WIMS Simulation of SCWR CANDU Geometry

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May 12, 2009

Abstract

One of six Generation-IV reactor technologies being studied is the use of supercritical water as a coolant. The advantages of using supercritical water include improved thermal efficiency, plant simplifications, and the ability to utilize existing turbine technologies. A model of the CANDU geometry lattice cell with supercritical water coolant using the code WIMS is examined. The model is a 43-pin fuel bundle with centre absorbing pin containing dysprosium oxide. This is compared to a WIMS model of a standard 37 element CANDU-6 bundle with supercritical water coolant. Studied are the effects of coolant density and dysprosium on reactivity based transients.

1 Introduction

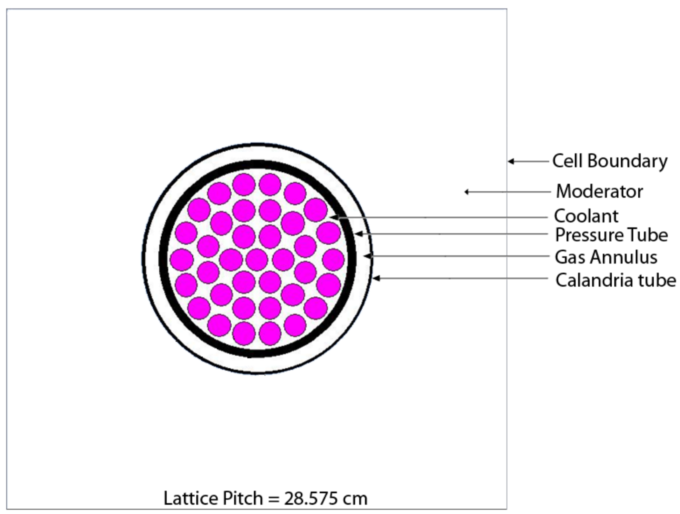
In order to be able to supply future world energy demands, nuclear energy will play a prominent role in terms of energy generation methods. To this end, significant research is being undertaken around the world on the next generation of nuclear reactor technology known as Generation IV. Ten countries make up the Generation IV International Forum (GIF) and between them are researching six vastly different reactor designs. The implementation of Generation IV reactors is currently planned for around the year 2030 [1]. Some of the major goals of the Generation IV program are to develop new reactor technologies to provide enhanced safety, longer reactor life and increased profitability as well as being more proliferation resistant. The Gen IV initiative is concerned also with the environmental impact of nuclear energy. Environmental benefits would be realized through a reduction in nuclear waste via improved fuel management, recycling and reprocessing of used fuel, and through the breeding of new fuel from ^{238}U and thorium. Also, applications have been identified [1] for large scale hydrogen production to fuel the emerging hydrogen economy and desalinization of seawater providing secondary environmental and economic benefits.

Currently, one design being studied is the Supercritical-Water-Cooled reactor (SCWR). The SCWR is essentially a pressurized water reactor (PWR) where the light water coolant remains above the thermodynamic critical point of water (647 K and 22.1 MPa), 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, approaching 44% [1, 2] (or greater than 50% efficiency through the use of reheat channels [3]), as compared with around 33% for current PWRs. The SCWR will also bring considerable plant simplifications due to the single phase coolant, eliminating the use of steam generators, dryers and steam turbine. The containment will therefore be substantially smaller than current containment structures. Additionally, a majority of modern fossil fuelled power plants use a supercritical water system and as such, turbine technology has already been developed for electricity generating applications.

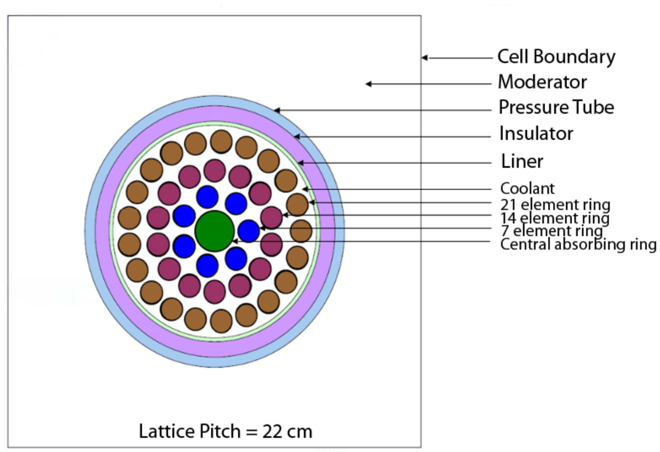
The latest evolution of the pressure tube reactor design by Atomic Energy of Canada Ltd. is the Generation III+ Advanced CANDU Reactor (ACR). Looking past the ACR, the SCWR pressure tube design is a natural evolution of the CANDU reactor. Given the similarities to the existing CANDU, the proposed CANDU-SCWR is expected to be operating around 2025 [4]. The CANDU-SCWR is envisioned to incorporate many similar features to the ACR including light water coolant, reduced lattice pitch compared to the CANDU-6 reactor, and slightly enriched uranium as a fuel. The high pressures involved with using supercritical water favour the pressure-tube design since the fabrication of a large pressure vessel to withstand the high pressures will be more challenging.

2 Description of cell models

In this study, the code WIMS-AECL is used to model the lattice cell geometries. The lattice cell consists of the fuel elements surrounded by cladding, coolant, pressure tube, calandria tube and moderator. Two different fuel geometries are modelled. The first is the traditional 37-element CANDU-6 lattice containing natural uranium dioxide fuel pellets. Envisioned for the CANDU-SCWR are fuel bundles of the CANFLEX geometry: a 43-element rod cluster containing slightly-enriched uranium dioxide (SEU) as well as a central absorbing pin composed of dysprosium oxide and depleted/natural uranium. This fuel type has been designed specifically to have a low void reactivity coefficient. The two lattice cell geometries are shown in Figure 1.



(a) CANDU-6 Lattice Cell Geometry



(b) SCWR Lattice Cell Geometry

Figure 1: Lattice Cell Geometries

The CANDU-6 geometry contains four rings of fuel elements with 1, 6, 12, and 18 fuel pins repectively. The radius of all fuel pellets is 0.6122 cm and are clad with a 0.0418 cm thick zircalloy-IV sheath. Surrounding the fuel elements is a 0.45 cm thick Zr-2.5Nb pressure tube and a 0.14 cm zircalloy-II calandria tube with a gap of 0.83 cm between them filled with CO_2 gas. The lattice pitch for the CANDU-6 geometry is 28.575 cm. One difference from the standard CANDU-6 used here is that the calandria tube is removed and a 0.7 cm thick ZrO_2 insulator is used on the inner surface of the pressure tube. The insulator allows more heat to be transferred to the coolant and protects the pressure tube from the corrosive nature of the coolant, allowing the use of zirconium alloys [4]. The model used natural uranium fuel with 0 MWd/t burnup and a supercritical light water coolant at 25 MPa pressure.

The SCWR geometry also contains four rings of fuel with 1, 7, 14, and 21, fuel pins respectively. The centre absorbing pellet has a radius of 0.627 cm while the outer three rings have pellets of 0.533 cm radius. All pellets are clad with 0.4 cm thick zircalloy-IV. In the SCWR the calandria tube is again removed and a ceramic zirconium oxide insulator is placed between the fuel and the pressure tube with a thin liner on the inside surface of the insulator. For this model a fuel enrichment of 1% was chosen along with a 0.9 cm thick ZrO_2 insulator. The lattice pitch is 22 cm for the SCWR geometry.

The SCWR is planned to operate with a coolant inlet temperature of 350°C and outlet temperature of 625°C. For a heat transport system pressure of 25 MPa, this corresponds to a density change from 625.5 kg·m^{-3} at the inlet to 67.58 kg·m^{-3} at the channel outlet [5].

3 Results

At constant pressure, as water passes through the critical point, the density decreases very rapidly. A plot of the density versus temperature[1] is shown in Figure 2.

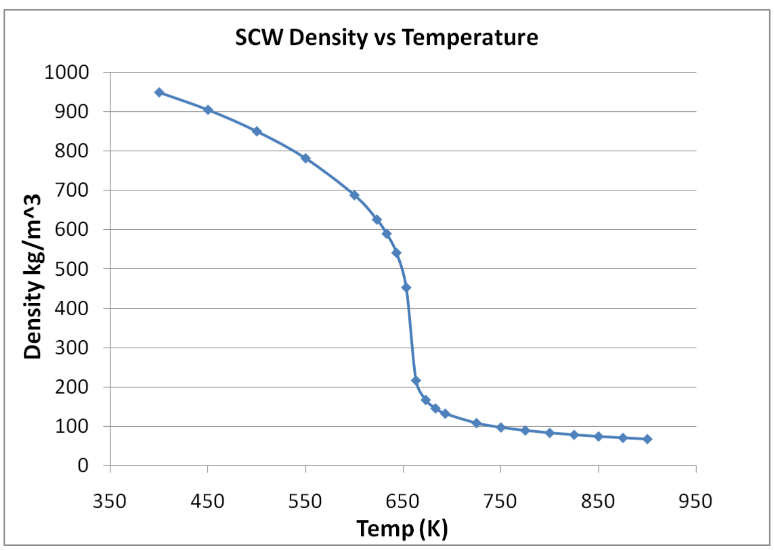


Figure 2: Density of water vs. temperature at 25 MPa through critical point

The designed inlet temperature of the SCWR is below the critical point of water, this results in the coolant undergoing a rapid density change as it passes through the fuel channel. To see this effect on reactivity, a WIMS model was created of a CANDU-6 geometry lattice cell. The change in reactivity in response to a temperature increase of the light water coolant was calculated. The range of temperatures correspond to the range bounded by the proposed inlet and outlet temperatures of the fuel channel. All models created here do not take into account leakage, that is, all models use infinite lattice boundary

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

conditions. Shown in Figure 3 is the change in infinite reactor multiplication constant k_∞, in response to coolant temperature increase for a standard 37 element fresh fuel cell.

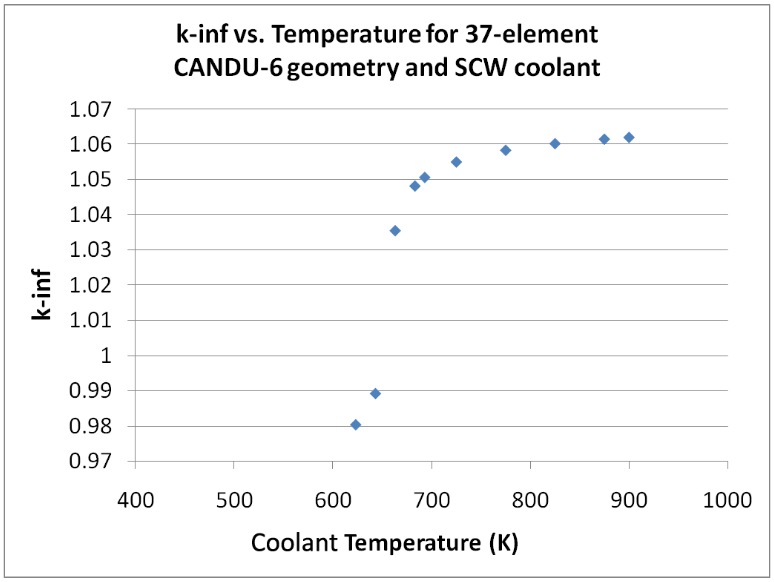


Figure 3: Multiplication constant vs. Temperature for 37 element CANDU-6 geometry lattice cell with supercritical water coolant

As seen, the decrease in density along the channel introduces approximately 78 mk of reactivity to the channel. This increase will occur around the first few fuel bundles. This effect could be seen to add a large flux tilt in the axial direction. However the CANDU reactor is suited to handle this. By using bi-directional coolant flow through the channels, this effect can be limited. As well, the practice of fuelling with flow will also serve to reduce this effect by adding fresh fuel to the inlet end of the channel.

The SCWR lattice cell was also modelled using the above SCWR geometry with centre pin containing absorbing Dy_2O_3 mixed with natural uranium. The initial test used a 20% volume dysprosium oxide concentration in the centre element with subsequent tests using 10% and 0%. The increased dysprosium concentration in the centre element is found to lower the overall reactivity, as well as reduce the reactivity increase through the critical point. For 0% Dy_2O_3 (i.e. 100% natural uranium) this reactivity increase was found to be approximately 34 mk, while for 10% and 20% the increases were 14 mk and and 6 mk respectively. These results are shown in Figure 4.

Reducing the lattice pitch and thereby increasing the ratio of coolant volume to moderator volume allows the coolant to have more of a role in moderation. This is an approach used in the ACR to reduce coolant void reactivity. In the SCWR the reduced lattice pitch will have the same effect, as will the use of enriched fuel and the use of a dysprosium absorber. Combined, these have the effect of reducing the reactivity increase cause by the transition to supercritical conditions. This is evidenced by comparing the CANDU-6 result (+78 mk) to the CANFLEX geometry result ($<$ +34 mk).

One unexpected result from the 43 element bundle were two decreases in reactivity before and after the increase in reactivity from the transition to supercritical water. The cause was postulated to be due to the addition of dysprosium to the fuel bundle. This was confirmed by tests using 43 element lattice cells with varying amounts of Dy_2O_3 ranging from 0-20% content by volume. The 0% case showed no deacreases in reactivity, while the 10% case showed the two decreases in reactivity, although smaller in magnitude than the 20% case.

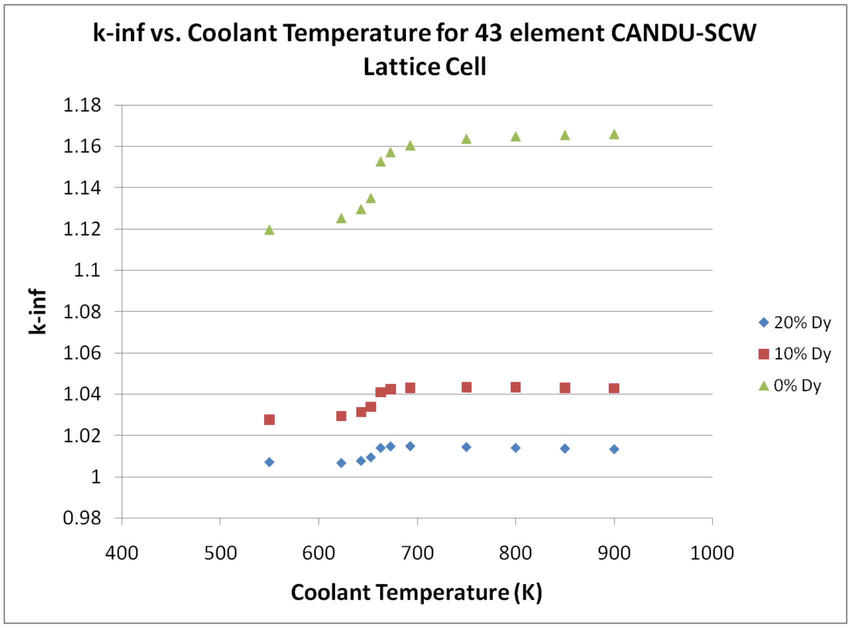


Figure 4: Multiplication constant vs. Temperature for 43 element CANFLEX geometry lattice cell with Dy_2O_3 concentrations of 0%, 10%, 20%

4 Future work

It has been seen that the change in density as light water passes through the critical point in the fuel channel leads to an increase in reactivity. The increase can be limited through the use of dysprosium oxide in the central element of the fuel bundle. The results here indicate the concentration of dysprosium should be "optimized" to allow desired burnup, as the fuel irradiation time, i.e. rate of fuelling, will depend upon the dysprosium content of the bundle. This has implications for both front end and back end costs. Furthermore, parameters such as lattice pitch and enrichment levels should also be optimized.

To this point all simulations have used only fresh fuel with enrichment of 1%, while the enrichment specified in literature [4, 6] is typically around 4%. As well, all fuel temperatures used in the simulations so far have used an average fuel pellet temperature of 960 K. This is the temperature used for a CANDU-6 lattice cell in the WIMS-AECL user manual [7]. Plans for future research therefore include studying:

- Effect of fuel temperature
- Effect of burnup
- Effect of pitch size and enrichment.

References

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