement in TEPLATOR Graphite Reflector

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ABSTRACT

An ex-core neutron flux measurement is a crucial system for all common power reactors. It is necessary to monitor neutron flux and control the chain reaction therefore the ex-core neutron flux measurement is one of the main safety and control systems. The main advantage of this arrangement of detectors is a fast response on neutron flux change, which determines the reactor power change. Regarding to the new reactor concepts, it is important to deal with improved detection systems suitable for these reactors. Many of the modern reactor concepts are based on the graphite moderator or reflector, which is also case of a TEPLATOR. The TEPLATOR is a solution of district heating system based on heavy water as a moderator and graphite as a reflector. TEPLATOR is designed to use irradiated fuel from the commercial PWR or BWR reactors, which has low to intermediate burnup. This article is focused on verification of possible use of the special neutron measuring system placed in the graphite reflector. The Monte Carlo code Serpent was used for calculations performed in this article.

1 INTRODUCTION

A neutron flux measurement is an important part of the I&C system in every nuclear power plant because of its link to control of the chain reaction. Nowadays, the modern nuclear power plants are proposed for power generation and it is challenging to focus on choosing the suitable neutron flux monitoring system. The neutron flux measurement can be usually divided in two groups: in-core and ex-core measurement. The main advantage of the ex-core detectors arrangement is a fast response on neutron flux change, which reflects a change of the reactor power.

This paper focuses on feasibility assessments of the ex-core detectors in a graphite reflector, which surrounds a TEPLATOR core. The TEPLATOR is an innovative concept for the district and process heat production developed in the Czech Republic [1]. The main idea of this concept is using already irradiated nuclear fuel from PWRs, which is stored in interim storage or in spent fuel pools. The concept provides lower environmental footprint and efficient utilization of the nuclear fuel. TEPLATOR is designed for thermal power range 50 - 200 MW and continuous heat supply by implementing an energy storage system. There are several variants for TEPLATOR and one of them is TEPLATOR DEMO, see in the Figure 1. This design uses atmospheric pressure, 55 irradiated fuel elements, heavy water as the moderator in a calandria and as a coolant in a fuel channels and graphite as the reflector. The assumption is to operate for 2x 270 days, which corresponds to two standard heating seasons. There is also a solution for countries that do not operate PWR and do not own irradiated fuel and this solution can be using special fuel made of SEU or natural uranium designed for the TEPLATOR construction [2]. Like any other reactor the TEPLATOR needs the I&C systems for controlling. In this paper, an initial survey of the ex-core detectors position in the graphite reflector is presented.

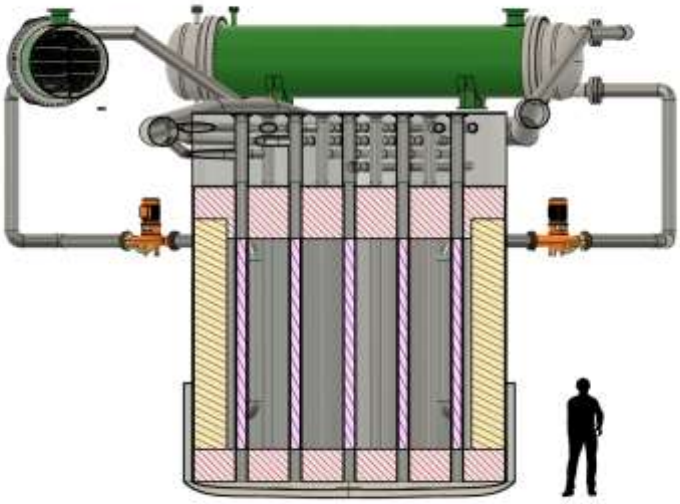

Figure 1: Schematic of the TEPLATOR – side view

2 NEUTRON FLUX DETECTION IN TEPLATOR

A functional sample of the neutron instrumentation is under development by dataPartner s.r.o. in cooperation with Research Centre Řez s.r.o. and University of West Bohemia, which will be suitable for a nuclear reactor with graphite moderators or reflectors. This project is a part of the research and development of the technical solution for the emerging nuclear reactors [3]. The main idea of this paper is to implement the ex-core neutron flux measuring apparatus into the TEPLATOR core.

2.1 The model of TEPLATOR in Serpent

The simplified model of TEPLATOR was created in the Serpent 2.1.30 [4]. The TEPLATOR DEMO will use the already irradiated fuel from PWRs, which is not burnt up to its regulatory and design limits. For this simulation, a standard type of hexagonal nuclear fuel VVER-440 type with an average burnup 34 750 MWd/MTU is assumed, which represents average fuel burnup of the spent fuel pool inventory. The fuel is modelled with the optimal pitch considering the heavy water as moderator and as coolant. The fuel assemblies are placed in hexagonal channels (Figure 2.), which are composed of two zircaloy hexagonal tubes with space between tubes filled with a low-pressure CO_2 as a thermal shielding. The fuel channels are placed in a calandria filled with heavy water, which is surrounded by the 45 cm thick graphite reflector. Whole model can be seen in Figure 3a and Figure 3b. [5][6]

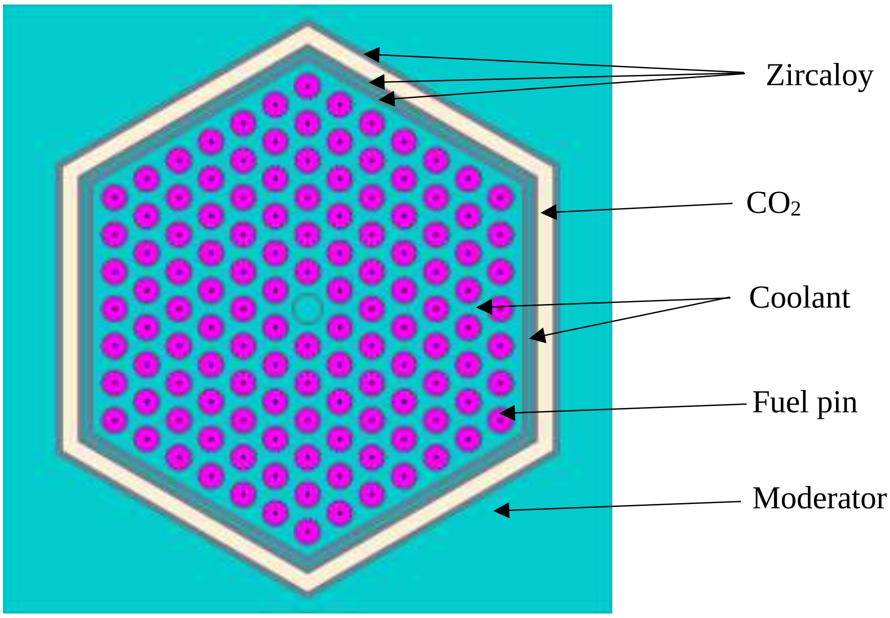

Figure 2: The composition of the fuel channel

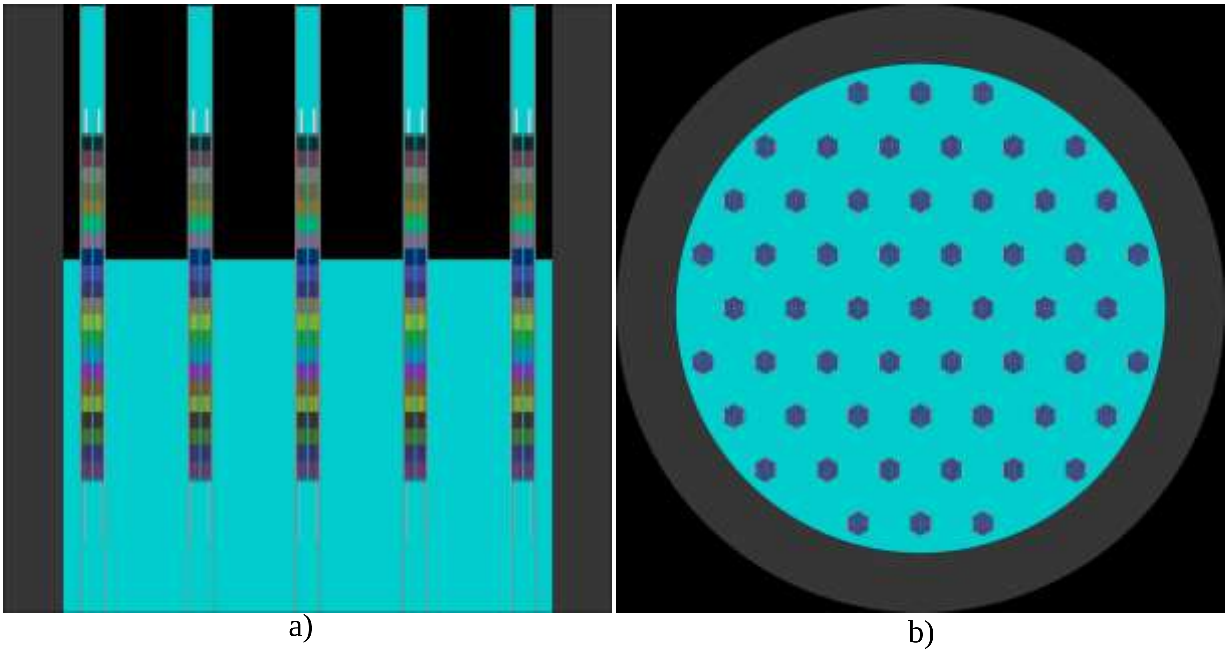

Figure 3: The model of TEPLATOR core – a) side view, b) view from above

A critical level H_{cr} of the moderator, which is in the calandria, can be seen in the Figure 3a. The change of moderator level is used for reaching criticality of the reactor and for regulating the nuclear chain reaction. The moderator level is 161.3 cm at the beginning of fuel cycle and it is measured from the bottom of active part of the fuel assemblies in the Serpent model.

2.2 The calculations in Serpent

All calculations were carried out in the code Serpent 2.1.30 with 25 000 neutrons, 10 000 histories and 50 inactive cycles and the ENDF/B-VIII.0 nuclear data library was used. An uncertainty of the calculations is around 3 % in thermal and epithermal groups. For the fast neutrons the uncertainty is around 13% and, because the field of interest is mainly in thermal neutron group, the uncertainty was considered as sufficient.

2.3 Neutron flux profile in TEPLATOR

The ex-core detection of neutron flux is important because of its quick response on the change of reactor power. In-core detection is not subject of this paper, although such instrumentation can be deployed with same importance. The ex-core detectors are usually placed in biological shielding at PWRs [7]. First approach was to determine whether is possible to place the detectors behind the reflector. However, the concept of TEPLATOR is designed with the 45 cm thick graphite reflector so there were doubts about a sufficient detector response. It was decided to calculate a radial neutron flux profile according to this assumption.

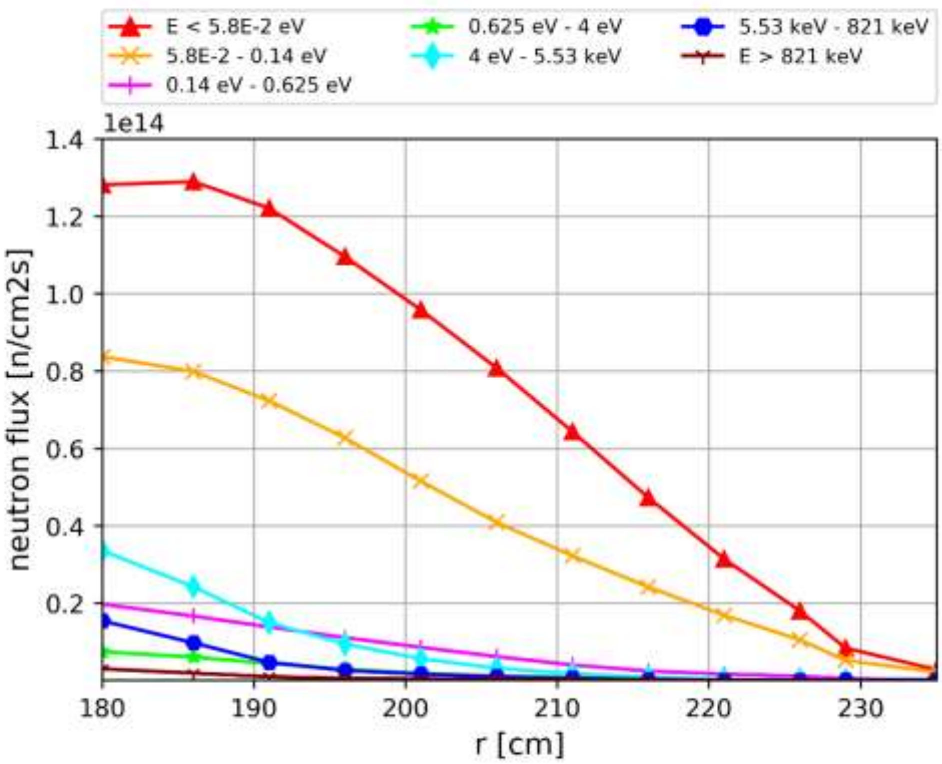

Figure 4: Radial neutron flux, 7-group energy structure, detector in the middle of the fuel assembly height under the moderator level

A set of calculations were made with 5 cm step to show the radial neutron flux profile in the reflector (Figure 4). The first step is placed 5 cm in front of the reflector in the moderator and the last step is 5 cm behind reflector where the biological shielding should be located. For this purpose, the detector was placed in the middle of the fuel assembly height, which is under the moderator level where the highest neutron flux was assumed (Figure 5). A 7-group energy structure was used, the pre-defined CASMO available in code Serpent. The Figure 4 proves that the position of detectors behind the reflector would be inappropriate. The detectors will reach much better response to thermal neutrons (the curve with the highest neutron flux in the Figure 4) if placed in a very first centimetres of the reflector.

A layout of the ex-core detectors based on these results was designed. In the neutron instrumentation apparatus developed by dataPartner, the fission chambers will be used with the following dimensions: 15 cm length, 0.7 cm diameter, which served as a basis for the purposes of this article. The fission chambers can supress a gamma induced signal by using a Campbell operational mode and have high sensitivity to thermal neutrons. A 60° symmetry of the core was used as shown in the Figure 6a. Due to the regulation by moderator level and the fuel assembly length, the 4 axial ex-core detectors were chosen in the following positions: D1 at 230 cm, D2 at 154 cm, D3 at 93 cm and D4 at 28 cm from bottom of active part of the fuel assembly shown in the Figure 6b. It should be also possible to find out a shape of axial neutron flux profile with this layout.

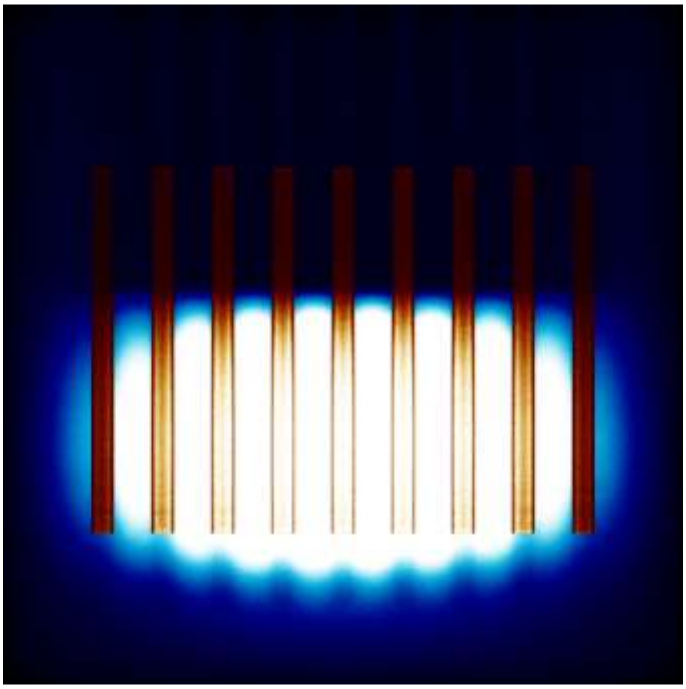

Figure 5: Distribution of the thermal neutron flux and fission rate

It is clearly recognizable from calculated results that the fast neutrons contribute much more to the total neutron flux in the detector D1, placed above the moderator level, than in detectors under the moderator level (see the Figure 7 in comparison with Figure 4). It can be also clearly seen that the peak in thermal neutron flux is within the reflector around 200 cm of the model dimension, which corresponds to 15 cm thickness of the reflector. On the other hand, the properties of heavy water are demonstrated in responses of the D2, D3 and D4 detectors to the thermal flux that are under moderator level. The neutrons are slowed down much faster and the thermal neutron peak is located near the border of the reflector and moderator, which caused that the neutron flux is flattened and slightly shifted towards the reactor core in these three detectors (Figure 4). In reality it is a composition of two reflective materials with different properties, so it is not easy to predict results without previous calculations. Neutron flux in the detectors D2 and D4 is very similar to detector D3. These results confirm that the position of detectors is propriate in very first few centimetres (around 5 cm). According to this, also the axial profile of neutron flux was calculated as shown in the Figure 8.

The Figure 8 demonstrates distribution of the axial thermal neutron flux profile during the TEPLATOR operation. As the fuel is burning up, the level of moderator (to maintain criticality) is rising. Another 4 moderator levels were set for determining the axial profile during operation with equal distance between first critical height H_{cr} = 161.3 cm and the upper part of the reactor calandria (191 cm, 221 cm, 252 cm and filled calandria 350 cm). The calculations were carried out with the fuel at the beginning of cycle – “fresh fuel”. The subject of the further research will be verification of axial neutron flux change during burnup.

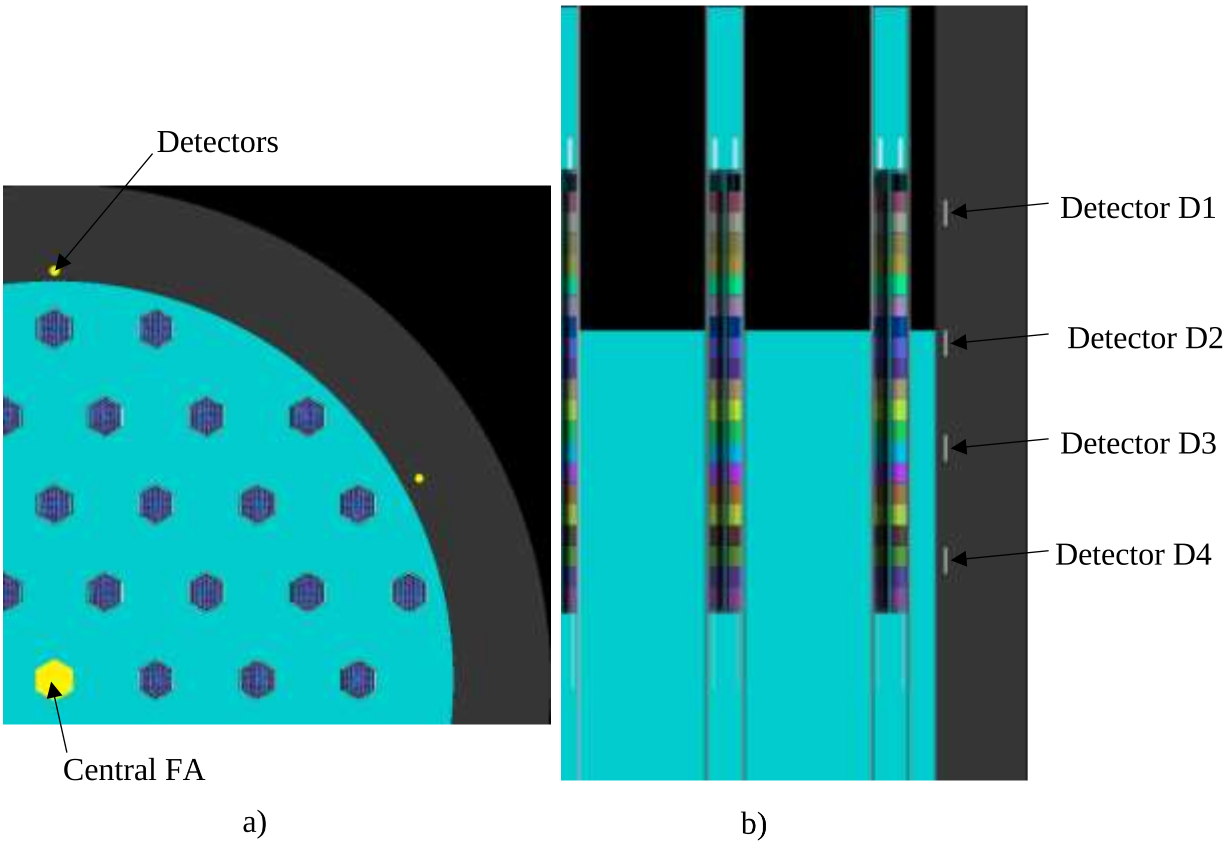

Figure 7: a) 60° symmetry of the detectors b) Axial position of the ex-core detectors

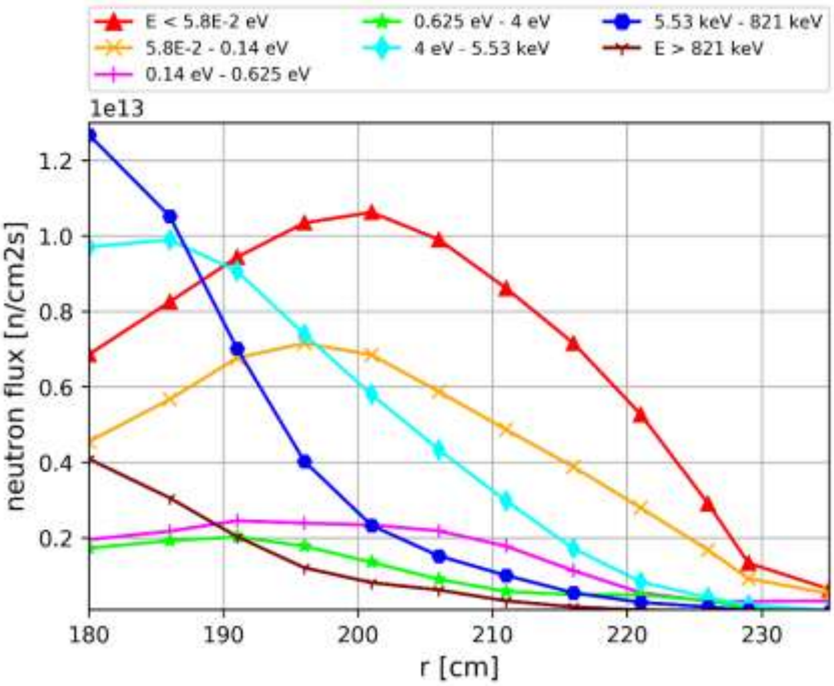

Figure 6: Detector D1 – Radial neutron flux – 7-group energy

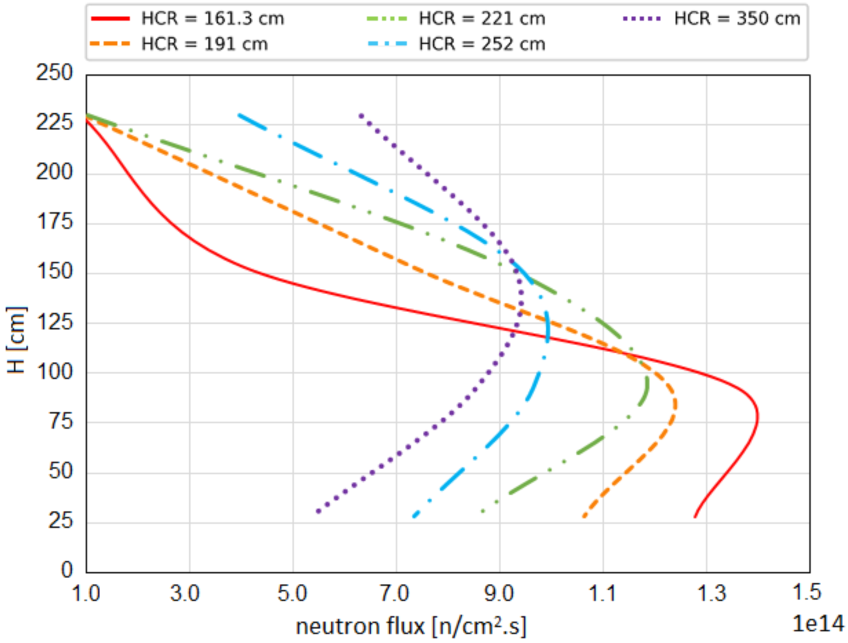

Figure 8: Effect of the moderator level on axial neutron flux profile distribution – 1. group thermal neutrons

3 CONCLUSION

This article aims at possibility of the ex-core measurement implementation in the TEPLATOR, which is a new concept of the reactor using already irradiated fuel for district heating. We tried to find a suitable placement of detectors in the reactor. The first idea was to place detectors behind the graphite reflector and thus implement the ex-core detectors in TEPLATOR. The calculations were carried out with the detectors placed in the middle of the fuel assembly height under the moderator level in the reflector, where the highest axial thermal neutron flux is expected. The idea of placing detectors behind the reflector has been refuted by calculations of the radial neutron flux distribution, since it showed the peak of thermal neutron flux within 5 cm of reflector thickness. The highest thermal flux is at the beginning of the reflector, which is consistent with the requirement on ex-core measurement to be as close as possible to the reactor core, in order to prevent reactor core from appearing as a point neutron source. First 5 centimetres of the reflector appear as the most appropriate position of detectors in radial direction obtained from the results. The layout of the detectors composed of four axial detectors using 60° symmetry and complete radial and axial profile of neutron flux was created and calculated. The axial profile shows the change of neutron flux distribution during operation time.

Further research will aim at detailed analysis during the fuel burn up and on the behaviour of the neutron measurement during operation time, i.e., dependence of a calibration on the fuel burn up, harder neutron spectra or potential redistribution of reactor power in radial direction. Also, an effect of the radial and axial position of the detectors in the reflector and optimization of the detectors' response will be investigated. The next step is to find out a possibility to map a distribution of the neutron flux in the whole reactor core both in radial as well as in axial directions, as is it possible when using the standard in-core detectors.

ACKNOWLEDGMENTS

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