Nuclear Science and Technology Symposium - SYP2022
Helsinki, Finland, 1-2 November 2022

Ongoing Serpent 2 neutronics studies of Jules Horowitz Reactor

Jussi Peltonen
VTT Technical Research Centre of Finland
Kivimiehentie 3, 02150 Espoo, Finland
jussi.peltonen@vtt.fi

ABSTRACT

Jules Horowitz Reactor (JHR) is being built in southern France at CEA Cadarache. Its scheduled start of operation is in the 2030s, after which it will serve as the new European centre for nuclear material testing. VTT's has contributed various in-kind deliveries for the construction of the reactor in the past, and our future contributions will involve computational core analyses as well, utilizing the Finnish Kraken framework solvers. Hence, VTT's Monte Carlo neutronics code SERPENT 2 is used to create a neutronics model of the JHR, taking advantage of the pre-existing Constructive Solid Geometry (CSG) structures on which the CEA's TRIPOLI-4 neutronics models were built. This paper describes the completed and ongoing SERPENT 2 analyses of the JHR, which include benchmarking, core-component lifetime analyses and in-detail dosimetry and heat deposition analyses of specific JHR test devices.

1 INTRODUCTION

Jules Horowitz Reactor (Réacteur Jules Horowitz) is a tank-in-pool material testing reactor under construction at CEA Cadarache in southern France, located about 60 km north-east from Marseille. It will support the pre-existing power plants via lifetime extension and safety improvements, facilitate optimization of the generation III power plants and serve a valuable role in the development and qualification of advanced fuel material.

Furthermore, the expertise developed throughout the project will support the nuclear industry and future decisions of the European countries related to the construction of new nuclear power plants and designs [1]. This work has been completed as a part of 3-month research exchange visit at CEA Cadarache, for which one of the objectives was to promote international collaboration of early PhD stage researchers.

JHR offers a suitable environment for normal, incidental and accidental testing of material and fuel under irradiation for various power reactor technologies. The in-pile and out-pile instrumentation enable high quality R&D experiments. The reflector is built with several displacement systems, which make it possible to fine-tune a large spectrum of neutron fluxes and dpa rates for various experiments which support the development of current and modern power plant technology. These systems also enable the production of medical isotopes.

These experiments support the development and validation efforts of computational models for a wide range of phenomena, such as the transient behaviour of fuel materials. Consequently, JHR will answer the needs of both industrial and scientific parties by offering cost-effective solutions to a variety of research interests.

SERPENT 2 is a continuous-energy Monte Carlo neutronics code which has been developed at VTT Technical Research Centre of Finland since 2004 [2]. It is widely used for traditional reactor physics applications such as spatial homogenization, criticality calculations, fuel cycle studies and reactor modelling. Other applications include coupled solutions with other reactor physics solvers, and photon and neutron transport simulations which can be applied to dose rate, shielding and medical physics calculations.

The initiative behind JHR is run by a consortium consisting of research institutes from several European Member States, including CEA (The French Alternative Energies and Atomic Energy Commission) and VTT Technical Research Centre from Finland. VTT's share of the JHR operation time is 2%, for which the interests of Finnish nuclear industry fill be first and foremost considered.

2 STRUCTURE OF JHR

Figure 1 shows the core of JHR, which comprises of 34 fuel elements and 24 inter-element positions in an aluminum rack surrounded by a beryllium reflector. As seen in Figure 2, the fuel elements are hollow cylinders with curved plates of high density low-enriched uranium in three sectors assembled with stiffeners.

Positions 101, 105, 203, 207, 303, 307, and 313 in the in-core contain fuel elements with a 32 mm diameter cylindric space in which testing devices can be installed, while positions 103, 211, and 301 reserve an 80 mm diameter space in which either a larger testing device or an additional fuel element can be installed. There are 27 control rod positions in the elements' centers, of which 4 are safety rods, 4 are piloting rods, and the rest are compensating rods. The core is contained in a low-pressurized aluminium vessel.

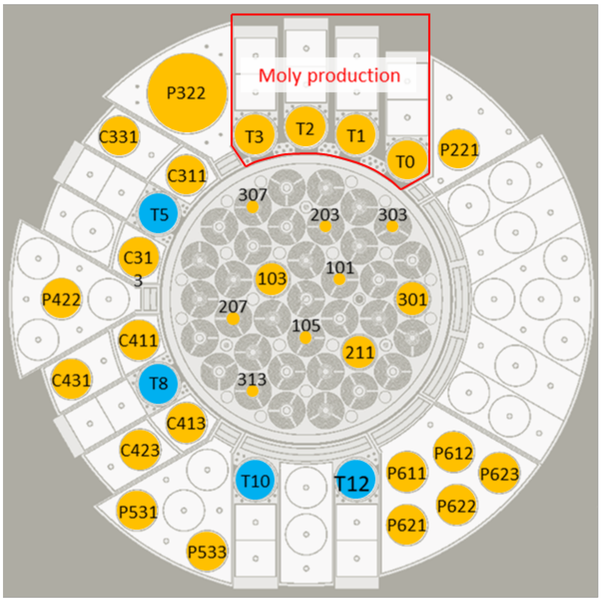

Figure 1: Experimental positions in JHR [3].

The reflector surrounding the core consists of beryllium elements cooled by water channels. In the south-east sector, a Zircaloy gamma screen is placed between the core and the beryllium elements to provide shielding and reduce gamma heating in the reflector. Inside the reflector, there are eight displacement systems where experimental devices can be put to be irradiated under PWR and BWR conditions.

T0, T1, T2, T3, T5, T8, T10, and T12 are the heads of the displacement systems as seen in Figure 2, which can be retracted from the reflector to a desired location for an ideal radiation field. The first four are largely utilized for the manufacture of medical isotopes, while the others provide experimental PWR&BWR conditions for fuel research.

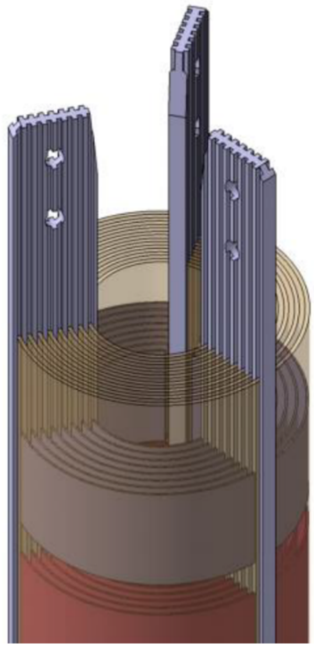

Figure 2: Schematic of the JHR fuel element [3].

3 COMPUTATIONAL MODEL

The first Serpent 2 model of JHR was created for a benchmarking exercise, in which the predictions of flux distribution and heat deposition throughout the core and reflector were compared to the TRIPOLI-4 calculations performed by CEA. Two configurations in particular were studied: a start-up core with fresh fuel at the beginning of life (BOL) and a reference core at the end of a 27 Equivalent Full Power Day (EFPD) cycle. A visualization of the former can be seen in Figure 3. CEA's GADGET tool was updated in the process to have the option to generate a SERPENT 2 CSG-geometry, facilitating future modelling in this project.

French RCC-MRx design and construction code [4] necessitates that reactor materials have maximum tolerable limits in terms of thermal and fast neutron fluences. For some materials embrittlement is driven by thermal flux-induced reactions, whereas for others the fast flux has a larger impact. In a similar vein, excessive heat deposition in the reactor components and testing devices is to be avoided. Current work beyond this paper attempts to characterize the lifetime of different reactor materials by finishing the spectral analyses of these materials in relation to the RCC-MRx code. An illustration of the thermal flux distribution in beryllium reflector blocks can be seen in Figure 4.

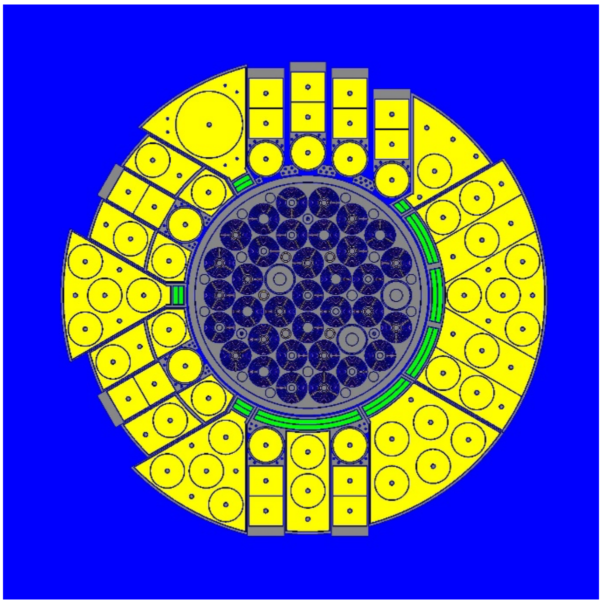

Figure 3: SERPENT 2 geometry plot of the benchmarking configuration [3].

The two benchmarking exercises had one major difference: in the former, the initial fuel composition is homogenous for all of the 34 fuel elements, whereas in the latter one the composition is heterogenous due to the burnup accumulated up until the end-of-cycle. Therefore the latter calculation uses material compositions calculated by HORUS3D/N burnup calculations, and requires ten times as much input data as the BOL calculation.

The reactor is operated at nominal power of 100 MW in both of the scenarios, and the cross sections are taken at room temperature to facilitate comparisons between the codes. The SERPENT 2.1.33 energy depletion model which estimates the impact of delayed gammas [5] requires the use of ENDF/B-VII.0 libraries, whereas the TRIPOLI-4 reference calculations were performed with JEFF3.1.1. Hence the cross-section libraries were not the same for both of the codes. A total of 10^8 neutrons were modelled in 500 cycles of 200000 neutrons. The calculations indicate a good agreement between the two codes, although the differences in heat deposition models resulted in TRIPOLI-4 producing slightly more conservative estimates.

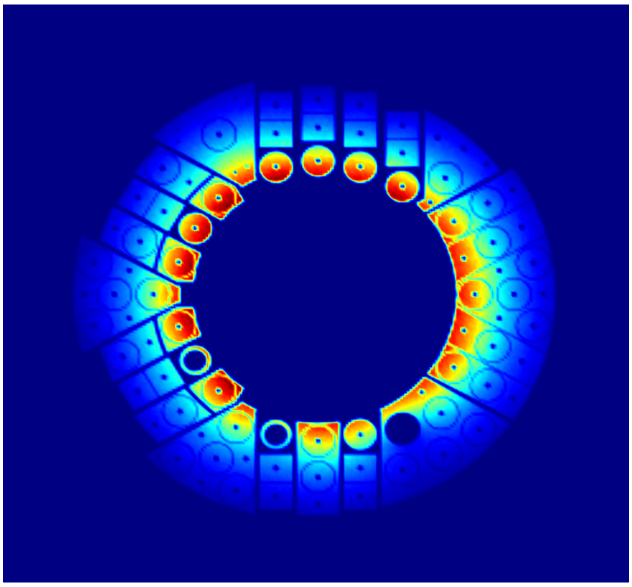

Figure 4: Thermal flux distribution in beryllium reflector blocks.

Besides the whole-core analyses, a device for ageing of pressure vessel steel OCCITANE [6] has been studied with respect to heat deposition and reaction dosimetry. In order to design the device optimally for the experiments aiming to study the radiation damage in the pressure vessel steel, the ratio of the fast and thermal fluxes needs to be well-defined within the reflector position in which the device will be installed. Furthermore, the heat deposition in the device should not exceed a set limit. Special attention needs to be similarly paid to the neutronic evolution of the device structures, such as the boron carbide shield which undergoes transmutations that fundamentally change its shielding properties. A schematic of the OCCITANE device can be seen in the Figure 5 below.

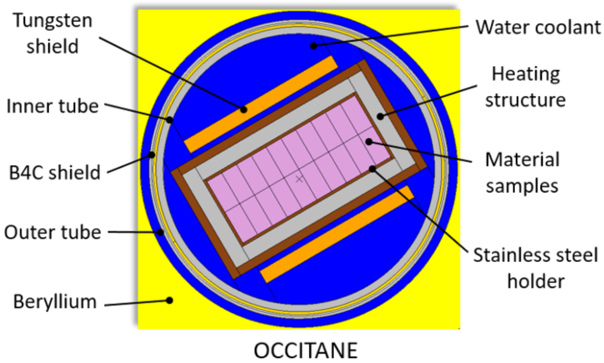

Figure 5: Schematic of the OCCITANE test device.

4 CONCLUSIONS

SERPENT 2 models have been developed for the Jules Horowitz Reactor as VTT's contribution in the reactor project. These models use the same method for generating CSG as CEA's neutronics code TRIPOLI-4, and the codes' results have been compared in previous benchmarking. This benchmarking indicated a good agreement between the codes in relation to the heat deposition and neutron flux distributions throughout the reactor.

The current focus in the project is to characterize the lifetime of various reactor materials in relation to the French RCC-MRx design and construction code. For this characterization, the neutron fluences of components such as beryllium blocks and zircaloy screens must be solved for different energy groups over the years of operation, studying the neutron-induced reactions which cause material degradation in each material.

Another current research topic within the project is the optimization of OCCITANE test device, which is designed to study the ageing of pressure vessel steel. The dosimetry properties, flux distribution and heat deposition must be within set ranges for the experimental setup this device is intended for.

ACKNOWLEDGEMENTS

I thank CEA's David Blanchet & Gilles Bignan for their continued collaboration with this research and my PhD. I'd like to acknowledge the support of my co-workers and SERPENT developers Jaakko Leppänen, Ville Valtavirta and Riku Tuominen on the guidance they gave me during this project. Furthermore, I thank Ville Tulkki, and VTT's mobility team for making this research exchange happen despite the delays caused by COVID. This project was funded by a grant offered to me by Fortum & Neste Foundation, the Finnish Research Programmes on Nuclear Safety SAFIR2022 and CEA.

REFERENCES

[1] G. Bignan, C. Colin, J. Pierre, C. Blandin, C. Gonnier, M. Auclair, F. Rozenblum, "The Jules Horowitz Reactor Research Project: A New High Performance Material Testing Reactor Working as an International User Facility – First Developments to Address R\&D on Material", The European Physical Journal Conferences, (2016).

[2] J. Leppänen, M. Pusa, T. Viitanen, V. Valtavirta and T. Kaltiaisenaho, "The SERPENT Monte Carlo code: Status, development and applications in 2013", Annals of Nuclear Energy, vol. 82, pp. 142-150 (2015).

[3] J. Peltonen, D. Blanchet, "SERPENT 2 & TRIPOLI-4 Neutronics Benchmarking of the Jules Horowitz Reactor", PHYSOR2022 conference proceedings, (2022).

[4] D. De Meis, "RCC-MRx design code for nuclear components", RT/2015/28/ENEA, (2015).

[5] R. Tuominen, V. Valtavirta, J. Leppanen, "New energy deposition treatment in the SERPENT 2 Monte Carlo transport code", Annals of Nuclear Energy, vol. 129, pp. 224-232 (2019).

[6] D. Blanchet, M. Anthony, H. Carcreff, S. François, P. Guimbal, B. Pouchin, "Assessment of irradiation performance in the Jules Horowitz Reactor (JHR) using the CARMEN measuring device", ANIMMA 2021 conference, (2021).