Simulations of Single Pin Cell and CANDU-SCWR Lattice Cell Using 2D Transport Codes WIMS and NEWT

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Abstract

The supercritical water reactor is one of six Generation IV reactor designs and is currently being studied by Canada. The use of supercritical light water as a coolant will provide many benefits due to plant simplifications and improved thermal efficiency. Here, a model of a CANDU-SCWR lattice cell was simulated using two 2D neutron transport codes, WIMS and NEWT. Two lattice cell geometries are used in these simulations. The first is a single pin fuel cell, similar to that of a pressurized water reactor. The second is a 43-element CANFLEX geometry fuel bundle with a centre element containing a mixture of dysprosium oxide and natural uranium. A comparison between the two transport codes is made for the single pin cell while the effects of coolant density on reactivity are examined for different cases of fuel burnup for the CANDU-type lattice cell.

1 Introduction

A design being studied as a Generation IV reactor candidate is the Supercritical-Water-Cooled reactor (SCWR). The SCWR is essentially a water-cooled reactor using a light water coolant that is above the thermodynamic critical point of water (647 K and 22.1 MPa) during part of the thermodynamic cycle, eliminating boiling and thus remaining single-phase within the system. Keeping the coolant at a high temperature allows a greater thermal efficiency over current designs. Commonly cited efficiencies are around 44% [1, 2] or higher (greater than 50% efficiency through the use of reheat channels [3]), as compared with around 33% for current PWRs. As well, the higher heat capacity of supercritical water means less coolant will be needed to cool the reactor. The SCWR is also expected to bring considerable plant simplifications due to the single phase coolant and direct power cycle, eliminating the use of steam generators, dryers and steam turbine in favour of a the smaller supercritical water turbine currently seen in modern fossil plants. The elimination of these components should allow for a smaller containment structure, hopefully reducing the capital cost required to build such reactors. Both fast and thermal neutron spectrum designs exist, as well as pressure vessel and pressure tube variants. The thermal spectrum pressure-tube design is the focus of Canada's Generation IV research.

From the reactor physics perspective, some of the biggest challenges arise from the materials required for components such as pressure tubes and fuel cladding which must be able to withstand corrosive supercritical water conditions and a radioactive environment. For other materials such as the heavy water moderator and light water coolant, a great deal of information is already known from experiments and performance. For the SCWR, the coupling between thermalhydraulic

behaviour and core physics is very important, perhaps even moreso than in existing reactors. This comes as a result of the large variation of many important properties of the light water coolant as the transition through the critical point is made. An important example is shown in Figure 1[1]. Here the density of light water is shown for the pressure anticipated for the SCWR, i.e. 25 MPa. The large variation in density seen around 650 K is a result of the transition through the pseudo-critical temperature. This marked change in density will also occur in the fuel channel of the SCWR, as the proposed inlet and outlet temperatures are 623 K and 898 K respectively. This presents a challenge in determining the overall physics response of the channel and core.

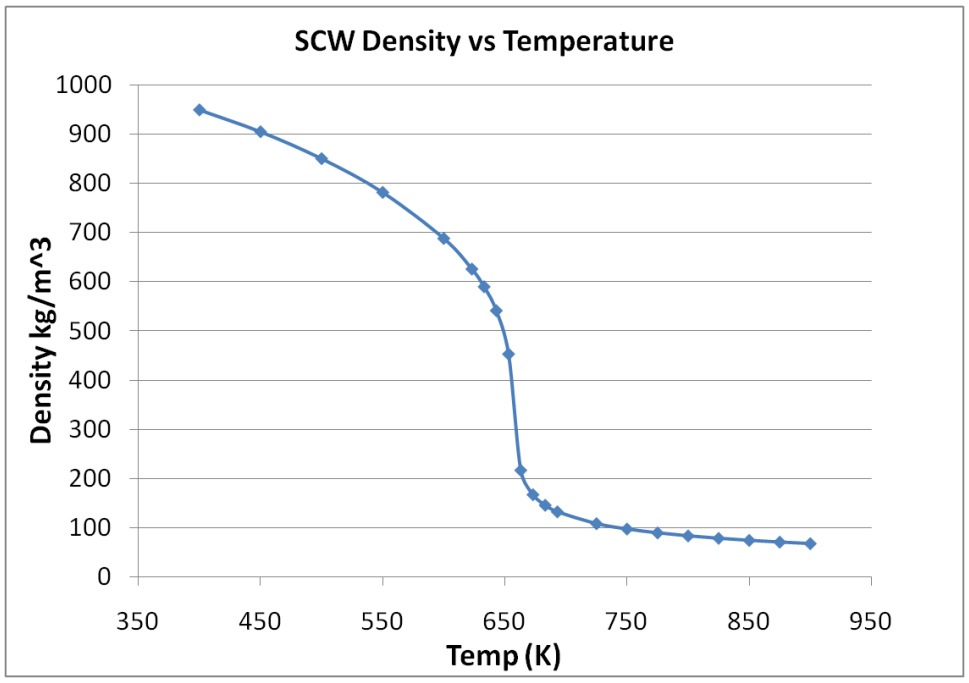

Figure 1: Density of water vs. temperature at 25 MPa through critical point

2 Description of Codes

Two neutron transport codes were used in the simulations, WIMS-AECL Release 2-5d [5] and NEWT [6], part of the SCALE6 software package developed by Oak Ridge National Laboratory.

WIMS-AECL is a 2D neutron transport code used by AECL to analyse the physics of a CANDU lattice cell. It uses the ENDF-B/VI cross-section library and can perform transport calculations in up to 89 energy groups. Calculations are performed using a collision probabilities approach.

NEWT (New ESC-based Weighting Transport code), is a 2D transport solver included as a part of the SCALE6 package. It has the capability of using a number of cross-section libraries, including ENDF-B/V, ENDF-B/VI, and ENDF-B/VII, in as many as 238 groups. The calculations are performed using the extended step characteristic approach, an extension of the step characteristic approximation allowing for the use of generalized cells made up of arbitrary polygons in the dis-

[1]Data from MS Excel macro by Dr. B. Spang, http://www.cheresources.com/iapwsif97.shtml

cretization of the problem geometry [6]. This can be contrasted with WIMS-AECL which models the problem geometry in concentric annuli around the center of the lattice cell.

3 Description of Models and Results

The results of two studies are presented here. The first is a comparison of two single fuel pin cells with a supercritical water coolant/moderator shown in Figure 2. This geometry is typical of a pressurized water reactor lattice cell with a fuel to moderator ratio of approximately 0.5. Two enrichments were used in the simulation, 1% and 4% enriched UO_2. Only fresh fuel has been used in these simulations, i.e. no burnup calculation has been performed. The fuel elements have a radius of 0.633 cm with a 0.04 cm thick clad of Zirconium-IV alloy. Fuel temperatures were calculated for each coolant temperature case from the solution of the 1-D radial heat diffusion equation, with coolant temperature as a boundary condition on the outside of the cladding.

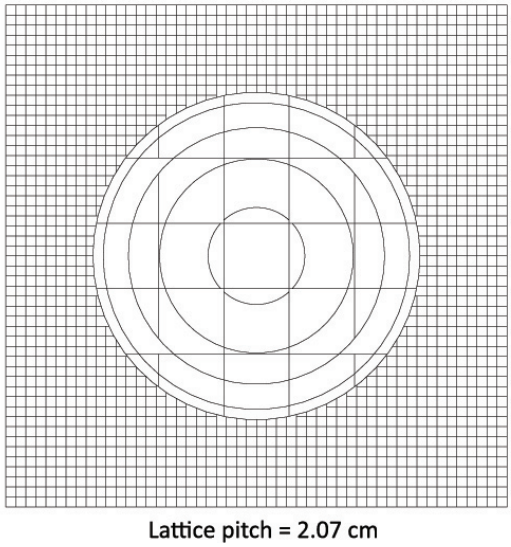

Figure 2: Single pin cell

This lattice cell was simulated in both WIMS and NEWT for various temperatures of supercritical light water coolant at 25 MPa. The calculations were performed using the ENDF-B/VI cross section library, using 89 groups for WIMS and 238 groups for NEWT. The choice of the maximum number of groups is made to reduce the importance of flux spectrum chosen for use in the flux weighting of the cross-sections. For comparison, the same trials were run using NEWT with a 44-group ENDF-B/V library.

As can be seen in tables 3 through 6, the two code produce similar results for the higher density, low temperature case where the coolant is in purely liquid-like phase, but produce significantly different results for the supercritical phase coolant. Also, an interesting observation is made for the comparison between the WIMS and NEWT-238 group calculations. For the 4% enriched fuel, WIMS consistently predicts a higher value than NEWT for k_∞, while for the 1% enrichment level, WIMS predicts a consistently lower value, with the exception of the 623 K case.

Coolant Temperature (K)	Coolant Density (g/cm^3)	k_∞ (WIMS)	k_∞ (NEWT)(ENDF-B/VI) (238 group)	k_∞ (NEWT)(ENDF-B/V) (44 group)
623	0.6260	1.41546	1.41345	1.42350
673	0.1670	1.10601	1.10389	1.12276
750	0.0971	0.98226	0.97385	0.98867
825	0.0782	0.94677	0.93040	0.94301
900	0.0674	0.93041	0.90386	0.91499

Table 1: 4% enrichment case

Coolant Temperature (K)	Coolant Density (g/cm^3)	k_∞ (WIMS)	k_∞ (NEWT)(ENDF-B/VI, 238 group)	k_∞ (NEWT)(ENDF-B/V, 44 group)
623	0.6260	1.02293	1.02150	1.0322
673	0.1670	0.82619	0.83151	0.85011
750	0.0971	0.69465	0.70493	0.71876
825	0.0782	0.64369	0.65637	0.66744
900	0.0674	0.61111	0.62498	0.63407

Table 2: 1% enrichment case

4% enrichment	
$\Delta\rho$ (mk)(NEWT V6-238 - WIMS)	$\Delta\rho$ (mk)(NEWT V5-44 - WIMS)
-1.0	4.0
-1.7	13.5
-8.8	6.6
-18.6	-4.2
-31.6	-18.1

Table 3: Reactivity Difference between WIMS and NEWT for 4% enrichment case

1% enrichment	
$\Delta\rho$ (mk)(NEWT V6-238 - WIMS)	$\Delta\rho$ (mk)(NEWT V5-44 - WIMS)
-1.4	8.8
7.7	34.1
21.0	48.3
30.0	55.3
36.3	59.3

Table 4: Reactivity Difference between WIMS and NEWT for 1% enrichment case

For the comparison between WIMS and the NEWT-44 group calculation, the same divergence of results is observed with increasing coolant density for the 1% enrichment case. There is no observable pattern, however, when comparing these results for the 4% enrichment case. Future work will look into the reasons for the differences between codes.

4 WIMS Calculation of CANDU geometry bundle with supercritical water coolant

A similar calculation was performed with WIMS for a 43-element CANDU geometry fuel bundle. The calculation has not yet been performed with NEWT as a result of difficulties in performing the resonance self-shielding calculations with the concentric geometry of the CANDU fuel bundle.

The model used is consistent with literature on the CANDU-SCWR [4, 7]. It consists of a fuel bundle of the CANFLEX geometry: a 43-element rod cluster containing enriched uranium dioxide (4%) as well as a central absorbing pin composed of a mixture of 15% (volume) dysprosium oxide and natural uranium. All fuel elements are clad with zirconium-IV and are contained within a Zr 2.5% Nb pressure tube. A 1 cm thick ZrO_2 ceramic insulator is placed on the inside of the pressure tube to reduce heat loss to the moderator and to protect the pressure tube from the corrosive supercritical water conditions [7]. The fuel bundle is moderated by heavy water, and cooled with a supercritical light water coolant. The lattice pitch chosen is 24 cm. The lattice cell geometry is shown in Figure 7.

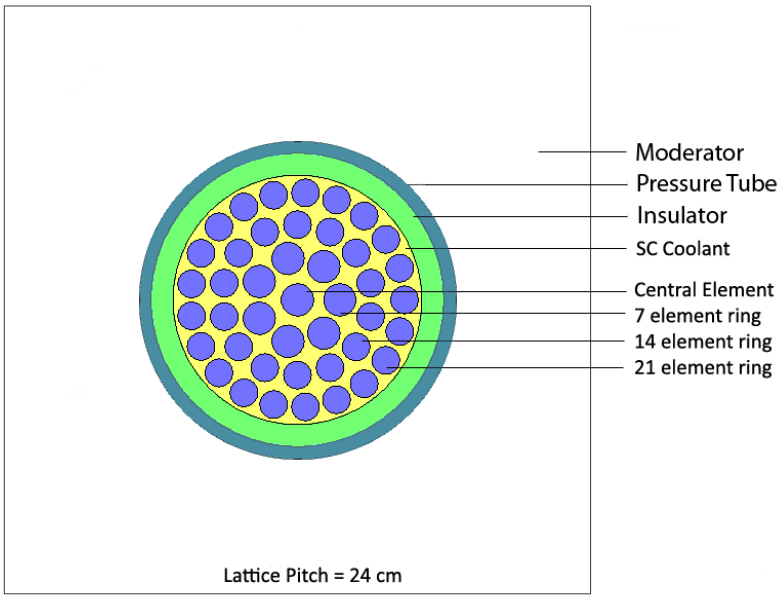

Figure 3: 43 element CANDU fuel bundle lattice cell

The result of the WIMS calculation is shown in Figure 8. The calculation performed shows the effect of density decrease on reactivity for four burnup cases: fresh fuel, low burnup (≈6500 MWd/T), moderate burnup (≈18000 MWd/T), and high burnup (≈30000 MWd/T).

This graph shows the increase in reactivity as a result of the coolant transition from liquid to supercritical water condition which takes place between 623 K and 700 K. For fresh fuel this reactivity increase introduces around 44 mk of reactivity, while for the high burnup fuel approximately 30 mk of reactivity is introduced. The difference can be explained as a result of the increase of plutonium in the fuel, specifically Pu-239. This is similar to the effect of coolant void reactivity

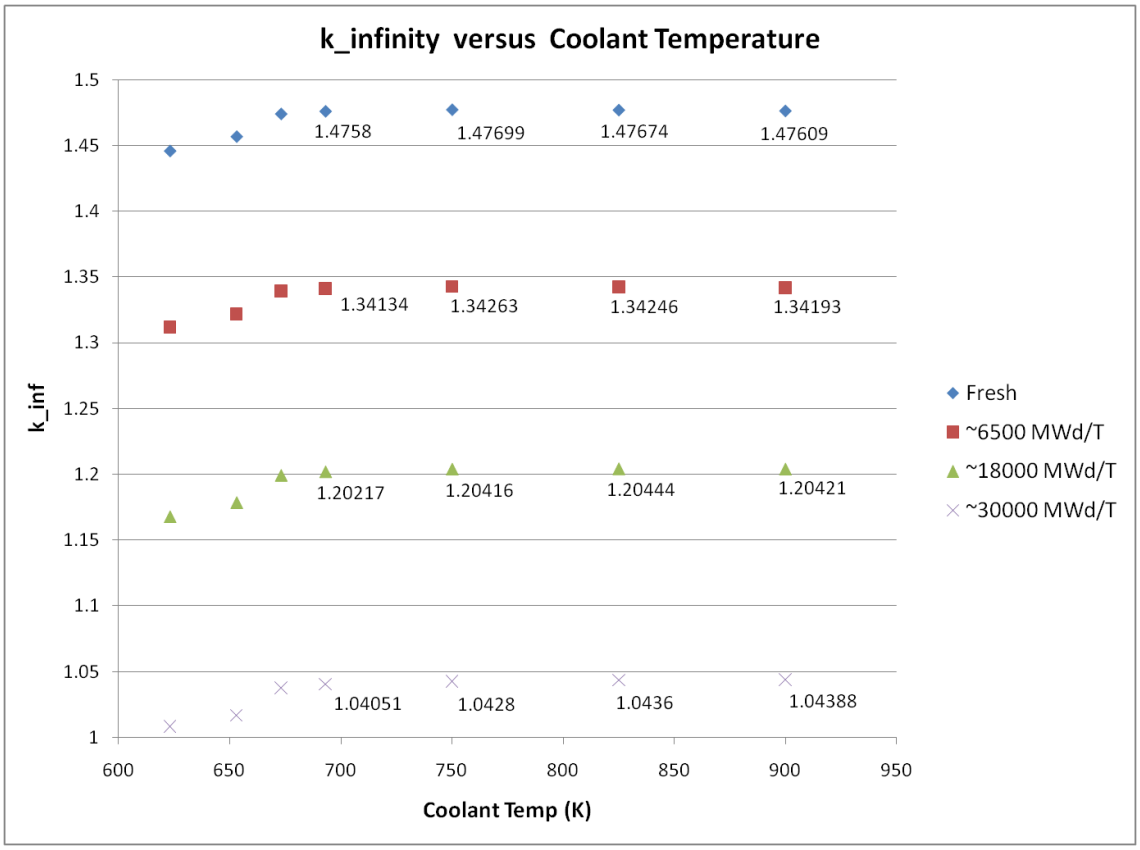

Figure 4: k-infinity versus coolant temperature for CANDU lattice cell

(CVR) in current CANDU reactors that have approximately positive 15-18 mk CVR for fresh fuel and 10-12 mk CVR for an equilibrium core [8].

Another interesting result is exhibited by the two higher burnup cases during the transition to supercritical coolant conditions. Examining the plot of density versus temperature for supercritical water reveals a small change in slope in the vicinity of 650 K. The change in reactivity corresponding to this change appears as a slight "step" change in the reactivity of the two high burnup cases. This is not visible in the two low burnup cases. This is thought to be a result of the higher coolant void reactivity in the fresh fuel cases, which will mask the effect of the "step" change.

Beyond the critical point as the coolant temperature increases, the reactivity is seen to decrease for the fresh fuel and 6500 MWd/T cases. Since density is still decreasing slowly over this range, it appears that the fuel temperature feedback provides a stronger reactivity effect than the reactivity increase caused by the decreasing coolant density. This is not the case for the two higher burnup cases where the reactivity increases slightly (around 3 mk) over the 700 K to 900 K coolant temperature range. This effect can be explained by the change of the fuel temperature coefficient with burnup. As the burnup increases, the fuel temperature coefficient will become less negative such that the coolant density effect overrides the fuel temperature feedback at higher burnups.

5 Conclusions and Future Work

This paper has presented a comparison between two 2-dimensional neutron transport codes, WIMS-AECL and NEWT. It has been seen that for the case of a single fuel pin lattice cell the codes produce similar results for the reactor multiplication constant, k_∞, for lower coolant temperatures, but produce significantly different results as the coolant temperature increases through supercritical temperatures. Pending investigations are looking into the reasons behind the differences.

In addition, the result of a WIMS simulation of a 43-element CANDU lattice cell with supercritical water coolant has been presented. It has shown the effect of the transition through the critical point on the reactivity of the lattice cell for four burnup cases. Future plans involve modelling the same lattice cell configuration using NEWT and comparing the results to those in this paper.

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