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Preliminary study results relating to the Tunisian subcritical reactor-assembly project

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***Abstract*—The National Centre of Nuclear Sciences and Technology (CNSTN) plans the installation of a subcritical reactor-assembly to support development of human resources, for the national nuclear power programme and to perform applied research and development in the nuclear field. The subcritical assembly will be extremely useful, particularly for carrying out research projects by scientists, which will enable them to develop understanding of some specific concepts relevant to nuclear reactor physics.**

Studies relating to the location selection, the technical characteristics of the facility and the core modeling are in progress and, for some of them, almost finalized. The strategy necessary for the enhancement of utilization and sustainability of the expected subcritical assembly is also under elaboration.

Validations of the reactor core modeling and optimization are made through cross checking of different reputable Monte Carlo codes, notably the Geant4 (the version 10) simulation toolkit. The resulting numerical modeling is of relevance not only for the technical feature optimization of the subcritical assembly, but also, for contributing to validations of the recent nuclear data librariesrecently implementedin Geant4.

This paper presents an overview of the state of artand progress of the subcritical reactor project implementation and preliminary reactor core model results carried out using Geant4 version 10.

Keywords*— *Neutron kinetics; nuclear reactor; subcritical assembly; Monte Carlo modeling; Geant4 version 10.

I. INTRODUCTION

A subcritical assembly is an outstanding example of a simplified low cost reactor which serves numerous purposes, including education, training, experimental research and providing practical experiences on the fundamental and applied physics of fission process and of a nuclear reactor. Several recent facilities of subcritical assembly[1,2] demonstrate today this wide list of applications, satisfied by the inherently safe subcritical design, capable of sustaining nuclear chain reaction without reaching criticality. These conditions enable gaining first-hand practical experience on a nuclear reactor, with minimal radiation exposureand without any risk of criticality accident.

The implementation of a subcritical assembly in the CNSTN (National Centre of Nuclear Sciences and Technology; a public institute belonging to the Tunisian Ministry of High Education and Scientific Research), is already considered of interest by national industrial community and research and academic institutions.

The project of implementing the subcritical assembly has started in 2012. The studies, of this Tunisia's first nuclear facility, are currently focused on the finalization of the feasibility study and the bidding specifications. The design, construction and commissioning phases of the project are expected for 2016-2017.

The core modeling and optimization of the subcritical assembly are made through cross checking of Monte Carlo codes. For the case of the Geant4 code [3], some specific capabilities (particularly, for the simulation of the interaction of neutrons with matter at neutron energies up to 20 MeV) has been nearly extended [4]. These improvements provide today more accuracy when performing Geant4 (the version 10.1) simulations, particularly, of a fission nuclear reactor.

The subcritical assembly modeling with Geant4 will enable to optimize the core, and also, to assess the real improvement in that version 10.1 of the Monte Carlo code.

The foreseen subcritical assembly will be light water moderated, and loaded with commercially available fuel; natural or low enriched Uranium (with maximum level of enrichment equal to 4%). The effective multiplication factor (k_{eff}) will be less or equal to 0.90. The neutron emission rate, at an in-core irradiation position, will be sufficiently higher in order to ensure an already identified list of applications.

II. FACILITY DESIGN AND FORESEEN APPLICATIONS

The subcritical assembly is being designed in order to be able to provide operators and users with an inherently safe tool, simple, reliable and easily operated with minimum operation and maintenance requirements. Parts of the subcritical assembly will be also easily accessible for demonstration, inspection, and experimental purposes.

The subcritical assembly will be uranium (natural or low enriched) fueled and light water moderated and reflected. The reactor will be driven by an extraneous neutron source, made with the combination of plutonium-beryllium or americium-beryllium. The core consists of few hundred of fuel pins, loaded into a water-filled vessel (cf.Fig. 1.).

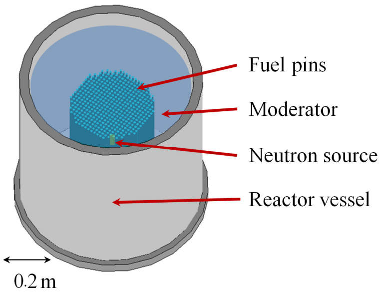

Fig.1 Simplified view of the reactor core key components.

The neutron source will be driven, by a pneumatic control drive, into the reactor core. To shut down the reactor, the same source will be driven back to its storage flask.

Various nuclear experiments and measurements will be provided by the subcritical assembly, including: subcritical extrapolation experiment for fuel loading, source jerk experiment, Rossi-alpha measurement experiment, Feynman-alpha method measurement, neutron flux distribution (axial, radial and absolute) measurement, neutron energy spectrum measurement, neutron activation analysis (list of elements, that could be detected and analyzed, will be established), and measurement of the neutron temperature. The neutron source oscillating experiment is also considered.

At least one in core irradiation position will be implemented, for the neutron activation analysis and to irradiate samples. The associated handling tools and suitable shielding, for the samples, are already seen.

III. NUMERICAL MODELING OF THE SUBCRITICAL REACTOR

The modeling of subcritical reactor, schematized in Fig. 1, was carried out using the Monte Carlo code Geant4. This code is developed, revised and supported by an international collaboration from the high energy physics community, and was, particularly, currently used to perform simulations of complex particle detectors. Recently, a new set of various standard nuclear data libraries has been created and included into the format used by the Geant4 simulation package [4]. These improvements enable accurate modeling of the interaction of low energy neutrons with matter and allow effective possibilities of comparison with other codes, like MCNPX [6] by using same standard neutron data libraries.

The physical process list included in our model was drawn by evaluating the importance of the respective cross-sections of various processes for the studied particle energies.

The model of the reactor vessel, discussed in this paper, is a 1.0 m height stainless steel tank, with 1.0 m inner diameter and 10 cm in thickness. 144 low enriched uranium-dioxide (4% ^{235}U) fuel pins are loaded into the water-filled vessel. The fuel pins fulfill an equivalent cylindrical volume of 20 cm in radius and 65.5 cm in height. The moderator contained into the vessel is a deionized and distilled light water.

The extraneous neutron source corresponding to the following modeling results, is a plutonium beryllium (Pu-Be) source, characterized by an activity of 0.8 Ci, a neutron intensity of 1.1×10^6 n/s and the spectrum energy detailed in [7].

The motivations of beginning by using a simplified model of subcritical assembly (as described behind) was essential in order to start by validating the possibility of using the Geant4 version 10 and to initiate producing accurate results relating to such facility.

The first steps of the simulation, using the developed model, consist of producing initial neutrons, with the physics parameters (flux and energy spectrum) as described above, which enable to reproduce quite perfectly the real comportment of the extraneous Pu-Be neutron source.

The generated fast neutrons turn into thermal neutrons when scattering and undergoing succession of collisions inside the moderator. These physics processes induce progressive decrease of the neutron kinetic energies. Fig. 2 illustrates examples (selected randomly) of neutron thermalization and slowing down, recorded by the subcritical assembly core model. The neutron energies were lowered, as expected, inside the moderator until reaching, for some of them, the required conditions (particularly, the required energy, corresponding to a significant cross-section) for an absorption by a fuel element.

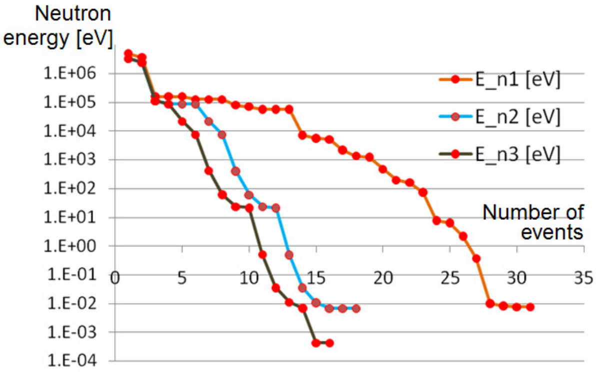

Fig.2 Neutron thermalization inside the subcritical assembly core. Energy evolutions of three samples of neutrons are plotted correspondingly for each physical process recorded between the generation and final capture/absorption.

Since the neutron thermalization and the activation of ^{235}U fission processes where validated, we developed additional probing with the aim of checking the effective energy released in and following the fission of ^{235}U by the recorder thermal neutrons. The obtained results were compared to the experimental and theoretical data detailed in [8].

The same probing effort was also useful for validating the repartition, as a function of the mass number, of the produced fission fragments. The average of the fragment mass, when ^{235}U undergoes fission was, as expected, about 118. The masses of the resulting fragments (strontium, zirconium, technetium, cesium, xenon, iodine, etc.) were around 95 and 137, which is in agreement with ^{235}U fission data.

On the other hand, we have studied the neutron (fast and thermal) distributions inside the reactor core and generated by the developed model.

The neutron flux profiles at an horizontal or vertical plane, in the middle of the reactor vessel (at the same position of the extraneous neutron source) illustrate coherent results mentioning normal distributions centered around the neutron source and with flux values dominated by the continuous emitted flux of the source (1.1×10^6 n/s).

Fig. 3 illustrates 2D normalized neutron flux distribution at a horizontal plane placed 15 cm below the neutron source.

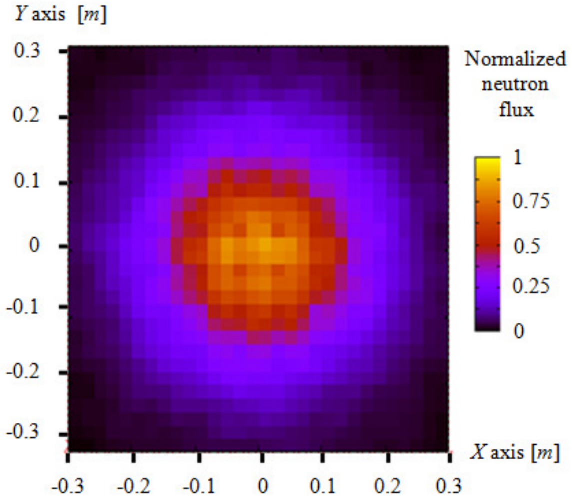

Fig.3: Normalized neutron flux distribution in a horizontal plan, centered inside the subcritical assembly core, 0.15 m below the neutron source position.

Fig. 3 demonstrates nearly similar behavior to a normal profile. The differences arise in some secondary peaks of neutron flux that appear outside the central position of the neutron distribution. Similar secondary neutron flux peaks were also recorded with an equivalent facility of subcritical reactor [9]. Neutron flux profiles illustrated in [9], reveal the apparition of secondary peaks when selecting and grouping thermal neutrons as a function of their energies.

Also as first verifications of the developed model, using Geant4 version 10.1, we performed a basic test of numerical approach to criticality. This test consists of increasing the level of enrichment of the fuel, by keeping unchanged all the other physics and technical parameters of the model. The result was, as expected, the divergence of the number of computed processes, starting from the level of enrichment delimiting the reactor criticality.

IV. CONCLUSIONS AND PERSPECTIVES

Results of modeling a simplified design of a subcritical reactor were performed by using the last version (10.1) of the Monte Carlo code Geant4. Most of the obtained results were validated by comparisons with other experimental and numerical studies.

These results are promising for the development of complementary work of more accurate validations, with an exhaustive design of the subcritical reactor. This same work will assess also the recent improvements in that version 10.1 of Geant4.

In parallel, a further important work of modeling [10] is performed by using the MCNP-5 code [11]. The whole final work will enable benchmark exercises using the two different Monte Carlo codes, and will constitute a part of the needed efforts that have to be exerted for the implementation of the subcritical assembly project.

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