Canadian Supercritical Water Reactor Modeling Using G4STORK

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Abstract

The Canadian Supercritical Water Reactor design was simulated using G4STORK. The results showed the expected trends but the determined Keff of 1.253±0.001 with a Coolant Void Reactivity (CVR) of -25mk differed greatly from the results achieved using MCNP of Keff=1.2914 and a CVR of -14mk. This discrepancy is partly due to the different data libraries used and the mixing of different temperature libraries in MCNP, but is also likely due to a difference in the physics methodology. Work is ongoing to further clarify reasons for discrepancies and improve the efficiency of the simulation.

1. Introduction

The primary focus of this project is the simulation of the Supercritical Water Reactor (SCWR) designed by AECL and the extension of the G4-STORK software. The main design goal of the SCWR is the improvement of the thermodynamic efficiency over current Canadian reactors by taking advantage of the superior heat transfer properties of supercritical water [1]. The use of supercritical water has the potential to push the thermodynamic efficiency of the reactor up to 45-50% from its current 35%. Since the supercritical water remains in a single state throughout its journey through the core, a simpler thermodynamic cycle can be used because there is no need for evaporators and condensers. The safety of the reactor is also increased by this feature since there is no longer boiling along the channels causing hot spots and other adverse effects. Another key aspect of the Canadian SCWR design is the use of MOX fuel made up of plutonium and thorium. The main advantages of using thorium are 2-fold: it is completely safe to handle before entering the core and it is far more abundant than natural uranium, greatly extending the potential life span of nuclear power based on our current reserves. The advantages of using plutonium are that some of its isotopes are highly fissile thus very effective at breeding the thorium into fissile uranium, and that it can potentially be extracted from the waste of CANDU, from LWRs or from nuclear weapon reserves. The use of this plutonium extracted from the waste would allow for better fuel economy, and less expensive storage of the final waste (since it will no longer produce as much decay heat); while the burning of plutonium present in nuclear weapon reserves offers a reduction in the proliferation of plutonium. The SCWR design is still under development and thus requires simulation using various reactor kinetics software to improve the design and ensure its safety.

The software that was used to study the SCWR design in this project is called G4STORK which stands for Geant4 Stochastic Reactor Kinetics [2]. It was recently developed by McMaster's Department of Engineering Physics, using a particle physics toolkit created by CERN known as GEANT4. What makes G4STORK unique is that it keeps track of time, allowing it to model truly time dependent cases while using an on the fly Doppler broadening algorithm. These features give G4STORK the potential to produce more accurate descriptions of the neutron population inside the nuclear reactor than the majority of reactor kinetic software available.

2. Methods

The task given to me by AECL was to simulate a lattice cell of the SCWR reactor using periodic boundary conditions. Since the lattice cell is axially symmetric, only a quarter of the lattice was simulated in G4STORK since this increased the density of the neutron population within the geometry 4 fold without affecting the physics. Visualizations of the quarter lattice cell geometry used in G4STORK can be seen in Figure 1.

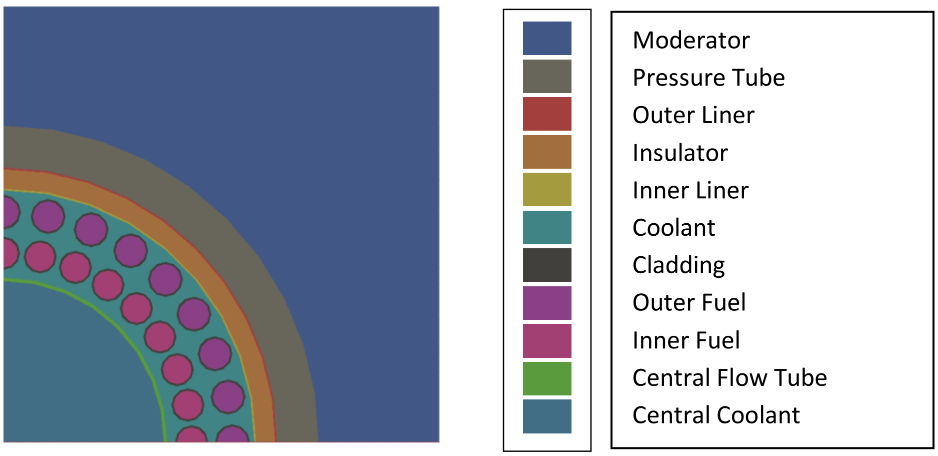


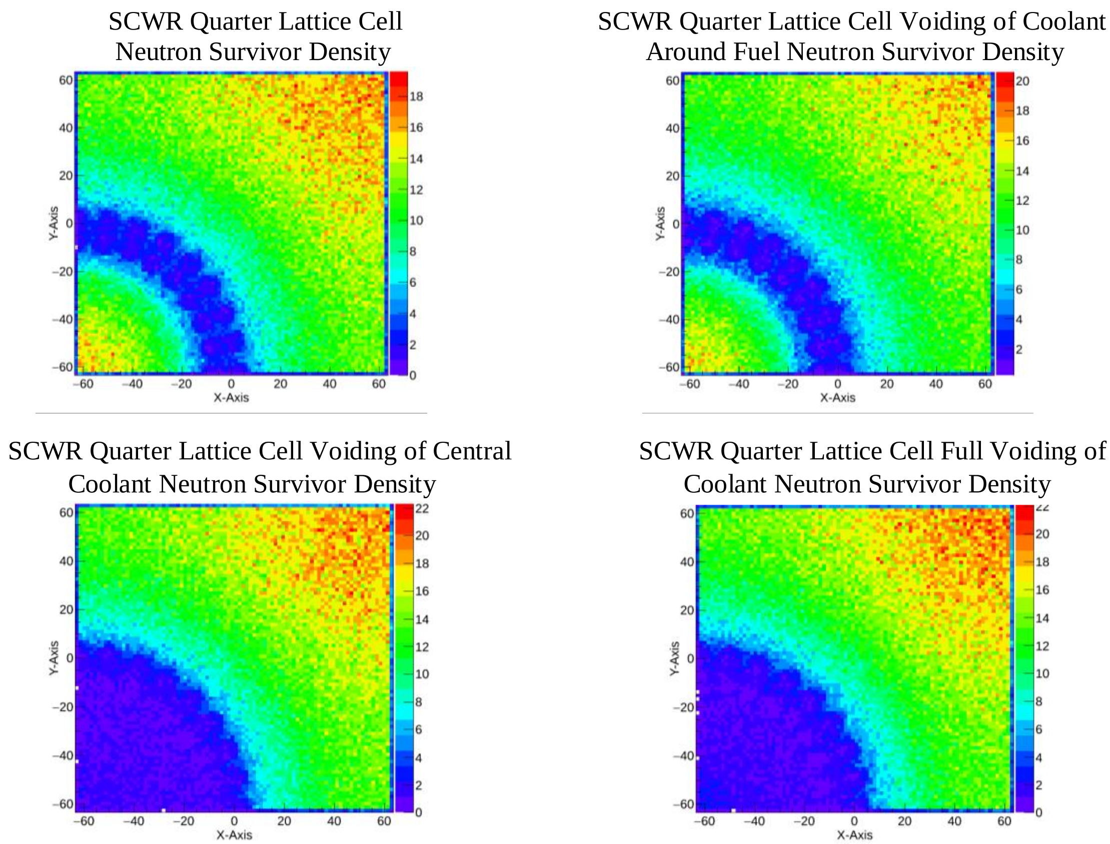
Figure 1 A color coded version of the geometry used in the quarter lattice cell simulation.

2.1 G4STORK

Starting with an initial guess as to what the equilibrium neutron position and energy distribution will look like, the G4STORK code works by tracking individual neutrons through a geometry provided by the user in steps of time [2]. At each time step, the important parameters such as Keff and Shannon entropy are determined and the neutron population is renormalized to the initial number of neutrons. These important parameters are not recorded into the final results until the spatial distribution of the neutrons has converged. The neutron distribution is said to be converged when the Shannon entropies of each of the last 25 time steps do not deviate from the mean Shannon entropy (taken from the last same 25 time steps) beyond a set limit. Thus, the closer the initial guess is to the actual final distribution, the faster the neutron population will converge. Since it is a stochastic simulation, the processes that the neutrons undergo as they move throughout the geometry are randomly selected from a list of potential processes that are weighted based on the probability of their occurrence. This is dependent on the isotopic composition of the material that the neutron is currently traversing and the kinetic energy of the neutron relative to the nuclei in its path. While the composition of the material is defined in the geometry by the user, the relative kinetic energy of the neutron to the nuclei is determined by the on the fly Doppler broadening algorithm.

3. Results and Analysis

The distribution of neutrons in the SCWR quarter lattice cell for the reference, fuel coolant voiding, central coolant voiding and full coolant voiding cases, as predicted by G4STORK, can be seen below in Figures 4, 5, 6 and 7. As expected neutron density is lowest near the fuel because of the high absorption cross-section of the isotopes present, and highest in the moderator regions furthest from the fuel for similar reasons. Little difference in the neutron distribution can be seen by comparing figures 4 and 5, or by comparing figures 6 and 7 indicating that the voiding of the coolant surrounding the fuel has little effect on the shape of the neutron distribution. This expected since the neutron density in the region around the fuel is already very low due to the high absorptivity of the fuel present and thus the perturbation of the coolant density in this region is unlikely to have a large effect on the shape of the neutron distribution. Also since there is equal amounts of the coolant around the fuel we do not expect it to shift the neutron distribution in either radial direction. However if we compare figures 4 and 6 or figures 5 and 7, in the latter cases the neutron distribution in the center of the lattice cell can be seen to dip when the coolant is voided. This is expected since the neutrons in those areas are no longer being moderated and are instead being reflected back the fuel at high energies, resulting in either the neutrons being captured by the fuel isotopes or in them flying out to the moderator.



Figures 4,5,6,7 Neutron density 2D histograms calculated from the reference, fuel coolant voiding, central coolant voiding and full coolant voiding cases of the SCWR quarter lattice cell simulation.

The distribution of fission sites for the SCWR quarter lattice cell reference, fuel coolant voiding, central coolant voiding and full coolant voiding cases, as predicted by G4STORK can be seen below in Figures 8, 9, 10, and 11. The inner fuel pins are composed of a larger percentage of plutonium than the outer fuel pins which is why they have a significantly higher density of fission events in figures 8 and 9 even though the neutron density is not significantly different between the outer fuel and the inner fuel in these two cases as shown by figures 4 and 5. Gradients in the density of fission events can be seen in figures 8, 9, 10, and 11 with clear maximums occurring along the surface of each fuel rod that is facing moderator or coolant and is not facing other fuel rods. This will be due to the higher neutron density in these areas and because the neutrons coming from these direction have been moderated and are more likely to induce fission.

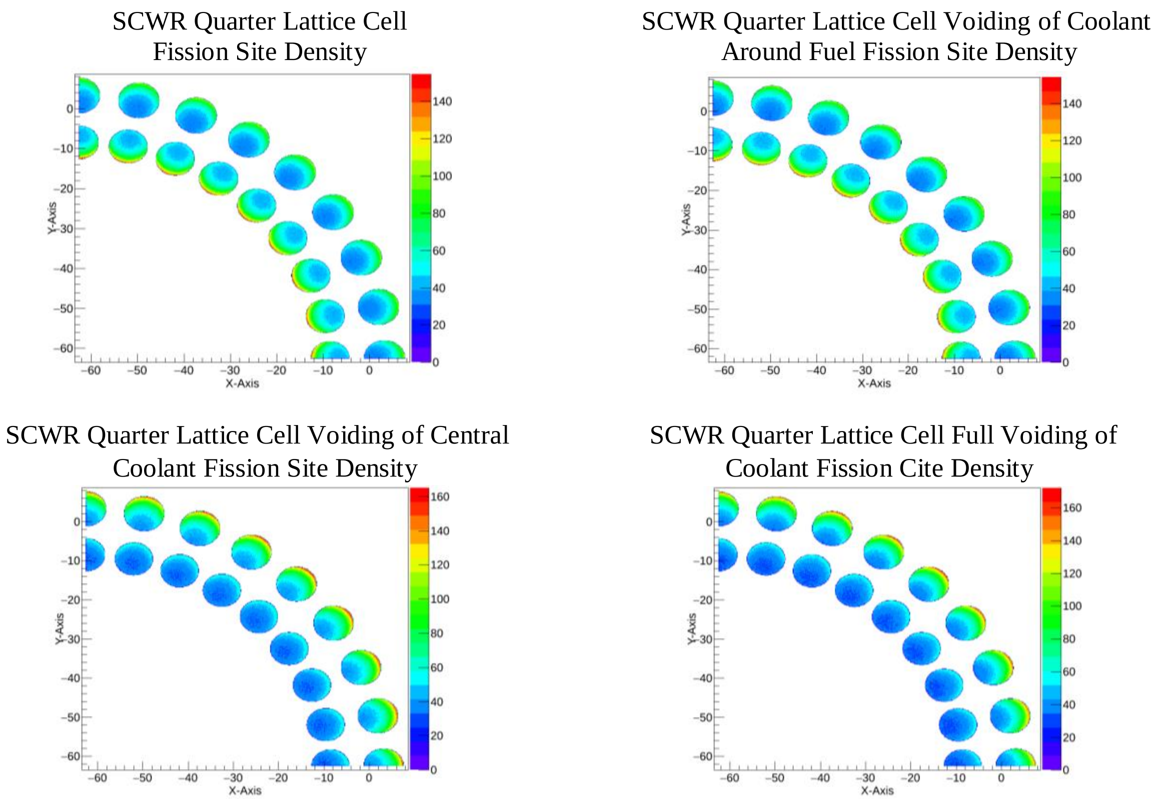


Figure 8, 9, 10, 11 Fission site density 2D histograms calculated from the reference, fuel coolant voiding, central coolant voiding and full coolant voiding cases of the SCWR quarter lattice cell simulation.

The Keff of the SCWR quarter lattice cell for the reference, fuel coolant voiding, central coolant voiding and full coolant voiding cases can be seen below in Table 1. The Keff received from the cooled and voided quarter core simulation was 1.253±0.001 and 1.215±0.002 respectively resulting in a CVR of -25mk. These results vary from the result achieved with MCNP which was 1.2914 for the cooled lattice cell and 1.2687 for the voided case resulting in a CVR of -14mk. Part of this discrepancy is due to the different data libraries used and the mixing of high and low temperature data libraries to achieve right temperatures in MCNP. However, I do not think that this accounts for all of the discrepancy, and further investigation into the methodology used by both codes will likely determine what is causing the difference. Although total voiding of the coolant causes a negative CVR, voiding around just the fuel rods causes a slight increase in the reactivity of the reactor. This effect would exacerbate hotspots occurring along the cladding, caused by local voiding.

Cases	Coolant Around the Fuel	No Coolant Around the Fuel
Central Coolant	1.253±0.001	1.258±0.001
No Central Coolant	1.206±0.001	1.215±0.002

Table 1 Shows the Keff of the SCWR quarter lattice cell for the reference, fuel coolant voiding, central coolant voiding and full coolant voiding cases

4. Discussion and Conclusions

So far the results produced by the SCWR reactor using G4STORK are significantly different from those produced by other simulations. Although much of the discrepancy can be attributed to the different data libraries used, the magnitude of difference suggests that there is an issue with the methodology as well. An in-depth analysis of the physics methodology currently used by G4STORK is currently being done in order to understand where the discrepancy is coming from and whether it is erroneous. In order to examine how the different data libraries used by G4STORK and MCNP, affect the results of each code, the MCNP libraries will be converted into the G4NDL format used by GEANT4, so that both codes will be using the same library. To perform this conversion, the undocumented final state libraries of GEANT4 have been analyzed and documented, but the software necessary to convert between the two data sets is currently still under development.

5. References

[1] Wang, D., & Wang, S. (2014). *A PRELIMINARY CATHENA THERMALHYDRAULIC MODEL OF THE CANADIAN SCWR FOR SAFETY ANALYSIS*. Chalk River: Atomic Energy of Canada Limited.

[2] Russell, L. (2012). *Simulation of Time-Dependent Neutron Populations*. Hamilton: McMaster University.