VALIDATION OF SERPENT 2 USING EXPERIMENTAL DATA FROM THE SPERT-IV D-12/25 RESEARCH REACTOR TESTS

J.C. ALMACHI, V.H. SANCHEZ-ESPINOZA

Institute for Neutron Physics and Reactor Technology, Karlsruhe Institute of Technology
Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen – Germany

M. MARGULIS

Nuclear Futures Institute, School of Computer Science and Electronic Engineering, Bangor University,
Bangor, LL57 2DG, United Kingdom

ABSTRACT

In this work, the analysis of two test scenarios of the SPERT IV D-12/25 reactor using the Monte Carlo Serpent 2 code is presented and the results are discussed. A first full 3D model of SPERT was developed to predict the critical condition characterised by four control rods position at 36.70 cm (measured from the lowest part of the fuel plate) and the transient rod completely withdrawn out of the core. The Serpent 2 code is validated against the experimental data described in the nuclear start-up report of SPERT IV. In addition, another full 3D model was elaborated for the simulation of the critical conditions with different positions of the control rods and of the transient rod. The maximal reactivity worth of the new transient rod position was estimated to be 2.64 $. In this case, the control rods position is 44.955 cm and the position of the transient rod is 21.915 cm. These investigations pave the way for the analysis of the transient rod ejection test with the high-fidelity coupled code Serpent2/Subchanflow.

1. Introduction

In recent years, several neutrons and thermal-hydraulic codes have been validated using experimental data in order to improve the prediction capability of simulation tools for both research and power reactors. Large volume of experimental data for research reactors was made available to the research community in the frame of the Coordinated Research Project (CRP) of the International Atomic Energy Agency (IAEA) from 2008 to 2013 this project, *Benchmarking against Experimental Data of Neutronics and Thermohydraulic Computational Methods and Tools for Operation and Safety Analysis of Research Reactors IAEA-TECDOC-1879*, generated a large amount of results of computer simulations for various conditions and geometrical configurations of eight research reactors [1]. For several years, simulation tools have been evolving and computational technological progress has allowed the implementation of innovative analysis methods such as high-fidelity simulations e.g., neutrons and thermal-hydraulics both coupled. High-fidelity simulations are in continuous development and are widely applied in power reactors. Several research groups tried to adapt numerical codes developed for power reactors to research reactors. This approach uses heuristic methods of calculations using equivalent plates, geometrical simplifications, and among other things, specific correlations for power reactors, [2–6]. In recent years several researchers have applied stochastic and deterministic neutronics codes for the analysis of the core of research reactors [7–12].

At the Karlsruhe Institute of Technology (KIT), high-fidelity multi-physics simulation tools for power reactors are under development in the framework of the participation to different European projects, e.g. H2020 McSAFE [13, 14]. The Monte Carlo Serpent 2 and Subchanflow thermal-hydraulic codes have been coupled under the Master-Slave approach at KIT for the analysis of transients. In 2019, the thermal-hydraulic code Subchanflow was extended and validated for the analysis of research reactor cores [15, 16]. The extended Serpent2/Subchanflow platform of codes has been used to analyse hypothetical transients of an MTR-core defined in the IAEA 10MW benchmark [17] and detailed steady state and transient analysis of an MTR-core at plate-by-plate and subchannel-by-subchannel level were performed and the results discussed in [18]. To validate Serpent2/Subchanflow, the experimental data (neutrons and thermal-hydraulic) of the SPERT-IV 12/25 reactor have been selected. First, in this work, the experimental neutronic data are used for the validation of the full 3D model of Serpent 2. Subsequently, a new criticality position is established based on the recommendations of [19] page 13 in which the transient rod is the one providing the reactivity. These investigations are an important precondition for the subsequent analysis of the transient test with the high-fidelity Serpent2/Subchanflow code. This paper consists of five sections. Section 2 describes the dimensions and initial conditions of the SPERT-IV D12/25 reactor configuration. Section 3 presents the assumptions necessary for the construction of the Serpent 2 model. Section 4 discusses the comparison of experimental data with the predicted results, and it characterises the new critical state of the reactor. Section 5 presents the conclusions and outlook.

2. Description of SPERT-IV reactor

This section presents a brief description of the geometrical parameters of the SPERT-IV reactor. In order to reduce the metrological differences involved in the transformation from imperial to metric units, a 3D model was built using the Autodesk-Inventor program [20]. Figure 1 (a) shows the dimensions in mm of the lower grid assembly made of 6061-T6 aluminium. It contains 81 internal holes to house the fuel assemblies. The active part of the reactor core is located in the centre of the lower grid. The core, Figure 1 (b), consists of 20 standard fuel assemblies, four control fuel assemblies and one transient fuel assembly for a total of 25. The fuel assemblies are housed in an assembly also made of aluminium, Figure 1 (c).

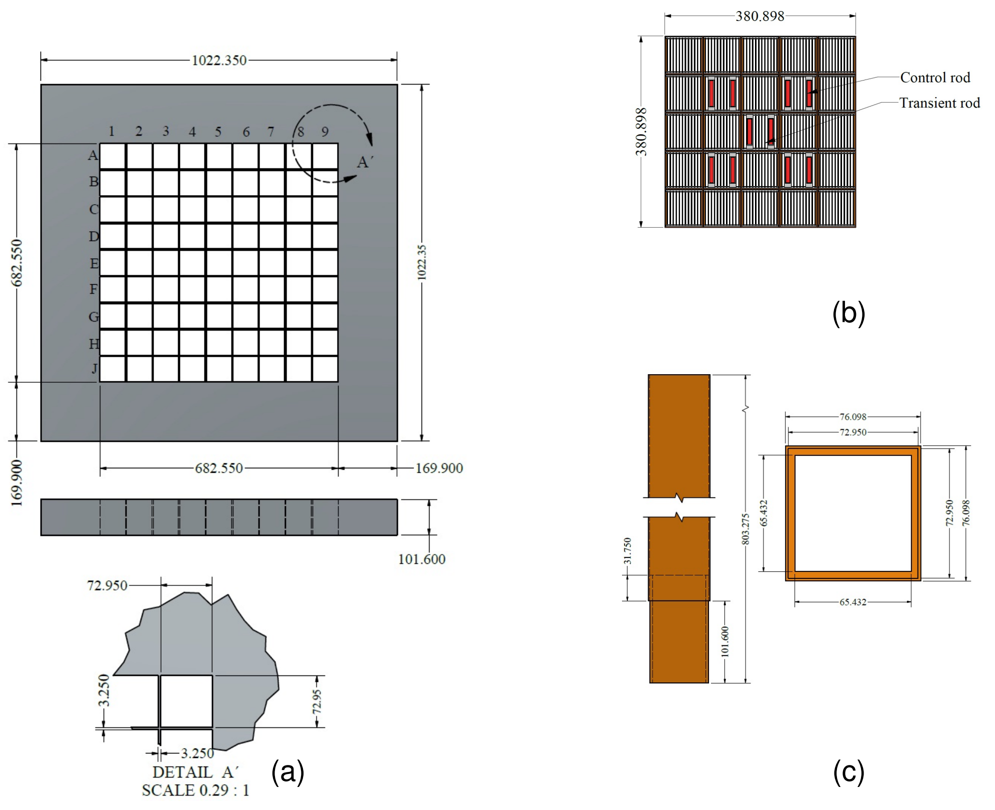


Fig. 1. SPERT-IV dimensions in mm of: (a) lower grid assembly; (b) core; (c) assembly can

Figure 2 (a) shows the dimensions of a standard fuel assembly (SFA) composed of 12 fuel plates (HEU 93 % enriched). Figure 2 (b) shows the dimensions of the control fuel assembly (CFA), which has a total of six fuel plates and at each end a space to accommodate the absorbent material (B-Al). The side plates supporting the cladding of the fuel plates are made of aluminium. The axial dimensions of the meat inside of the aluminium plate can be seen in Figure 2 (c). Finally, the axial dimensions of the control and transient rods are shown in Figure 2 (d).

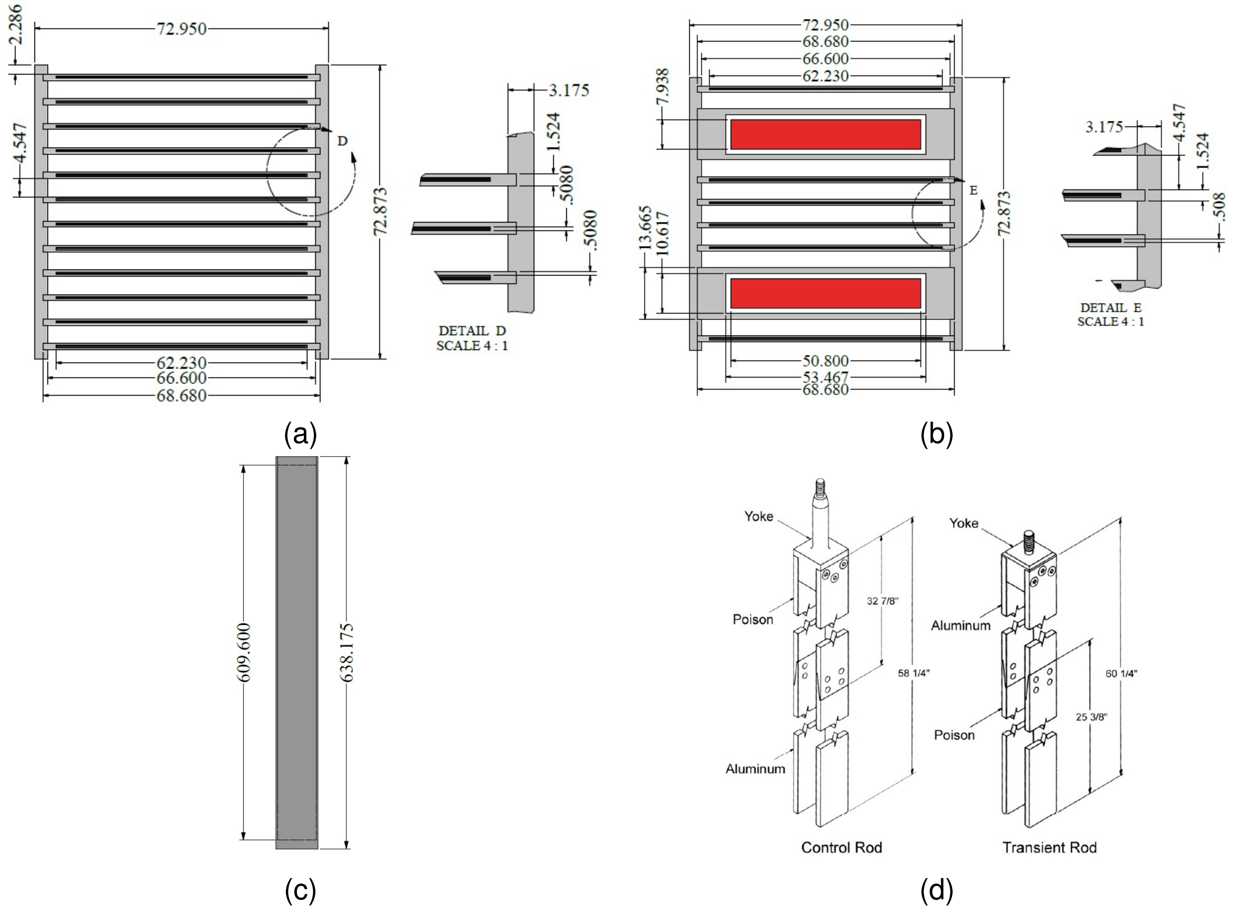


Fig. 2. SPERT-IV dimensions [20]: (a) standard fuel assembly in mm; (b) control fuel assembly in mm; (c) plate-fuel in mm; (d) control and transient rod in inch

Table 1 shows the main operating specifications for the neutronic tests. Material specifications in atomic density required for Monte Carlo calculations can be found in [20] on page 14.

Type of reactor	Open pool MTR type
Fuel type	UAl alloy Al clad flat plate fuel
Enrichment	HEU 93 %, 14.0 g ^{235}U
Reference pressure	Pool is open to the atmosphere
Nominal reference temperature	20 °C
Coolant	Light water
Moderator	Light water
Reflector	Light water
Poison material	Binal (B-Al)

Tab 1: Main operation conditions of SPERT-IV

3. Calculation tools

The Monte Carlo code Serpent 2 is used for the core analysis. It is a state-of-the-art code that uses the standard ACE Nuclear Data format for 3D continuous space-energy calculations [21]. This code is widely used for both static and dynamic calculations [22].

3.1 Serpent model and assumptions

A detailed Serpent model, i.e. at plate and subchannel level, was developed following the geometrical description presented in section 2. For the static neutronic calculations, the following aspects were used.

- Nuclear data library: ENDFB-VIII.0 [21]
- The control and transient rod will be moved by Universe Transformation (trans) [23]
- Axially, each plate is subdivided into 60 zones.
- A square detector of 0.1016 cm was used for thermal flux
- The absorber material is Binal (B-Al)
- The control rods are extracted in Z+ axis direction
- The transient rod is inserted in the Z+ axis direction
- The criticality calculations are performed with 200 inactive cycles followed by 1000 active cycles, each consisting of 10^6 histories.

In order to validate the results, the measured and calculated thermal fluxes were compared in two positions, E5 and D4, [24]. The data experimental were measured by means of cobalt wires located at different positions, see Figure 3. The energy cutoff for thermal flux was set to 0.5 eV.

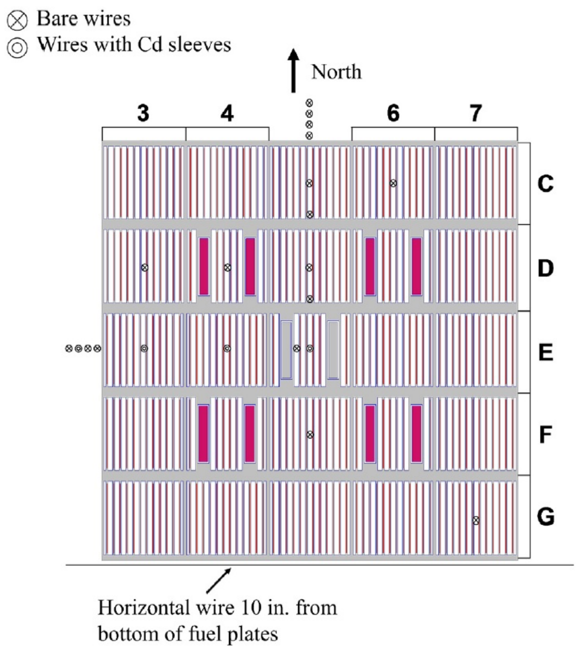


Fig. 3. Radial position of cobalt wires for thermal flux measures, [10]

To obtain the new critical state of the reactor, first, the control rods are extracted until a reactivity of $\sim$ 2.64 $ is reached. Then the transient rod is inserted until the reactivity is reduced to $\sim$ 0 $, see [19] page 13.

4. Comparison of the experimental data with the Serpent predictions

Figure 4 and 5 show the normalised axial thermal flux at positions D4 and E5 with a statistical error of $\pm$ 2 sigma compared with the measurement data. The highest statistical error is found around the peaks of the flux profile. The thermal flux has also been normalised, and a higher statistical error can be observed in the lower major peaks. In general, the results of Serpent are very close to the measured data at the two positions, and they are comparable to those presented in [10].

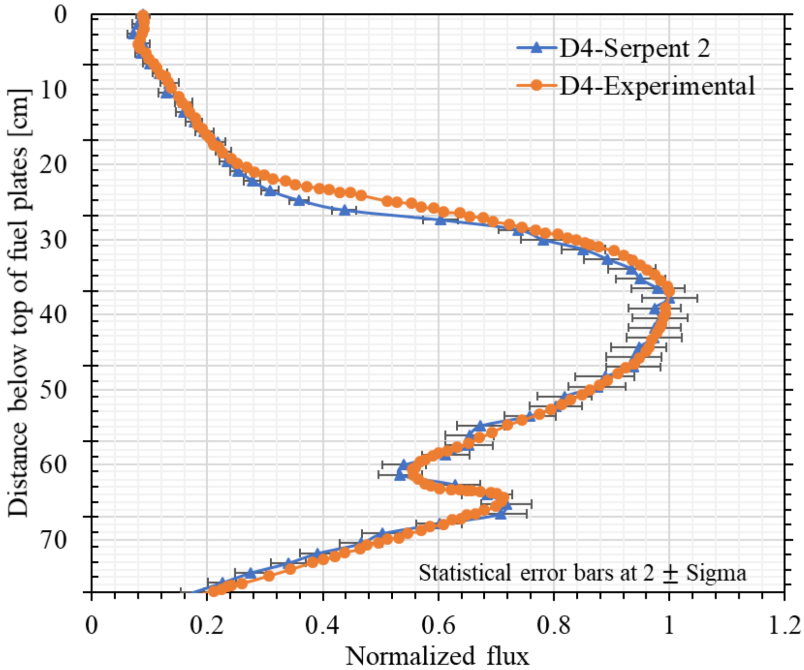


Fig. 4. Comparison of thermal flux detectors at location D4

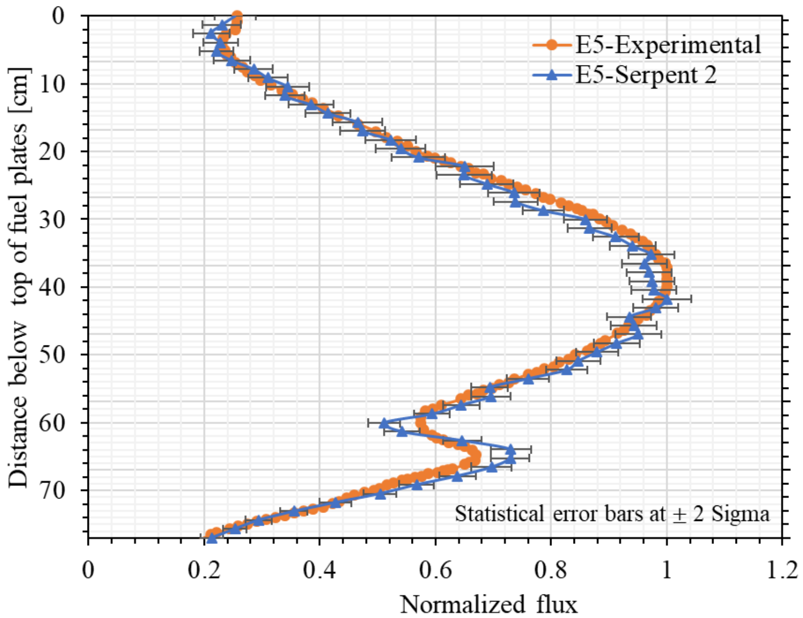


Fig. 5. Comparison of thermal flux detectors at location E5

Figure 6 shows the reactivity added to the reactor when the control rods are extracted step-by-step. The simulations were performed at different rod positions (6 positions measured from the lowest part of the active region of the plate, see Figure 2 (c). The βeff value calculated by Serpent, for reactivity estimation, was 749 $\pm$ 2 pcm using the Meulekamp Method [25]. A good agreement of the predictions with the experimental data is observed.

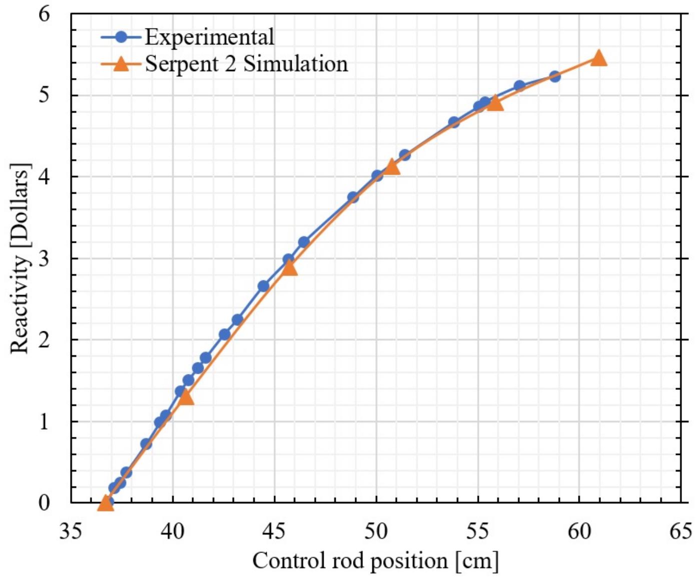
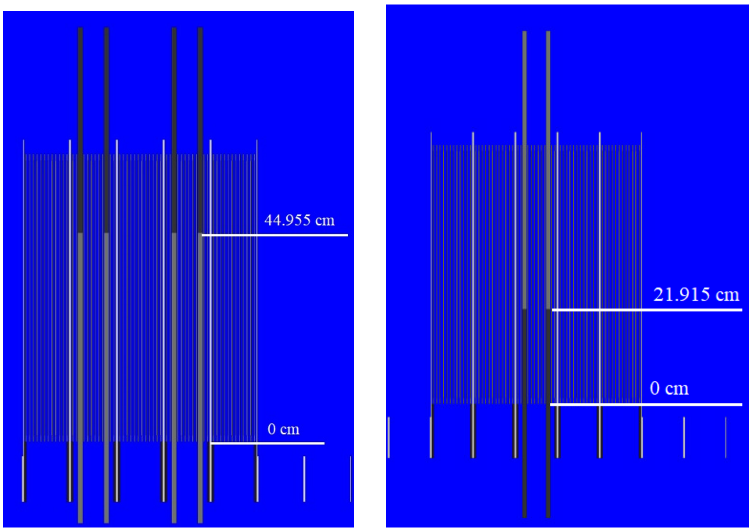


Fig. 6. Integral control rod worth comparison

The Serpent simulation time was about $\sim$ 5 hours for each position using an OpenMP compiler with 48 cores Linux 4.9.0-18-amd64. Figure 7 shows the positions of the control and transient rods for a new critical state with a factor keff of 1.00001 $\pm$ 0.00002. The dark part of the rods corresponds to the Binal absorber material. The control rods are extracted to add reactivity in the z+ direction, whereas the transient rod is introduced in the z- direction to decrease the reactivity.



(a) (b)

Fig. 7. Critically positions of: (a) control rods; (b) transient rod

Figure 8 shows the normalised thermal flux at positions D4 and E5 predicted by Serpent 2 with a statistical error of $\pm$ 2 sigma. Higher uncertainty is observed at the peaks. The curves were obtained with the control and transient rods inserted at the positions described in Figure 7.

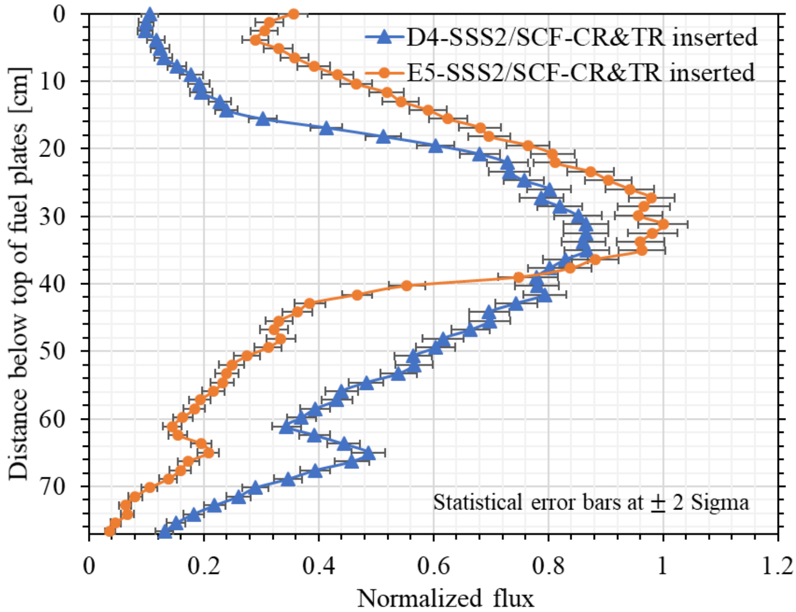


Fig. 8. Thermal flux normalised simulation, control and transient rods (CT & TR) inserted

Finally, Figure 9 shows the reactivity added by the transient rod at seven different positions. In case the transient rod is fully extracted from the core, a maximum reactivity of \$ 2.64 will be inserted into the core. The simulation time for each simulation was about $\sim$ 5 hours for each position using an OpenMP compiler with 48 cores Linux 4.9.0-18-amd64.

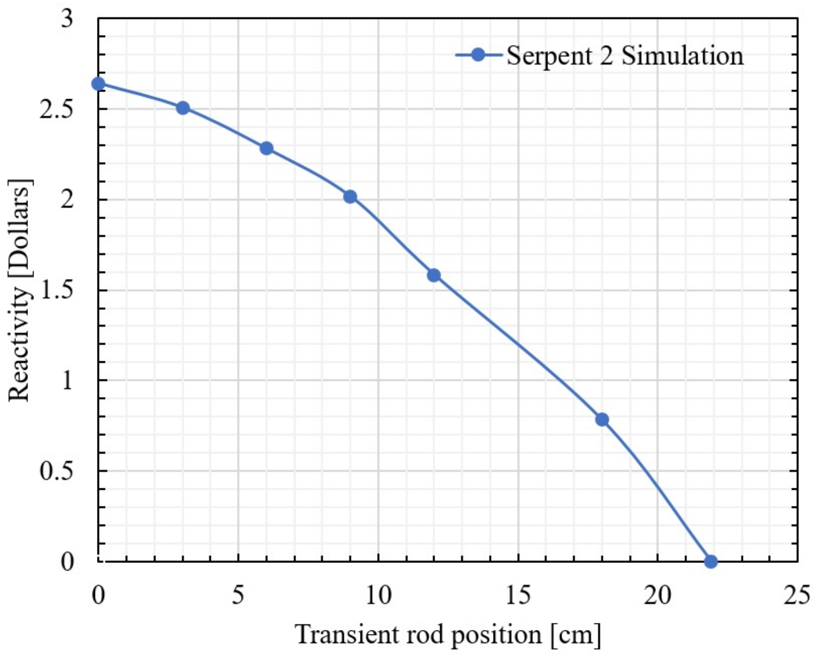


Fig. 9. Transient rod worth

5. Conclusions and outlook

The Serpent 2 code has been successfully validated against the experimental data of the SPERT-IV D12/25 reactor measured for static core conditions at two different radial positions (normalised thermal neutron flux obtained from the E5 and D4). The reactivity at different positions of the control rods was calculated, and the obtained reactivity curve was compared with the experimental data showing a good agreement. The new critical state of the core is characterised by a keff of 1.00001 $\pm$ 0.00002 with a position at 44.955 cm for the control rods and 21.915 cm for the transient rod. This new configuration will be used to determine the extraction rate of the transient rod for the high-fidelity calculations.

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