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Modeling of the TRIGA IPR-R1 Research Reactor with the Serpent2/RINNOVO Nodal Core Analysis Package

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Abstract

The Serpent2/RINNOVO nodal core analysis code system, a dedicated analysis tool for modeling research reactors, has the capability to accurately predict important core physics parameters involved in the safety of nuclear reactors, i.e., core reactivity coefficients, control rod worths and the shutdown margin, detailed core power distributions as well as the local neutron flux at various core locations of high importance, e.g., at irradiation rigs. In this work, a hexagonal model of the initial core of the Mark I type TRIGA IPR-R1 nuclear reactor has been created using the Serpent2/RINNOVO code system. Numerical results in terms of the core eigenvalue and the assembly power distribution have then been compared against corresponding full core Serpent2 reference results. In addition, an assessment of an appropriate neutron energy group structure to be employed by RINNOVO has also been performed using the recently implemented group condensation functionality in the latXS2Nodal data interface software product feeding Serpent2 generated nodal cross section data to RINNOVO.

1. Introduction

The IPR-R1 reactor is of TRIGA Mark I type designed and produced by General Atomics in 1960 [1]. This reactor has been extensively used in scientific research in the fields of radiochemistry, reactor dynamics, material science, crystallography, and radionuclide production.

Recent efforts to modernize and increase the accuracy in research reactor safety analysis methodologies and simulation capabilities have made room for the use of dedicated non-stochastic tools, such as the RINNOVO research reactor nodal core simulator [2]. In this regard, using such a deterministic approach aims to enhance the quality and productivity of engineering work conducted when operating such research reactors.

As an example of the superior speed of RINNOVO compared to Monte Carlo methods (Serpent2 in our case), full core results were obtained within minutes using RINNOVO compared to the order of days with Monte Carlo considering no parallelization. Even using a highly parallelized approach with Monte Carlo (in this study 7 nodes with 20 cores each), computing times around a few hours were still obtained. Consequently, RINNOVO is demonstrated to be very suitable for performing offline and online routine core calculations required for safe and optimized operation of research reactors. In addition, performing safety analyses that require extensive amount of calculations, can be performed in a very short time frame. In this regard, RINNOVO offers useful automation and a sophisticated graphical user interface (GUI) facilitating such set of simulations, as described in [2].

RINNOVO is a full three-dimensional (3D), multi-group core simulator based on an advanced nodal diffusion model that is capable of delivering highly accurate predictions of the core reactivity and flux distributions at a very low computational cost. The RINNOVO code package also offers a range of automated features that eliminates error prone user input in order to enhance both the quality and engineering productivity. A state-of-the art graphical user interface (GUI) facilitates core operations, such as component (e.g., assembly) shuffling and loading within the reactor core and between various reactor facilities being modeled, as well as efficient presentation and visualization of numerical results [2].

Serpent2 [3], a multi-purpose, 3D, continuous-energy Monte Carlo particle transport code developed by VTT in Finland, has the ability to model any level of geometrical complexity typically occurring in research reactors. In addition, Serpent2 provides functionality to perform lattice physics calculations in an automated fashion with inherent support for cross section spatial homogenization and energy condensation as well as for performing various types of branch calculations necessary to cover anticipated states of the considered fuel or reflector element in the core.

In this work, the Serpent2/RINNOVO code sequence is applied for modeling the initial core of the IPR-R1 TRIGA Mark I research reactor located at the Nuclear Technology Development Center (CDTN) in Belo Horizonte, Brazil [4][5]. In order to prove the feasibility of RINNOVO to analyze such type of small cylindrical reactors, a hexagonal model of the core has been utilized in this analysis. In the future, appropriate adjustments to this hexagonal model in terms of modified geometrical or material properties will be addressed to let it become more representative of the original cylindrical TRIGA core configuration.

Numerical results in terms of the core eigenvalue and assembly power distribution have then been compared against corresponding full core Serpent2 reference results using a similar methodology as reported by Ref. [6]. In addition, as modeling the TRIGA reactor is very challenging due to its very small size and heterogeneity with strong flux gradients imposed both spatially and in the energy domain, an assessment of an appropriate neutron energy group structure to be employed by RINNOVO has also been conducted. This is facilitated using the recently implemented group condensation functionality in the latXS2Nodal data interface code system providing Serpent2 generated nodal cross section data to RINNOVO [7]. In this way, only one set of Serpent2 lattice physics calculations is necessary to be performed employing some reference fine group structure, i.e., 69 groups in our case, as a starting point for such a study. Using the latXS2Nodal code to condense cross section data, any desired group structure can be generated based on the reference group structure without rerunning Serpent2 again.

This paper is organized as follows. Section 2 provides basic information about the IPR-R1

TRIGA reactor core. In Section 3, a short overview of the methodology applied for modeling the IPR-R1 core with Serpent2/RINNOVO is given. Numerical results are presented and discussed in Section 4 whereas some concluding remarks are given in Section 5.

2. Description of the TRIGA Core

The IPR-RI has its core submerged in the bottom of a pool filled with demineralized light water, which has core cooling functions, neutron moderation and reflection and radiation shielding. The dimensions of the reactor's pool form a cylinder 6.6 m deep and 1.92 m in diameter [5].

The active part of the core contains 91 assemblies that can be filled with fuel elements, control bars, neutron source, channels for irradiation of graphite samples, and "false elements". These 91 positions are arranged in 6 rings concentric, named rings A, B, C, D, E, and F, with respectively 1, 6, 12, 18, 24, and 30 positions.

Each fuel element is composed of cylindrical bars of approximately 72 cm in length and 3.6 cm in diameter. These fuel elements exist in two types, the ones cladd in aluminum and those that are cladd in stainless steel. Each element consists of a homogeneous mixture of uranium metal and Zirconium Hydride containing from 8% to 8.5% by weight of Uranium enriched at approximately 19.81% [5].

Figure 1 shows the IPR-R1 original core configuration, and Table I contains data about fuel element composition for each fuel ring around the core centre.

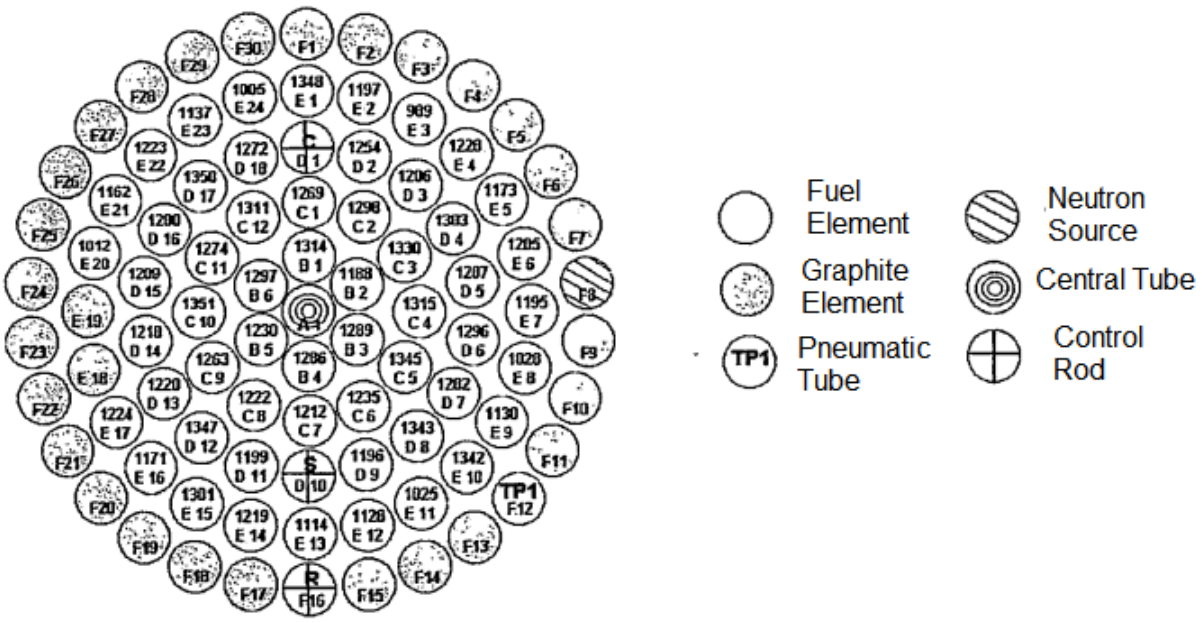

Figure 1: Original TRIGA core configuration

Other non-fissile elements compose the core of the reactor, which includes, neutron source, graphite elements, central tube, and control bars. The neutron source, as well as the graphite reflector, have the same dimensions as the aluminum fuel elements. They are intended to occupy the positions of the lattice of the the core that is unfilled by the fuel itself.

Table I: Original fuel elements composition

	Fuel ring B	Fuel ring C	Fuel ring D	Fuel ring E
Fuel density (g/cm^3)	6.29	6.29	6.29	6.29
Uranium Enrichment (%)	19.81	19.81	19.82	19.81
U-235 (% of total)	1.57	1.54	1.53	1.51
U-238 (% of total)	6.36	6.24	6.19	6.10
HZr (% of total)	92.06	92.21	92.28	92.39

The central tube is a device for irradiation consisting of an aluminum tube of 16.9 mm inner radius and 2.1 mm thick positioned in the center of the core and allowing the irradiation of samples in the position of maximum flow of neutrons.

Three cylindrical control rods are used to control the reactivity and to shut down the reactor. They are similar in composition, with the internal absorbent material measuring 38.1 cm in length with a 1.9 cm diameter. Table II shows the material composition of the graphite reflectors and the control rods.

Table II: Control Rod and graphite reflector composition

Control Rod	Graphite reflector
Mass compositon (%)	
B-10 = 15.52 B-11 = 62.48 C-12 = 21.76 C-13 = 0.24	C-12 = 98.9 C-13 = 1.1
Material density (g/cm^3)	
2.51	1.67

3. Serpent2/RINNOVO Core Analysis Methodology

3.1. Lattice Physics Methodology

In order to model the TRIGA reactor in RINNOVO, the considered core is subdivided radially and axially into various spatial subregions, for each of which nodal cross section data are generated by means of two-dimensional (2D) Serpent2 lattice physics calculations performed under a variety of predetermined conditions of state.

The resultant nodal cross section data are then processed by latXS2Nodal to generate a second order polynomial representation of the data as a function of the relevant state parameters defining the anticipated core conditions obtained during core operation. RINNOVO subsequently utilizes the polynomial data to construct nodal cross sections at the prevailing state of each node in the core being modeled.

3.2. Geometrical Lattice and Core Models and Applied Burnup Mesh

Although RINNOVO offers the possibility of modeling cylindrical cores, an approximate hexagonal representation has been adopted in this feasibility study to model the IPR-R1 TRIGA

research reactor. This was done in order to facilitate the cross section generation procedure using Serpent as explained in [7]. In Fig. 3, the radial projection of the 3D Serpent2 hexagonal core model (including the surrounding reflector) considered in this work is shown. In this core, the fuel pin locations are subdivided into zones, labeled from A to F starting from the core center moving towards the core periphery. Note that in the RINNOVO core model, the radial reflector is represented by an outer core layer of homogeneous hexagons with reflector material whereas the axial reflector (i.e., with different composition at the bottom and top of the core) is represented by a common axial reflector segment at each radial assembly location of the core. Also, it's important to notice that the core boundary conditions were set as vacuum, both in Serpent2 and RINNOVO models. The RINNOVO core configuration map is shown in Fig. 2.

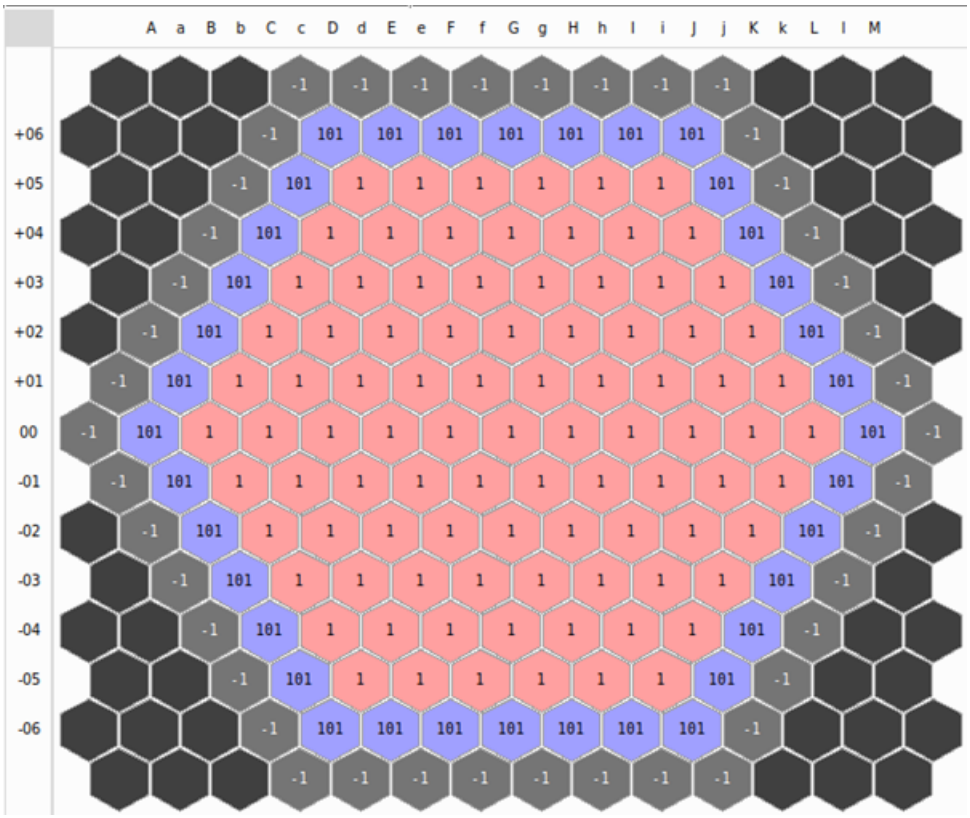

Figure 2: RINNOVO configuration map for the RINNOVO hexagonal core model.

The radial subdivision of the reactor core spatial domain into hexagons constitutes the basis for creating the geometrical configurations employed in the Serpent2 2D lattice physics calculations generating homogenized nodal cross section data to RINNOVO. In this regard, one distinguishes between fissile and non-fissile assembly elements, [1] the former treated as single-assembly configurations with reflective boundary conditions whereas the latter requires a multi-assembly configuration with the target homogenization region surrounded by its neighborhood containing some fissile material (i.e., typically few fuel pins). Again, reflective boundary conditions are

[1]Note that within the framework of modeling a TRIGA reactor, each fuel and non-fuel pin domain in the core is considered to be an assembly. This is in contrast to the conventional approach of power reactors, where an assembly consists of many fuel and non-fuel pins organized in a more or less regular manner to compose a fuel lattice.

applied at the outer boundaries of these multi-assembly systems. In Fig. 4, some of the typical Serpent2 2D lattice physics configurations used in this work are shown. In Table III and Fig. 5, the main geometrical properties of the core hexagons are summarized.

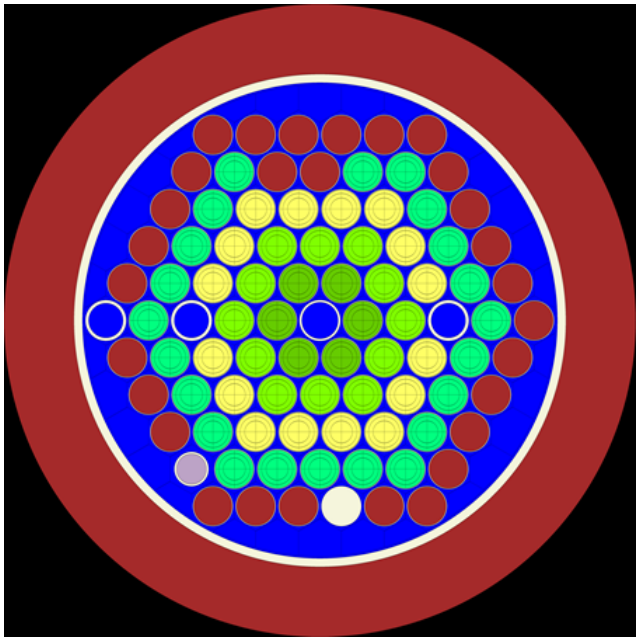

Figure 3: Radial layout of the 3D Serpent2 hexagonal core model.

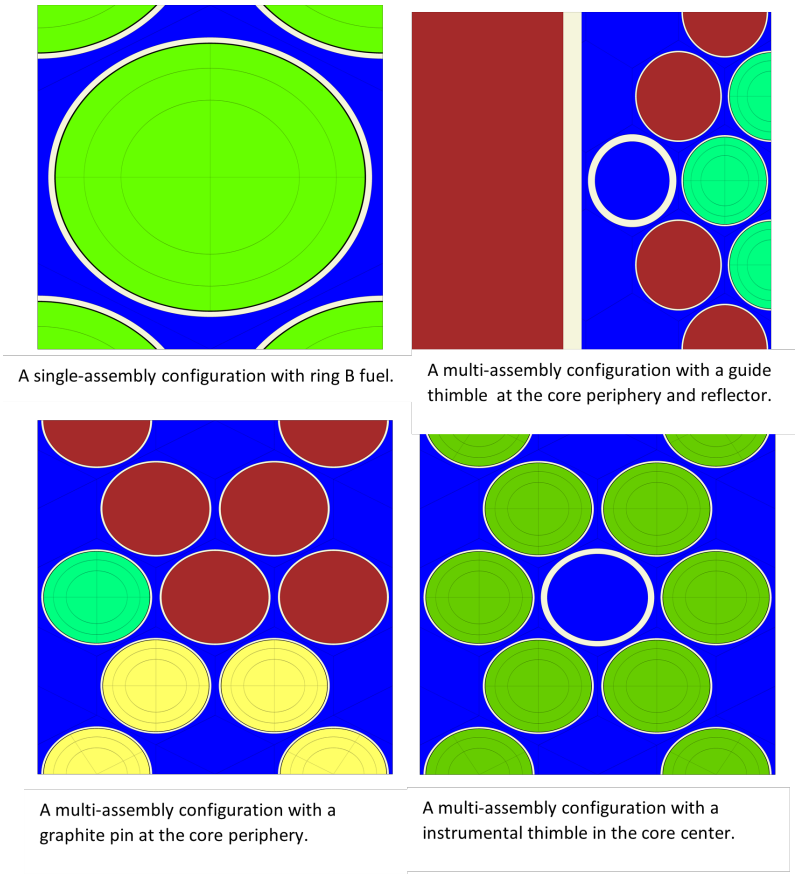

Figure 4: Some selected Serpent2 2D lattice physics configurations.

One should also recall that specifying a fine burnup mesh even for a single power calculation in Serpent2 is of crucial importance for gaining accuracy. This is because the update of the prevailing xenon distribution, i.e., equilibrium conditions in our case, is considered to be a "burnup" calculation in Serpent2. Consequently, the burnup mesh provided for the Serpent2 2D lattice physics/3D core reference calculations for burnable materials in the fuel are based on subdividing the fuel pins radially into 3 concentric rings of equal volume with 4 azimuthal sectors, and in the case of the 3D core model, axially into 20 zones of the same height.

3.3. Reference State Parameters

When it comes to the choice of appropriate reference or base values for the state parameters employed in **lattice physics calculations**, it is important to select values that are representative of the average (or nominal) condition prevailing during normal core operation. This is justified as long as the cross-section model of the nodal core simulator is designed to compensate for any impact that local variations of these state parameters have on nodal cross sections. Furthermore, it is anyhow quite challenging to foresee the conditions that the considered fuel element will be exposed to prior to the full core calculations. Consequently, core-averaged values for the fuel Doppler temperature (i.e., average value over the fuel element rings B-F) and ring-averaged values for the fuel mass have been used in the Serpent2 lattice calculations for the TRIGA reactor.

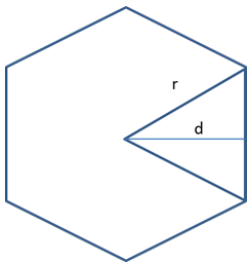

Figure 5: Layout of the hexagon geometry.

Table III: Basic geometrical data for core hexagons.

AF, Distance between the Core Centre and Ring F Center Line	19.8880 cm
Number of Core Rings	1 Center Tube + 5 Surrounding Rings (A, B, C, D, E, F)
Lattice Pitch p= AF/5	3.9776 cm
Triangle Height d = p/2	1.9888 cm
Triangle Base Length r	2.2965 cm
Hexagon Area	13.7016 cm^2

As concerns the selection of an appropriate reference coolant condition, the water density at a temperature of 300 K (27 C) and pressure of 1 bar was chosen in this analysis. In Table IV, the reference state parameters used in this work are summarized.

In the 3D full core simulations with both Serpent2 and RINNOVO, the assumption of isothermal conditions prevailing in the core was adopted since the two first cycles of the IPR-R1 reactor were operated at a reduced power of 30 KW. Therefore, both the fuel and moderator temperatures were set to 300 K in these full core simulations.

Table IV: Summary of applied reference state parameters.

	Fuel Elements		Central Tube	Pneumatic Tube	Neutron Source	Graphite Elements		CR Guide Thimbles	
Fuel Temperature [K]	453		453*)		453*)	453*)		453*)	
Power Density [W/g]	Ring B Ring C Ring D Ring E	9.22 9.38 9.48 9.64	9.22*)	9.64*)	9.52*)	Center Corner Periphery	9.54*) 9.64*) 9.64*)	Center Periphery	9.55*) 9.64*)
Cladding Temperature [K]	300		300	300	300	300		300	
Moderator Temperature [K]	300		300	300	300	300		300	
Coolant Density [g/cm^3]	0.99652		0.99652	0.99652	0.99652	0.99652		0.99652	

*) This value of the fuel temperature or power density corresponds to the average of applied values for the fuel element(s) in the vicinity of the target non-fissile region.

3.4. Conditions for Lattice Branch Calculations

In order to cover the majority of anticipated states of core operation, the state parameter values applied in the branch calculations need to be chosen so that any extrapolation is avoided. Consequently, the range of applied state parameter values as well as the calculation matrix are both application and reactor specific. In Table V, the state parameter values used in the Serpent2 lattice calculations for the IPR-R1 reactor are given.

Note that depletion at the reference base condition is normally performed at the state of equilibrium xenon whereas in all branch calculations (except for the xenon spectrum branches themselves), the xenon is kept fixed at its value obtained during depletion. Note also, due to the mathematical nature of the cross-section representation, any perturbation in a considered state parameter during a branch calculation specified by Table V is done by fixing all the other state parameters at their reference base values. Both unrodded and rodded (where relevant) branch calculations of Table V have been considered. All the lattice branch calculations have been accomplished by applying the automated burnup sequence functionality provided by Serpent2 [8].

Table V: State parameter values of Serpent2 lattice calculations for the TRIGA reactor.

State Parameter	Base Value	1st Perturbation	2nd Perturbation
Coolant Density [g/cm^3]	0.99652	0.99222	0.98805
Fuel Doppler Temperature [K]	453	300	673
Moderator Temperature [K]	300	313	323
Xenon Number Density [1/cm^3]	Equilibrium	Zero	N/A

4. Numerical Results

Not yet available at the time point of summary submittal. TRIGA core model created in RINNOVO will be used to achieve numerical results of the core eigenvalue. Also, the assembly power distribution will be obtained according to the nodal configuration. These parameters will be compared with those calculated using the 3D reference core model.

Regarding the neutron energy group structure, the latXS2Nodal code system will be employed to condense cross section data and generate different sets of group structures for RINNOVO, allowing a thorough analysis on whether the initial group structure choice was satisfactory. Possibly, an optimization process will be conducted to evaluate the best possible group structure for the TRIGA core model, aiming to establish reference parameters for further studies.

5. Conclusions

Will be addressed when all numerical results become available.

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