SIMULATION OF KSMR CORE ZERO POWER CONDITIONS USING THE MONTE CARLO CODE SERPENT

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Abstract

The interest in the development and deployment of Small Modular Reactors (SMRs) of different designs is increasing worldwide due to its economic attractiveness and unique safety features. At Karlsruhe Institute of Technology (KIT), an investigation has started to optimize the Korean's soluble boron operated SMR core concept (SMART) to a boron-free simplified SMR core with enhanced inherent safety features. The optimized core is called Karlsruhe Small Modular Reactor (KSMR). The optimization process of the KSMR relied on using innovative burnable poison rods for short and mid-term reactivity control during depletion. In addition, many proven PWR technologies were adopted in the design of the KSMR core. In this paper, a zero power Beginning of Cycle (BOC) evaluation at cold and hot conditions was performed using the Monte Carlo code Serpent. The evaluation focused on predicting the inherent safety features of the KSMR core; including excess reactivity, shutdown margin, feedback coefficients, and power distribution. The performed analysis presented a remarkable performance of the KSMR core. Those inherent safety parameters were found to be: excess reactivity at CZP (15,490 ± 4 pcm); cold shutdown margin (-6,936 ± 7 pcm); FTC (-2.06 pcm/K); and MTC (-55.04 pcm/K). The detailed analysis and discussions are presented in the paper.

1. Introduction

Karlsruhe Small Modular Reactor (KSMR) core has been developed at Karlsruhe Institute of Technology based on the Korean System-Integrated Modular Advanced ReacTor (SMART) design [1]. A previous investigation [2] has been accomplished for a generic SMART core based on available public data. That study concluded the need for additional investigations. The KSMR core share many features of the SMART core, for example both have the same number of fuel assemblies (FAs) in the core; FAs are based on 17x17 fuel pin arrays PWR proven technology; the reactor core is loaded with low-enriched uranium fuel and cooled and moderated with light water. However, what differentiates them is that the KSMR core is operated without boron. To compensate for high excess reactivity at Beginning of Cycle (BOC), the KSMR core utilizes a number of burnable poison rods.
In terms of safety, the KSMR core has a high negative Moderator Temperature Coefficient (MTC) which is a result of the absence of boron in the moderator. Hence, this feature is translated into an increased inherent core safety performance. Nevertheless, a high negative MTC could potentially make the core critical even with All-Rods-Inserted (ARI) in case of overcooling accidents such as main steam line break. Therefore, control rods should be designed properly to provide enough shutdown margin and eventually prevent recriticality in overcooling events.
Currently, the KSMR is planned to have once-through fuel cycle as employed in mPower [3]. Conceptually, such a fuel cycle strategy has an advantage over multi-fuel cycle by reducing outages period due to refueling. On the other hand, single batch fuel loading does not effectively utilize fuel compared to multi-batches loading which can be noticed clearly by the linear reactivity model [4].

The objective of this paper is to (a) generally address the challenges facing PWR-based SMRs core design; predict the: (b) reactivity change from hot to cold zero power; (c) cold shutdown margin; (d) fuel and moderator reactivity coefficient; and (e) 3D assembly-wise power distribution of the KSMR core by using the Monte Carlo tool Serpent.

2. Used Simulation Tool

Serpent [5] is a dedicated reactor physics code developed by VTT that performs stochastic modeling of particles using the Monte Carlo method. It uses continues energy rather than multi-group energy microscopic cross sections. In which the latter relay on an approximate self-shielding treatment in resonance regions. Unlike deterministic codes, Serpent has a flexible geometrical capability which allows high degree of accuracy to model complex geometries. For example, an explicit modeling of the structures surrounding the KSMR core (baffle, barrel, neutron pads, etc.) as well as axial structural details (spacer grids, end plugs, upper and lower nozzles, etc.) were modeled to account for their influence on core reactivity. Serpent has the capability to accurately represent S(α,β) thermal scattering data for ^{1}H at any selected temperature through the use of linear interpolation between S(α,β) thermal scattering data [6]. Also, to treat cross section temperature-dependent data by using Doppler broadening preprocessor that is similar to the one used in NJOY [7]. Both features yielded a better estimation of feedback coefficients for the KSMR core. The Serpent version and nuclear data library used in the current work is 2.1.27 and ENDF/B-VII.0, respectively. In this work, Serpent source files have been modified to produce legacy Visualization Toolkit (VTK) [8] file for post-processing purposes.

3. Core Design and Model Description

The design philosophy behind the KSMR core is to adopt many proven technology features from PWR technologies with an emphasis of not using soluble boron in the coolant. The advantage of having the boron-free operation is reflected in the elimination of the probability of boron dilution accidents. This issue is highly important for severe accidents especially if reflooding of the reactor core by seawater is considered. In such an event, core recriticality is mostly probable.

The KSMR core differs from advanced PWRs (such as EPR, AP1000, etc.) in terms of core size and fraction of rodded FAs. The KSMR core has few FAs in the core (57 FAs) with approximately half of the active length (2 m) of PWRs. Due to that, an increased neutron leakage is expected. The fewer number of FAs in the core leads to fewer degrees of freedom compared to large reactors. These two aspects make the design of the KSMR a challenging process. The fraction of rodded FAs in the KSMR core is 72% whereas in PWRs is below 50% [9]. The higher number of control rods in the core is due to the use of boron-free coolant. The Cold Zero Power (CZP) and Hot Zero Power (HZP) operating conditions for the KSMR are defined as follows:

- Cold Zero Power (CZP): Refers to a pressure of 0.1 MPa with both fuel and coolant temperatures at 300 K.
- Hot Zero Power (HZP): Refers to a pressure of 15 MPa with both fuel and coolant at 569.15 K.

The detailed Serpent model for the KSMR core is presented in Fig. 1

4. Zero Power Results

The simulations performed for the KSMR core include excess reactivity at CZP and HZP; cold shutdown margin; reactivity feedback coefficients; and 3D assembly-wise power distribution. In addition, a sensitivity study was performed to measure the influence of core baffle, barrel, neutron pad, spacer grids, and RPV on core reactivity.

Due to the inherent stochastic nature of Monte Carlo method, an adequate number of particles were used to establish reliable eigenvalue and 3D assembly-wise power distribution results. For each simulation, fission source convergence was monitored by Shannon entropy diagnosis of a mesh-based fission source data. This diagnosis led to a proper selection of the number of inactive cycles. For all cases mentioned above: 200,000 particles/cycle; 2000 cycles; and 300 inactive cycles were used.

4.1. Excess reactivity

The excess reactivity was simulated by extracting all control rods out of the core. Table 1 summarizes the excess reactivity at CZP and HZP conditions.

Table 1: KSMR Core Excess Reactivity at CZP and HZP

	Excess Reactivity (pcm)
At CZP	15,490 ± 4
At HZP	8,243 ± 4

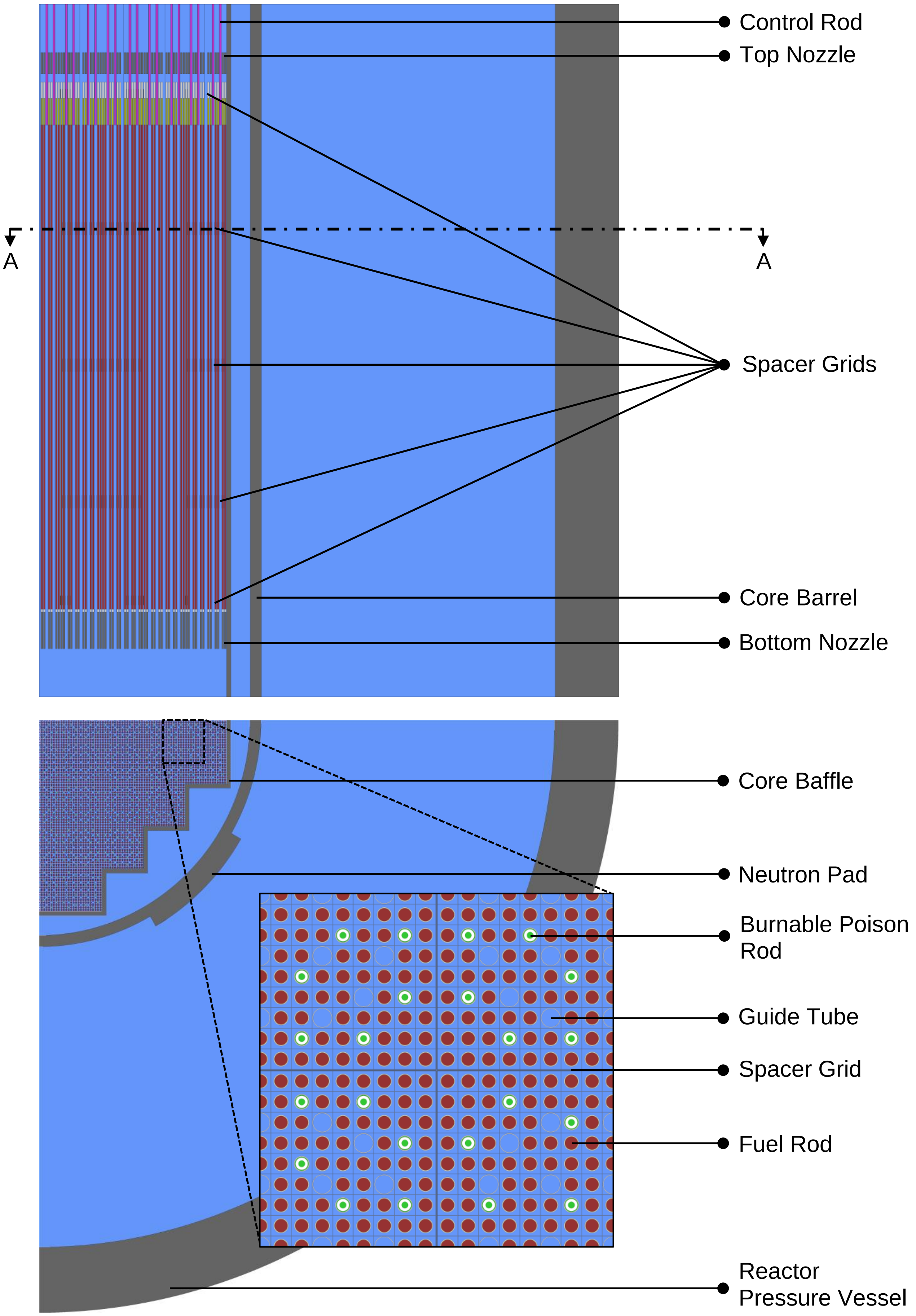


Fig. 1: Serpent Model of KSMR Core

4.2. Cold Shutdown Margin (CSDM)

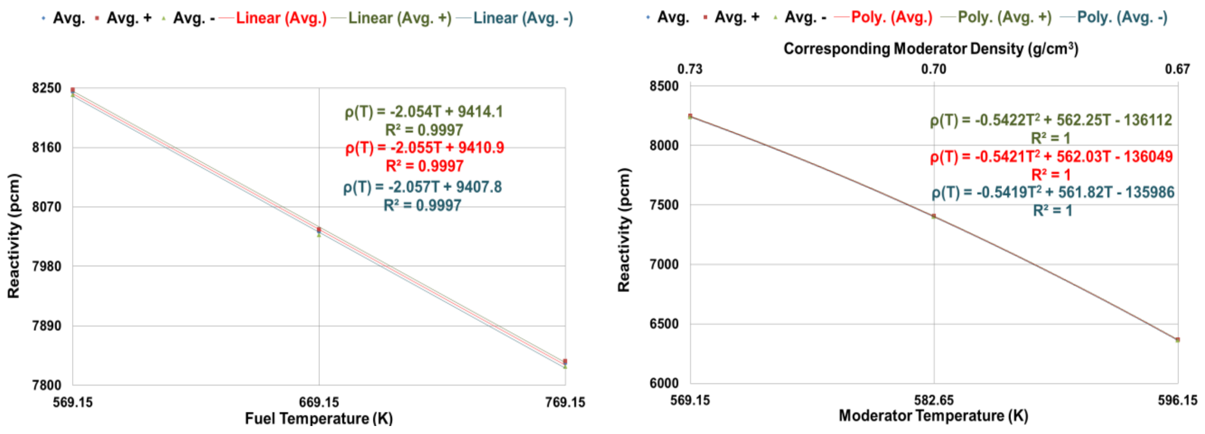
CSDM is defined as the amount of reactivity needed to make a reactor core in subcriticality condition at CZP. It is simulated by fully inserting all (shutdown and control) rods in the core. Taking a conservative approach, the CSDM was calculated instead of Hot SDM since the highest reactivity excess is at CZP. In normal practices, CSDM is evaluated with the highest worth control rod stuck outside the active core. In the KSMR core, the CSDM with single failure of highest control rod worth was found to be (-6,936 ± 7) pcm.

4.3. Reactivity feedback coefficients

Reactivity feedback coefficients are generally defined as a difference between two core reactivity states per a change in a given parameter. In this work, it was divided into two parts: Fuel Temperature Coefficient (FTC) and Moderator Temperature Coefficient (MTC). FTC is defined as the reactivity change due to an increase of fuel temperature per fuel temperature change, whereas the MTC is defined as the reactivity change due to an increase of moderator temperature and its corresponding density per moderator temperature change. The reactivity feedback coefficients were calculated at All-Rods-Out (ARO) as follows:

- Fuel Temperature Coefficient (FTC): The moderator temperature and density were both kept at HZP condition (569.15 K and 0.73371 g/cm^3) whereas fuel temperature was increased from 569.15 K to 769.15 K in 100 K step. Then, these results were fit linearly and the FTC was found from the slope of the fit line, as shown in Fig. 2.

- Moderator Temperature Coefficient (MTC): The fuel temperature was kept at HZP condition (569.15 K), then both moderator temperature and density were increased from 569.15 K (0.73371 g/cm^3) to 596.15 K (0.67056 g/cm^3) in 13.5 K step. After that, these results were fit quadratically and the MTC was found by evaluating the derivative of the fitted equation at 569.15 K, as shown in Fig. 2. The reason behind fitting these data quadratically is the non-linearity relationship between moderator temperature and density. At high temperatures an increase in the moderator temperature causes a larger reduction in density compared to an identical increase at low moderator temperatures.



(a) Reactivity vs. Fuel Temperature (b) Reactivity vs. Moderator Temperature

Fig. 2: KSMR Reactivity Trends vs. (a) Fuel and (b) Moderator Temperature

The reactivity feedback coefficients for the KSMR core are presented in Table 2.

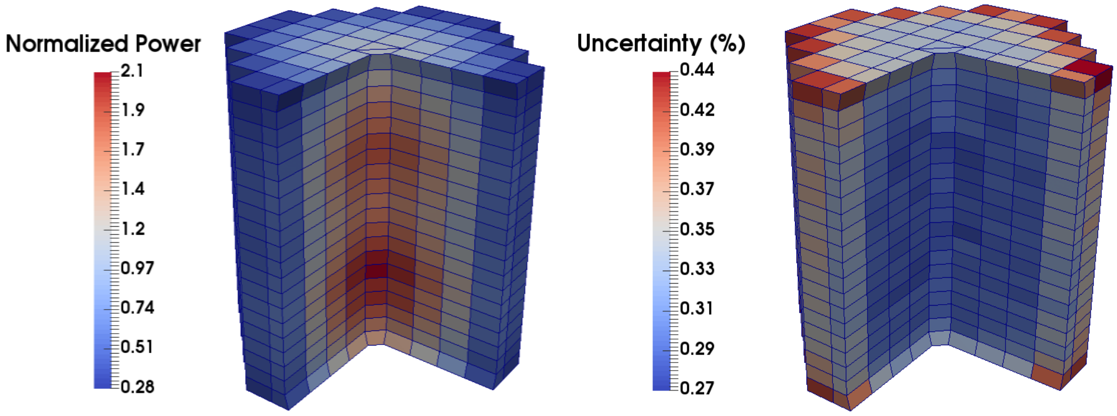
Table 2: KSMR Fuel and Moderator Temperature Coefficients

Fuel Temperature Coefficient (pcm/K)*	-2.06
Moderator Temperature Coefficient (pcm/K)*	-55.04

* The statistical uncertainty at 1σ was found to be < 0.1 pcm/K

4.4. 3D assembly-wise power distribution

In addition to the eigenvalue simulations at zero power, Serpent was also used to produce 3D assembly-wise normalized power distribution and its associated statistical uncertainty for the KSMR core at HZP and ARO. The axial discretization for scoring power data was set to be 20 axial regions. Fig. 3 presents the 3D normalized power distribution and Fig. 4 zooms into the hot channel (highest power FA) axial power distribution.



Normalized Power Distribution Statistical Uncertainty

Fig. 3: 3D Power Distribution at HZP and ARO for The KSMR Core

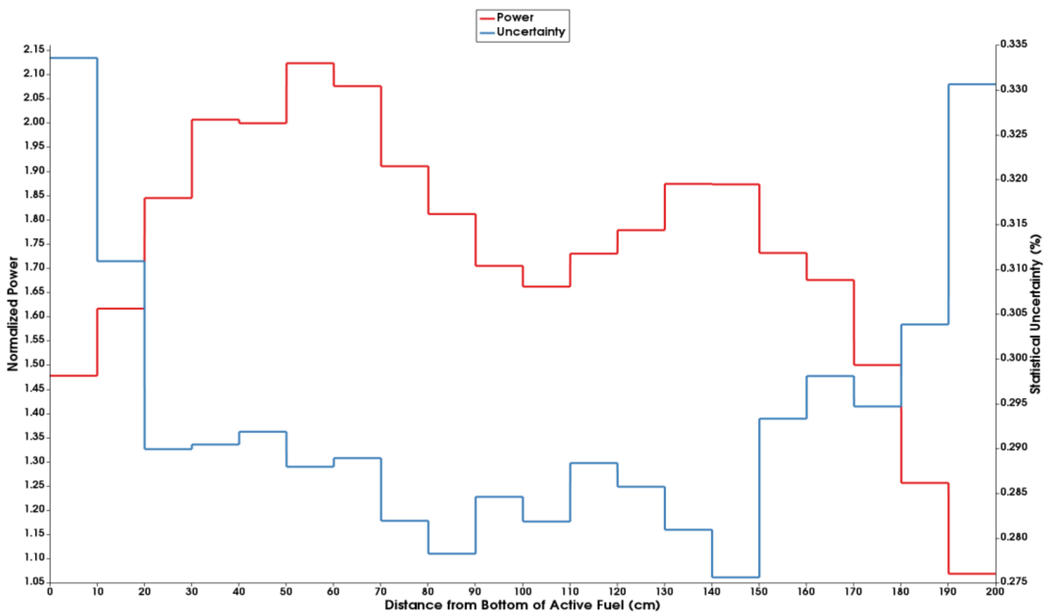


Fig. 4: Axial Normalized Power Distribution at the Highest Power FA for the KSMR Core

4.5. Sensitivity analysis

A sensitivity study was performed on the KSMR to study the impact of including detailed radial and axial structures (core baffle, barrel, neutron pad, RPV, and spacer grids) on core reactivity. The simulation was performed by calculating the reactivity worth of each of the mentioned structures at HZP and ARO. The main objective of this study is investigating the worthiness of including these structures in cross section generations. Table 3 summarizes the outcomes of this study.

Table 3: Reactivity Worth for Core Baffle, Barrel, Neutron Pad, RPV, and Spacer Grids

	Reactivity worth (pcm)
Core baffle	404 ± 4
Core barrel	Negligible†
Neutron pads	
RPV	
Spacer grids	237 ± 4

† The reactivity worth was found to be < 10 pcm

5. Discussions and Conclusions

The KSMR core design has been investigated at (cold and hot) zero power and BOC conditions. The carried out investigation focused on evaluating the inherent safety features and the adequacy of the control system by using the Monte Carlo tool Serpent. The investigation process showed a remarkable performance of the KSMR at zero power.

The excess reactivity, CSDM, reactivity coefficient, and power distribution have been analyzed. The excess reactivity of the KSMR was found to be (15,490 ± 4) pcm at CZP, which represents the highest possible excess reactivity in the core at BOC. In order to offset this large excess reactivity, a proper control system was designed. The control system must provide enough shutdown margin when all control rods in a reactor core are inserted in order to be an effective control system. In the KSMR core, the shutdown margin at the highest reactivity condition possible (CZP and failure of highest control rod worth) was found to be (-6,936 ± 7) pcm. This result proves the effectiveness of the designed control system.

Since the KSMR core was designed with boron-free moderator, the MTC was expected to be much higher compared to soluble boron operated reactors. The MTC was found to be (-55.04 ± 0.10) pcm/K. This large negative feedback coefficient may affect the core reactivity in case of overcooling accidents. A further investigation is required to insure that the control system can always provide sufficient negative reactivity in any possible accident scenario. The FTC of the KSMR core revealed similar results compared to large PWR which was (-2.06 ± 0.01) pcm/K.

The normalized power distribution of the KSMR presented an interesting behavior in which high power amount was around the bottom and top of the core. It can be noticed from Fig. 3 and Fig. 4 that higher power peak is found at the bottom of the core compared to the top of the core. This result is due to the fact that control rods are always presented in the top reflector when they are fully withdrawn. A further investigation is suggested to demonstrate the power peaking factor is within the acceptable limits when control rods at critical position and HFP condition.

Last but not the least, a sensitivity study was performed for the KSMR core which showed the importance of including core baffle and spacer grids on the calculation of core reactivity. The outcome of this study will be used in generating cross sections of the KSMR. The next step of analyzing the KSMR core is transient and HFP simulation. The former investigation will be possible by generating cross sections at different fuel and coolant temperatures to be used later in core simulators such as PARCS or DYN3D. The latter investigation will be possible thanks to the KIT coupled code Serpent-Subchanflow [10].

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