Monte Carlo Simulation of a Burnup-Averaged 78-Element Canadian SCWR and Similarity Study with the ZED-2 Test Reactor

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Summary

Properties of the 78-element Canadian SCWR with (Th, Pu)O_2 fuel are calculated for a burnup-averaged core. The similarity between the SCWR and existing ZED-2 test reactor experiments is analyzed and possible ZED-2 experiments are proposed. The modeling codes DRAGON and DONJON are used to develop an equilibrium core and the SCALE 6.0 package is used to perform similarity studies. The similarity between the SCWR and existing ZED-2 experiments is low. Possible test fuels are proposed to increase the similarity. The highest similarity of approximately 0.9 is achieved using a 13 wt% PuO_2 fuel.

1. Introduction

The SuperCritical Water Reactor (SCWR) is a new reactor design in which water in the supercritical regime is used as the coolant. There are currently a number of proposed design options for the SCWR. The most recent Canadian SCWR design proposed by Atomic Energy of Canada Limited (AECL) is fuelled by 78-element bundles with (Th, Pu)O_2 [1]. The fuel bundles are located in vertical pressure tubes surrounded by a heavy-water moderator and the reactor is refuelled in batches. In order to analyse the operational state of the reactor using computer simulations, the core has been averaged with respect to the burnup at the Beginning Of Cycle (BOC) and End Of Cycle (EOC) to produce theoretical equilibrium state core models. This allows for effects caused by the creation of fission products and the burning of the fuel to be included in the analysis.

When developing new reactor designs, even at an early stage, establishing similarities to test reactor designs is useful. A high degree of similarity between a test reactor and a reactor design implies that experiments performed on a small scale in existing facilities can be used to accurately correct simulations of the reactor design. Here, an analysis is performed of the similarity of the Canadian SCWR to an experiment performed at the ZED-2 test reactor at Chalk River Laboratories using (Th, Pu)O_2 fuel [2]. This similarity analysis is then broadened by designing potential experiments for the ZED-2 test reactor and comparing the similarities of simulations of the SCWR and those of the ZED-2 test reactor.

To develop burnup-averaged models, a combination of the lattice code DRAGON [3] and the diffusion code DONJON [4] is required. To perform the similarity analysis, the results from DRAGON and DONJON are then combined to develop average-burnup core models in the

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Monte Carlo code KENO, part of the SCALE 6.0 code package [5]. These KENO models can then be used in other SCALE 6.0 modules to produce sensitivity coefficients and perform similarity analyses with the ZED-2 test reactor.

2. SCWR Lattice Cell

The reference model of the SCWR developed by AECL was created using the lattice code WIMS AECL and consists of an infinite lattice model. For consistency, the geometry and composition of this model have been repeated as closely as possible using DRAGON. The lattice cell consists of a central absorbing pin surrounded by three concentric rings of fuel pins. The fuel is composed of (Th, Pu)O_2, with 13 wt% PuO_2. The fuel pins are surrounded by coolant under supercritical conditions, which is contained in a porous liner tube layer and a porous insulator layer, encased in the pressure tube. The fuel channel is surrounded by a D_2O moderator with a lattice pitch of 25 cm. Further information concerning the geometry and the composition of the lattice cell can be found at [1]. The lattice cell created using DRAGON is shown in the figure below.

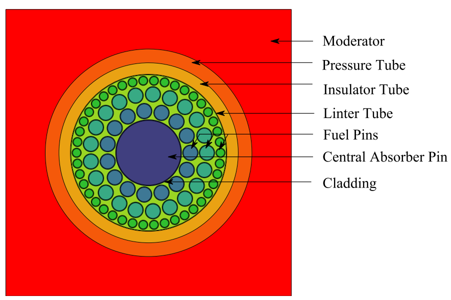

Figure 1 78-element Canadian SCWR lattice cell

3. Quarter-Core Diffusion Model

Using the homogenized cross sectional data for a lattice cell at various burnup steps, the burnup-averaged diffusion model was created using DONJON. The three-dimensional diffusion model consists of one quarter of the core with no reactivity devices, surrounded by a heavy water reflector approximately 65 cm thick. For the model that was developed, the full core was assumed to have 336 channels with ten 50 cm long bundles in each channel. The channels were modeled such that a different coolant density was applied to two bundles along each channel.

The Canadian SCWR is to be a batch-refueled reactor with a three-batch refueling scheme. Here, a cycle length of 500 days was used and an average exit burnup of 42 MWd/kg is obtained. The fueling scheme that was used in the quarter core simulation was chosen in an attempt to minimize the Channel Power Peaking Factor (CPPF), which is represented as the ratio of the maximum channel power to the average channel power of the core. For the core created here it is found that the CPPF at the BOC is 1.32 and at the EOC is 1.24.

4. Burnup-Averaged SCWR

In order to perform Monte Carlo calculations, KENO models of the burnup-averaged BOC and EOC quarter core were created. To do so the combined results of the DRAGON and DONJON calculations were required. Due to the computational expense of Monte Carlo methods, the 840 bundles in the quarter core could not all be modelled individually. Instead, the individual bundles were divided into burnup bins. A burnup bin is a single bundle burnup value that is used to represent a range of bundle burnups.

In the SCWR model, each set of bundles with the same coolant density has to be treated independently. Thus, burnup bins were created separately for each density region. Within each density region, three burnup bins were chosen. This means that a total of fifteen different bundle types were used in the Monte Carlo calculations (3 burnups x 5 coolant density regions). The choice of three burnup bins per density region was primarily due to computational limits. However, because the SCWR is a three-batch core it was a reasonable approximation. To choose the burnup bins, all of the bundles were divided into three equal sized groups and an average burnup of each group was taken.

5. Similarity Analysis of ZED-2 Test Reactor and the SCWR

The ZED-2 (Zero Energy Deuterium) test reactor is a low-energy reactor built by AECL in the 1960's and still operating today. It consists of a cylindrical tank filled with heavy water moderator in which fuel rods are hung vertically. The purpose of the ZED-2 reactor is to perform lattice physics experiments; it allows for both variable lattice arrangements as well as variable fuel types. Criticality in the ZED-2 reactor is achieved by increasing the moderator height.

In order to determine the applicability of experiments that have been performed at the ZED-2 test reactor to the analysis of the SCWR at the BOC and EOC, a similarity study has been performed. This was completed using the TSUNAMI-3D (Tools for Sensitivity and Uncertainty Analysis Methodology Implementation in Three Dimensions) SCALE6.0 module to compute sensitivity information [6], and TSUNAMI-IP (Tools for Sensitivity and Uncertainty Analysis Methodology Implementation—Indices and Parameters) to compute a similarity index [7]. The index analysed here is c_k, which represents the similarity of uncertainties in the nuclear data of the experiment and the application. A c_k value of 0 shows there is no similarity and 1 shows complete similarity between an application and an experiment [7].

Experiments were performed at the ZED-2 test reactor in which 36-element bundles with (Th, Pu)O_2 at approximately 1.745 wt% PuO_2 were placed into one channel in the centre of the core. The remaining channel locations had ZEEP fuel rods (natural uranium metal). To achieve criticality the moderator height in this core was 256 cm [2]. This experiment was modelled by T. Zhu using KENO [8]. The results of the calculations were then used in a similarity analysis with the SCWR. It is found that for the BOC equilibrium core the test experiment and the SCWR have a similarity index of 0.1893. For the EOC equilibrium core the similarity index decreases slightly to 0.1847. Thus, the test experiment performed has a low similarity to both configurations of the SCWR.

To increase the similarity between the test reactor and the SCWR, two changes have been made to the simulation of the experiment. The first change is to increase the number of channels fuelled with (Th, Pu)O_2. For the work performed here, cores fuelled with 1, 2, 4, 10, 19, and 27 fuelled channels were examined. The second change is to test different fuel types in the ZED-2 simulations. The fuel types used are summarized below followed by the resulting similarities.

Table 1 Possible ZED-2 test fuel compositions

Fuel Type	**Fuel Description**
Test Fuel 1	Original fuel used in ZED-2 Test Experiments: (Th,Pu)O_2 fuel with 1.745 wt% PuO_2
Test Fuel 2	ZED-2 Test Experiment Fuel with added Gadolinium Poison: (Th,Pu)O_2 with 0.5 wt% Gd
Test Fuel 3	ZED-2 Test Experiment Fuel with Increased PuO_2 Content: (Th,Pu)O_2 fuel with 2.745 wt% PuO_2
Test Fuel 4	Proposed Fuel for Canadian SCWR: (Th,Pu)O_2 fuel with 13 wt% of PuO_2
Test Fuel 5	Proposed Fuel for Canadian SCWR with added Gadolinium Poison (Th,Pu)O_2 fuel with 13 wt% of PuO_2

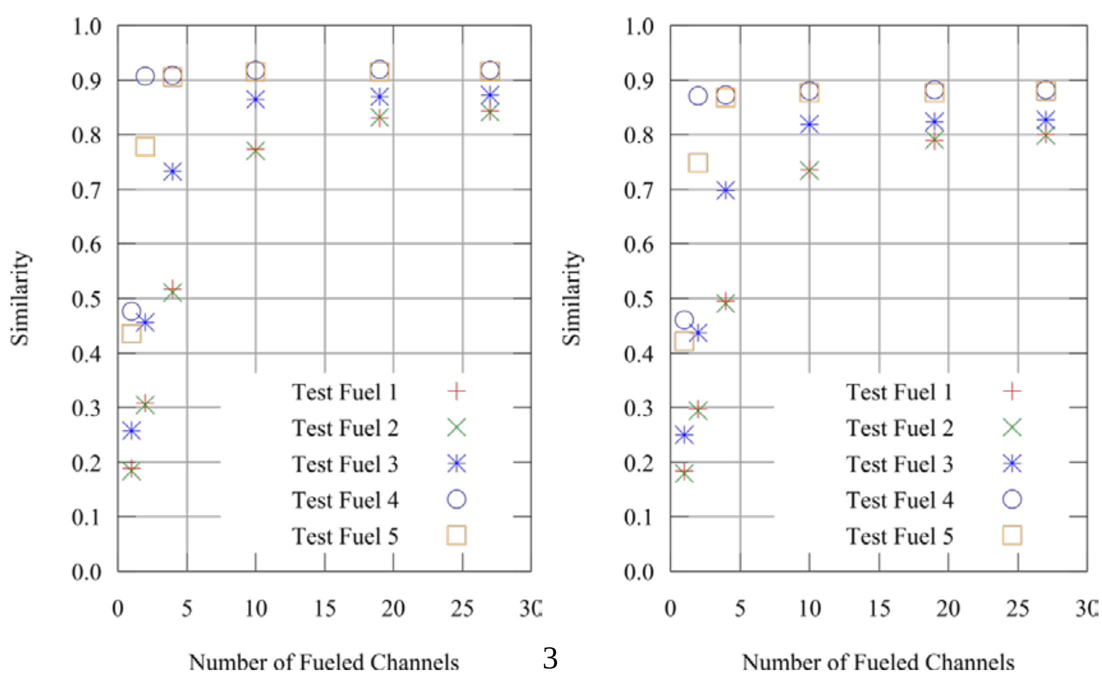

Figure 2 Similarity index at BOC (left) and EOC (right)

Figure 2 shows the similarity of the BOC and EOC SCWR core to the proposed ZED-2 core configurations. For each fuel type, it is found that as the number of fuelled channels increases, the similarity also increases until the results tend to converge towards a maximum value. After this point, increasing the number of fuelled channels has little effect on the similarity. Of the test fuels proposed, it is found that the highest similarity is achieved using Test Fuel 4 (13 wt% PuO_2). Using this fuel type a similarity close to 0.9 is found for both the BOC and EOC cores using as few as two fuelled channels.

6. Conclusions

The Canadian SCWR reactor design offers benefits over current reactor design types. For example, having created a burnup-averaged SCWR core for the BOC and EOC cores, it is found that the reactor yields a much higher discharge burnup than current designs, reaching 42 MWd/kg. To confirm potential benefits of the SCWR, it may be necessary to design experiments that can be used to correct full-core simulations. When designing experiments for this purpose, it is important to ensure there is a high similarity between the test reactor design and the application. A similarity analysis between existing experiments performed at the ZED-2 facility and the SCWR, finds a low similarity. Potential test fuels have been proposed and it is found that using a 13 wt% PuO_2 fuel type and two fueled channels a similarity of ~0.9 is achieved.

7. References

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