Mitigation of End Flux Peaking in CANDU Fuel Bundles using Neutron Absorbers

D. Pierce[1], P. K. Chan[1] and W. Shen[2]

[1] Royal Military College of Canada, Kingston Ontario, Canada

[2] Canadian Nuclear Safety Commission, Ottawa Ontario, Canada

(dylan.pierce@rmc.ca)

A Master's Level Submission

Abstract

The end-flux peaking (EFP) is a phenomenon where a region of elevated neutron flux occurs at the end regions between two adjoining fuel bundles in CANDU reactors. These peaks of high neutron flux lead to an increase in fission rate and therefore greater heat generation in the end regions. This increase in heat generation is of particular concern during accident conditions. It is known that addition of neutron absorbers into fuel bundles can help mitigate EFP, yet their implementation in CANDU reactors using natural-uranium fuel has not been pursued. Monte Carlo N-Particle code (MCNP) 6.1 was used to simulate the addition of a small amount of neutron absorbers strategically at the bundle ends. The model includes two half bundles with a single end region, with varying amounts of Eu_2O_3 within the last two pellets. This paper will present some preliminary results collected thus far.

Introduction

The end-flux peaking (EFP) is a phenomenon where a region of elevated neutron flux occurs at the end regions between two adjoining fuel bundles in CANDU reactors [2]. The geometry of the end regions consist of a D_2O coolant, Zircaloy bundle end plate and element end caps, and uranium dioxide fuel pellets [3]. In the end regions, thermal neutrons build up because the coolant and Zircaloy-4 both have much lower absorption cross sections than that of the uranium fuel. This discontinuity in absorption cross section leads to thermal neutron peaks at these locations [2]. The result of EFP occurring is a higher fission rate and therefore more heat production and higher temperatures in the fuel adjacent to the end regions [3]. Higher temperatures can lead to an increased risk for sheath strain, corrosion and fuel centreline melting. This could have significant impact on the integrity of the sheath and fission gas release during over-power or loss of coolant accident (LOCA) conditions [3].

When seeking to quantify the EFP phenomenon, an end flux peaking factor PF^{flux} is used. The end flux peaking factor is the ratio of the neutron flux in the end regions of the bundle to the neutron flux within the mid plane of the bundle [1]. PF^{flux} is calculated on a per element basis, giving the end flux peaking factor for each ring.

$$PF^{flux} = \frac{\Phi^{end}}{\Phi^{mid\ plane}} \qquad (1)$$

Burnable neutron absorbers have been used regularly within Light Water Reactors (LWR) for some time now but their use has not been implemented into Canada Deuterium Uranium (CANDU) type reactors, due to the primary concern of their effect on neutron economy [1]. By choosing an appropriate and a small amount of neutron absorber(s), unwanted behaviours within the reactor, such as Xenon free effects (refuelling transients) can be mitigated. Also since the amount is small, the absorber material will have minimal impact on the neutron economy. Properties of interest would be: neutron absorption cross section, the stability of the various isotopes, and the relative amount that needs to be present to provide substantial mitigation [1].

In Paquette et al. it was determined that the two absorbers which best addressed the criteria outlined above were gadolinium oxide (Gd_2O_3) and europium oxide (Eu_2O_3). Gd_2O_3 was used to mitigate the refuelling transients since it has a burn-out rate that matches closely with the Xenon build-up rate [1]. Eu_2O_3 was used to mitigate plutonium peaking since it has a long chain of stable isotopes that have a relatively large thermal absorption cross section [1]. Using these two absorbers it was concluded by Paquette et al. that ~300mg of Gd_2O_3 and ~700 mg of Eu_2O_3 can both suppress the refuelling transient and lower the axial plutonium peak [1]. The combined mass of the absorbers to the total mass of the fuel bundle represents ~$4\text{x}10^{-3}$ wt% per bundle, which is a very small amount per bundle [1].

Modelling

Monte Carlo N-Particle code (MCNP) 6.1 was used to simulate the addition of a small amount of neutron absorbers strategically at the bundle ends. In the MCNP 6.1 model, see Figure 1, 37 individual half elements are modelled for each half bundle. The fuel within each element is modelled as a solid rod, with the exception to the last two pellets. The last two pellets are defined separately for the purpose of adding Eu_2O_3 to the fuel. On the inside of each sheath there is a 20 micron CANLUB coating. CANLUB is a protective graphite coating added to each fuel element to help mitigate the effects of stress corrosion cracking. Calandria and pressure tubes surround the fuel bundles, for increased physical boundary conditions. Within the pressure tube heavy water exists as the coolant. The entire channel is then surrounded by heavy water as the moderator. The reflective boundary condition is applied to all external surfaces to ignore that neutron leakage (i.e., infinite lattice simulation).

The neutrons in the model are generated using the KCODE module. KCODE is a method used in MCNP primarily to calculate reactivity and steady state neutron distributions. The code calculates an appropriate neutron source term by propagating an initial guess and refining the source term for an additional iteration. It makes use of a Watt's fission spectrum to generate neutrons. The added benefit of simulating the neutrons using KCODE is that the simulation iterates, improving each time it runs.

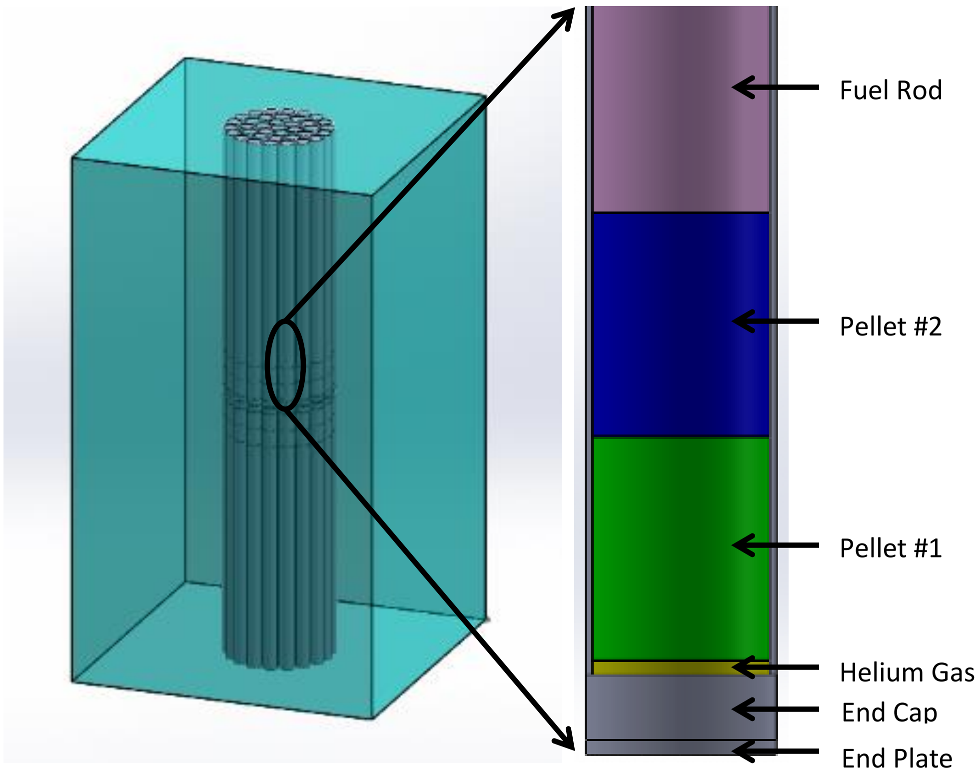

Figure 1: MCNP6 Modelling of CANDU End Region

Results

To ensure that the model was predicting the correct values for the peaking factors, comparison was done to both experiments done at the ZED-2 reactor at Chalk River Nuclear Laboratories, and to a similar model performed with DRAGON [Reference xxx]. The results are summarized in Table 1.

Table 1: MCNP 6.1 model comparison

Fuel Ring	**End Flux Peaking Factors in NU-37**		
	Experimental	**DRAGON**	**MCNP 6.1**
Center	1.268	1.257 (-0.9)	1.265 (-0.2)
Inner	1.246	1.236 (-0.8)	1.248 (0.2)
Intermediate	1.205	1.194 (-0.9)	1.212 (0.6)
Outer	1.142	1.127 (-1.3)	1.142 (0.0)

Note that the values in brackets beside the peaking factors in Table 1 represent the percent difference from the experimental results on each value. From Table 1, we see that the model done in MCNP is able to accurately predict the peaking factors of each fuel ring. Once the model was verified to be working, trials were done to determine the amount of Eu_2O_3 to be placed within the last two pellets. Another relevant conclusion taken from Table 1 is the peaking factors for each ring have different values. This means that the amount of Eu_2O_3 placed into each element will likely vary for each ring.

Figure 2, demonstrates the center element both without absorber added and the best case absorber case thus far. Included in the graph is a line showing the ideal peaking case, where the peaking factor is uniformly one within the fuel. It is less relevant how large the peaking factor is outside the fuel, since the fuel is the only material to undergo fission and thus generate heat. From Figure 2, the axial flux profile for the no absorber case appears exponential in nature with the curve peaking towards the end plate. The increasing nature of the curve means that more absorbing material should be placed within the end pellet to compensate.

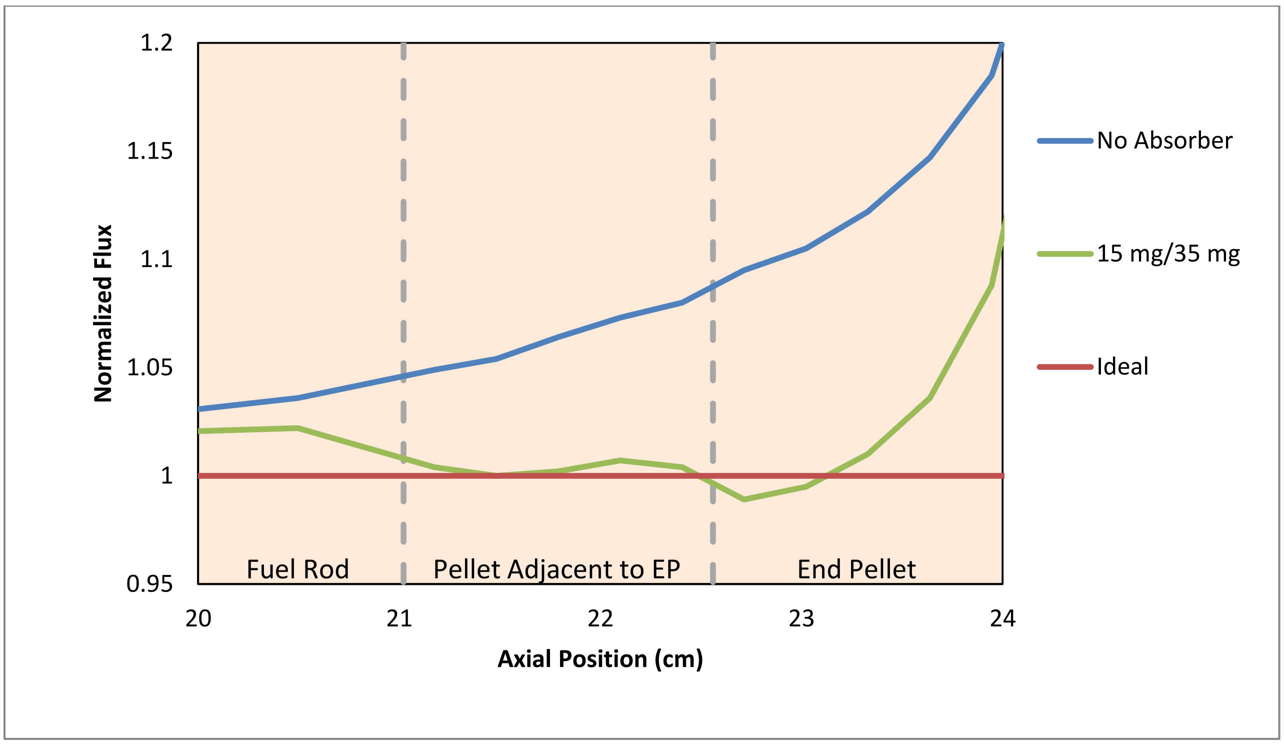

Figure 2: Axial flux profile for the center element. For the absorber trial the first number represents the amount of absorber placed in the pellet adjacent to the end pellet and the second number is the amount of absorber placed in the end pellet

Conclusions

EFP is a phenomenon where a region of elevated neutron flux occurs at the end regions between two adjoining fuel bundles in CANDU reactors. These peaks of high neutron flux lead to an increase in fission rate and therefore greater heat generation in the end regions. This increase in heat generation is of particular concern during accident conditions. In this work the simple method of adding absorber to the last two pellets was proposed. MCNP 6.1 was used to simulate the addition of a small amount of neutron absorbers strategically at the bundle ends.Two important conclusions derived from this work. The first conclusion being that neutron absorbers affect the flux profile even having only added small quantities. The second conclusion is that the correct amounts of absorbers added to the last two pellets can mitigate EFP. To better mitigate EFP would require changing the fuel stack geometry in the end regions. This change would have significant changes to the fuel manufacturing system and would not be advisable.

Future Work

Continuation of this project should include conditions during various stages of refuelling (in contact with a stainless steel pusher or coolant). Another continuation would be to include a temperature profile along the axis of the fuel element. The temperature profile allows for a better understanding the effects of EFP on temperature within an element. The next model will include the results from thesis work done by Lt. Cmdr Paquette at the Royal Military College of Canada as discussed in the introduction. Finally, burnup calculations will be performed to ensure the added absorber does not have a negative effect on the power profile.

References:

1) Balaceanu, V. and Hristea, V., *Study of the End Flux Peaking for the CANDU Fuel Bundle Types by Transport Methods*. Institute for Nuclear Research, Nuclear Energy for New Europe 2005, September 2005.

2) French, P. M., *Measurements of Bundle End Flux Peaking Effects in 37-element CANDU PHW Fuel*. Chalk River Nuclear Laboratories, October 1997.

3) Paquette, S., Chan, P. K., Bonin, H. W., French, C., and Pant, A., *Feasibility Study of Adding Neutron-absorber to Flatten the Core Axial Power Profile.* CANDU Owners Group Inc., OP-12-2037, July 2013.