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

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Abstract

End flux peaking (EFP) is a phenomenon where a region of elevated neutron flux occurs between two adjoining fuel bundles. These peaks lead to an increase in fission rate and therefore greater heat generation. It is known that addition of neutron absorbers into fuel bundles can help mitigate EFP, yet implementation in Canada Deuterium Uranium (CANDU) type 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 within the fuel pellets. This paper will present some preliminary results collected thus far.

1. Introduction

End flux peaking (EFP) is a phenomenon which affects the flux profile of a fuel bundle and occurs in the end regions that separate two individual bundles [2]. The geometry of the end regions consist of a D_2O coolant, Zircaloy bundle end plate and end caps, and uranium dioxide fuel pellets [3]. In the end regions, thermal neutrons build up due to the coolant and Zircaloy-4 having a much lower absorption cross section, σ_a, than the uranium fuel. This difference 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].

1.1 Burnable Neutron Absorbers

Burnable neutron absorbers have been used regularly within Light Water Reactors (LWR) for some time now. Their use has not been implemented into Canada Deuterium Uranium (CANDU) type reactors, due to the concern of their effect on neutron economy [4]. Therefore, an appropriate absorber must be chosen to mitigate unwanted behaviours within the reactor, such as xenon free effects (refuelling transients), while having minimal effect on the neutron economy [4].

Properties of interest for a neutron absorber, are the overall cross section at a given energy, i.e. thermal energy neutrons (0.025 eV), and the cross section of the interaction products.

A good neutron absorber will have a high initial cross section but once the nuclei interact with the neutrons the products (daughters) have much lower cross sections. This difference in cross section is a key in controlling the duration of absorbers to be effective.

In Paquette *et al.* it was determined that gadolinium oxide (Gd_2O_3) and europium oxide (Eu_2O_3) met the criteria outlined above. 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 [4]. 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 [4]. Using these two absorbers it was concluded by Paquette *et al.* that ~300mg of Gd_2O_3 and ~700 mg of Eu_2O_3 within a fuel bundle can suppress both the refuelling transient and lower the axial plutonium peak [4]. The combined mass of the absorbers to the total mass of the fuel bundle represents ~$4x10^{-3}$ wt% per 24 kg bundle, [4].

1.2 End Flux Peaking

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 [4]. PF^{flux} is defined for a single element in each element ring. Meaning there is a representative PF^{flux} for each ring.

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

In the following figure, EFP is shown in terms of how neutrons can get trapped in the end regions. Neutrons are not absorbed as much in the end region as in the UO_2 fuel. The lower neutron absorption within the Zircaloy, gap and coolant leads to the build-up of neutrons in the end regions and subsequently EFP.

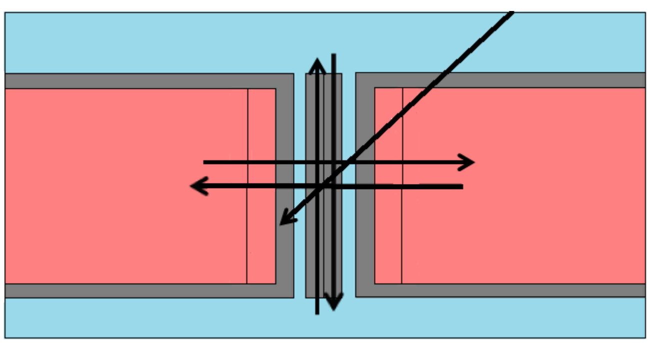

Figure 1: End Flux Peaking is created due to trapping of thermal neutrons, from all sources, in the end regions

2. Geometry Specification

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 neutron absorbers 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 the 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.

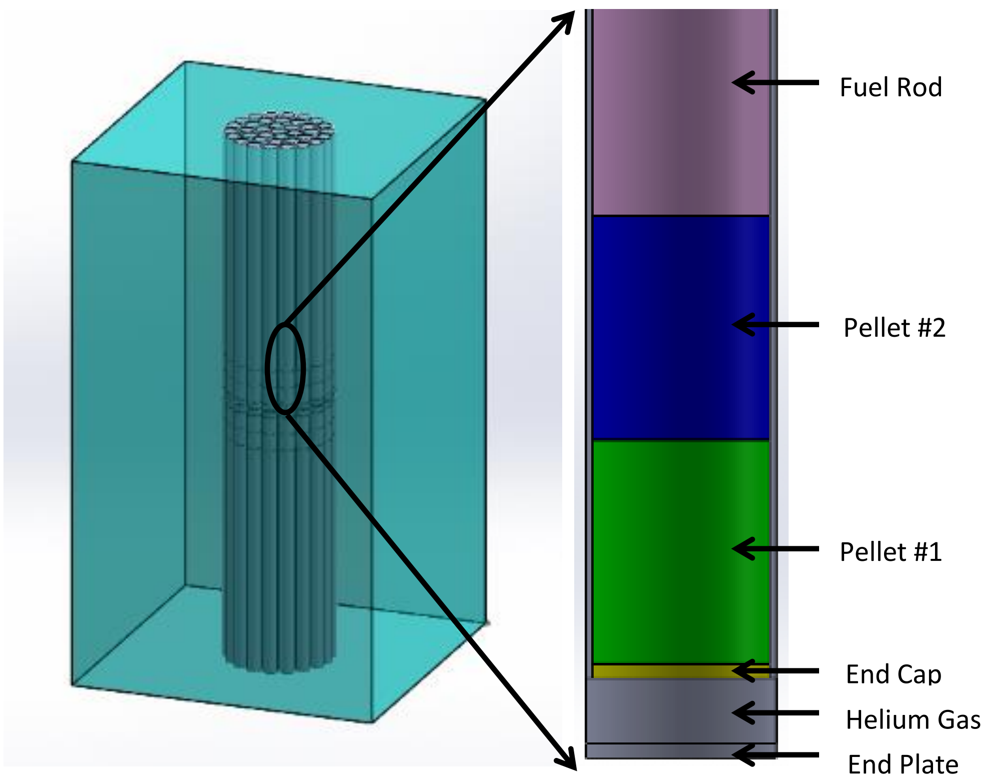

Figure 2: Two half CANDU bundle model, including blown up cross section of a fuel element

3. Results

3.1 Model Validation

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 [5]. 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, one could see that the model done in MCNP is able to accurately predict the peaking factors of each fuel ring. Once the model was 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.

3.2 Preliminary Absorber Trials

The first set of trials included the use of both gadolinium and europium oxide, used in either a single or two pellet configuration. In the single pellet configuration the absorber was placed within the end pellet, whereas the two pellet had absorber place in both the end pellet and pellet adjacent to the end pellet. In the preliminary trials only one absorber was tested at a time. Using one absorber with a fixed amount in each pellet eliminates the issue of mixing up pellet location during fuel manufacturing. Since there would be no observable differences between a pellet doped with europium or a pellet doped gadolinium as the absorber.

Trial and error was used to determine the amount of absorber placed in each pellet to provide optimal mitigation of EFP. The smallest required amount of absorber was determined to be 1 mg. This providing the starting absorber amount for the preliminary trials.

Preliminary results are summarized in the following sections. An ideal case of uniform neutron flux along the entire length of the fuel rod is indicated by a red dashed line. Graphs illustrated in the following sections are results obtained from EFP in the center element. Since the center element has the largest EFP factor, see Table 1. Therefore if significant mitigation can be shown for the center element then the concept of using a small amount of absorber to mitigate EFP is applicable to all fuel elements.

3.2.1 Gadolinium Trials

The first set of trials are the gadolinium trials. Figure 8 shows the single pellet gadolinium trials, where gadolinium is placed into the end pellet only. The graph shows the affect of gadolinium on the axial flux profile. Gadolinium has such a high absorption cross section that only a small amount can cause the flux to drop below the centerline flux value in the end pellet. Additionally, placing the gadolinium within the end pellet has no significant mitigating effects on the flux shape within the adjacent pellet. To better mitigate EFP, the absorber should be added to both the end pellet and its adjacent fuel pellet.

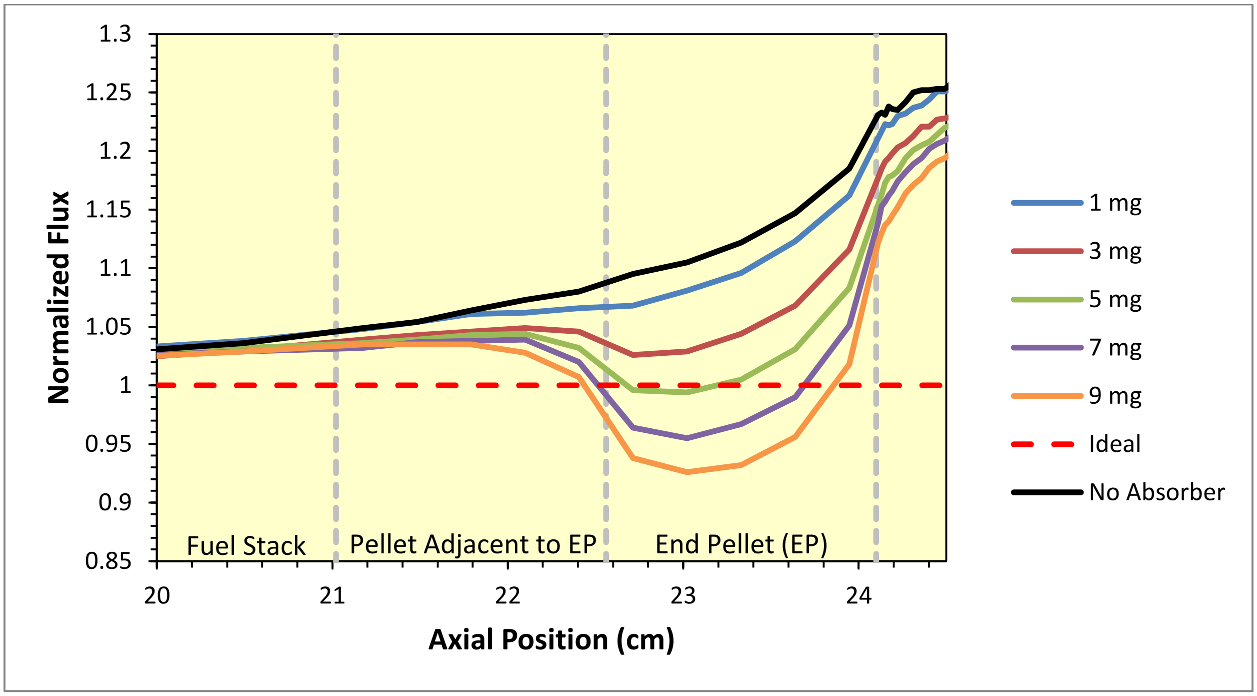

Figure 3: Preliminary absorber trials with various amounts gadolinium placed in the end pellet.

Figure 4 shows the results for the two pellet gadolinium trials. In these trials the same amount of gadolinium is added to both the end pellet and its adjacent pellet. Again as with the single pellet gadolinium trials, the addition of gadolinium has a significant effect on the shape of the flux profile. Doubling the amount of absorber has a more significant effect of lowering the flux profile, as shown in Figure 4. This drop in the axial flux profile is far too extreme for mitigating EFP.

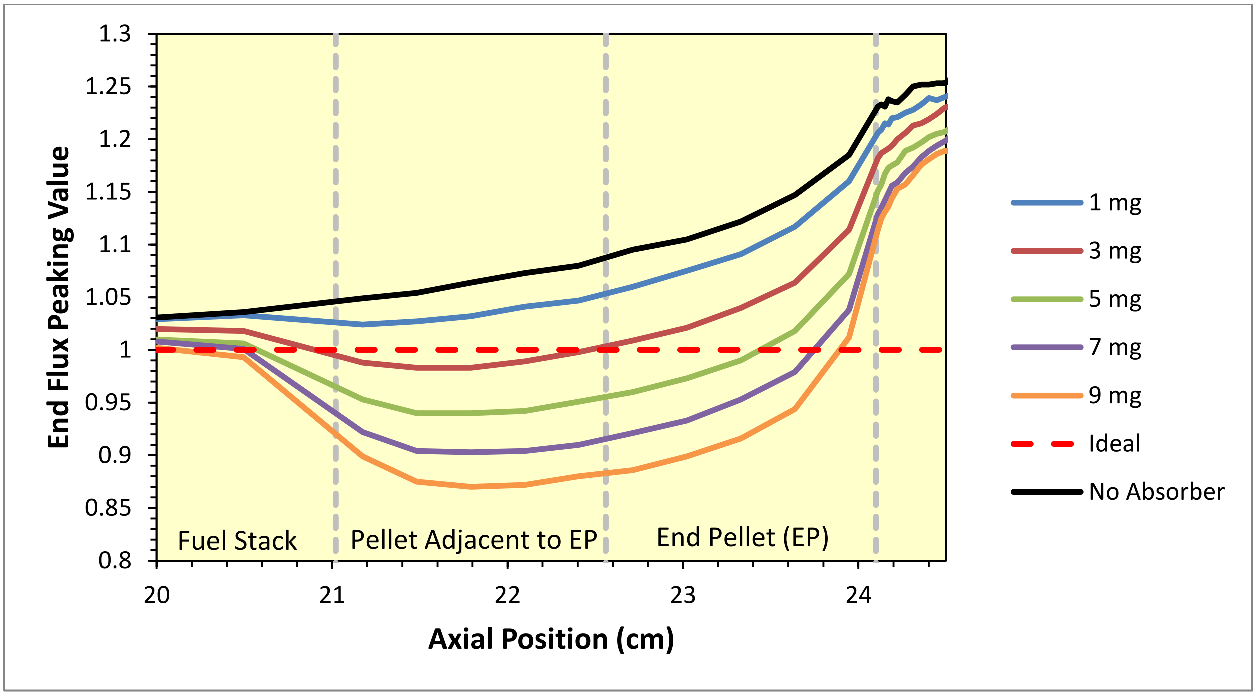

Figure 4: Preliminary absorber trials with various amounts of gadolinium placed with both the end pellet and the pellet adjacent to the end pellet. Same amount added to each pellet.

These trials show that gadolinium is too effective an absorber of neutrons for the purpose of mitigating EFP. Better control of the flux profile is required and such drastic changes are not ideal. Less than 5mg in the end pellet and less than 3 mg in the adjacent pellet provide mitigation of EFP without causing significant dropping below the centerline value. The next trials shown are those with europium.

3.4 Europium Trials

Europium has a lower absorption cross section than gadolinium for neutrons. Europium should provide a more controllable way of mitigating the flux profile.

Similar to the gadolinium trials, single pellet trials were done first with absorber placed within the end pellet. Results are shown in Figure 5. As expected, europium causes a much smoother flattening of the axial flux profile. Additionally, the range of preliminary trials does not provide a case where significant EFP mitigation could occur. To obtain significant mitigation, a larger amount of europium must be placed within the fuel pellets. The single pellet europium trials also show that placing absorber in the end pellet has little effect on the flux shape within the adjacent pellet. To obtain a flux profile closer to the ideal case, absorber will likely need to be included in both the end pellet and the adjacent fuel pellet.

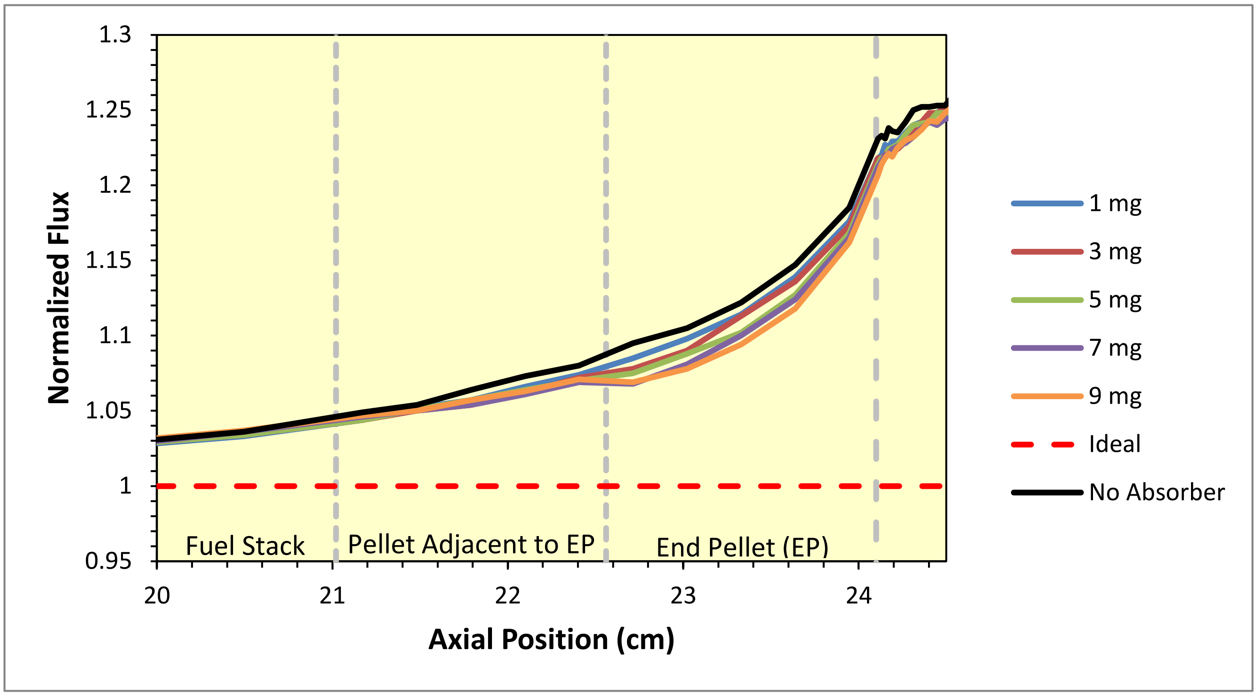

Figure 5: Preliminary absorber trials with europium placed with the end pellet

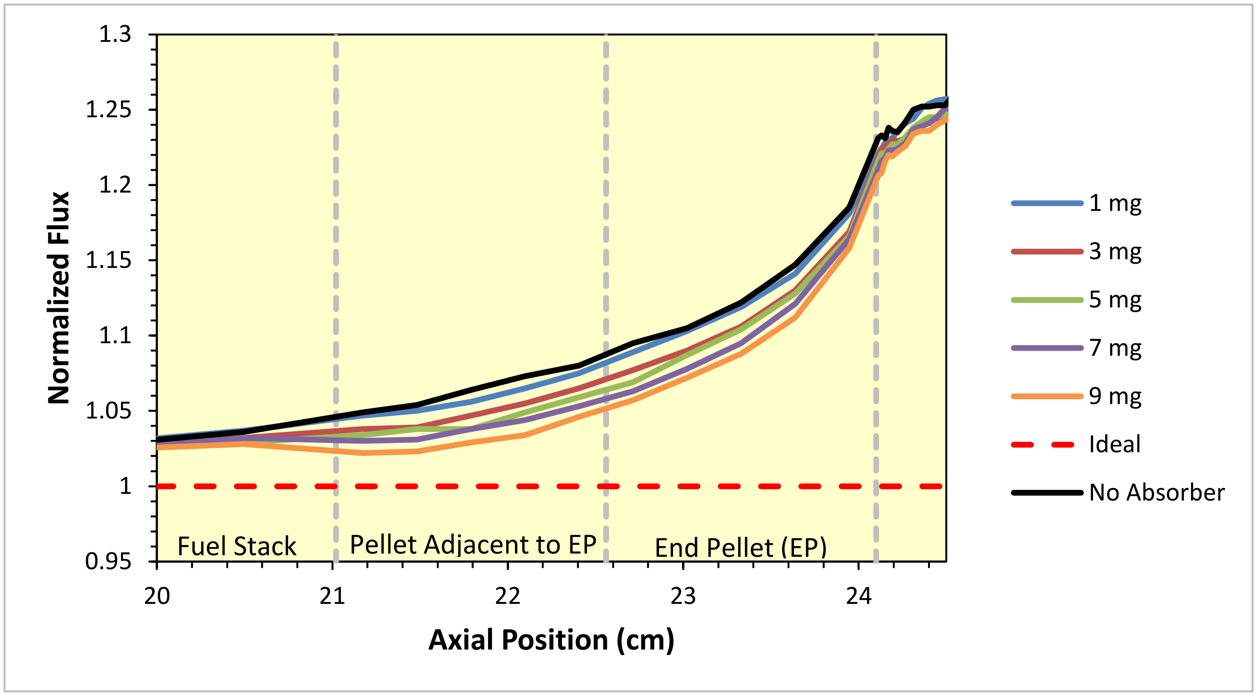

Figure 6: Preliminary absorber trials with europium placed in both the end pellet and the pellet adjacent to the end pellet, same amount in each pellet

Figure 6 shows the two pellet europium trials. These trials share similar features to single pellet europium trials. For example, the europium has begun to flatten the flux profile and has done so in a much smoother manner than the gadolinium trials. By adding the same amount of absorber to each pellet the axial flux profile better approaches the ideal case, but these preliminary trials still need to be improved.

From the preliminary gadolinium and europium trials, the following conclusions can be obtained. First, gadolinium has too large a neutron absorption cross section to smoothly mitigate EFP by itself. Second, the amount of absorber in the end pellet will need to be larger than the amount placed within the adjacent pellet. Finally, europium is a more viable option as an absorber since control of the axial flux profile is more easily obtained.

3.5 Europium and Gadolinium Trials

To show that more absorber needs to be placed within the end pellet, a mixed absorber trial was prepared. In this set of trials, gadolinium was placed within the end pellet. Since gadolinium is a more effective neutron absorber and the effects of EFP are more significant within the end pellet. Europium was placed within the adjacent pellet, since it is less effective and the effects of EFP are less significant in the adjacent pellet.

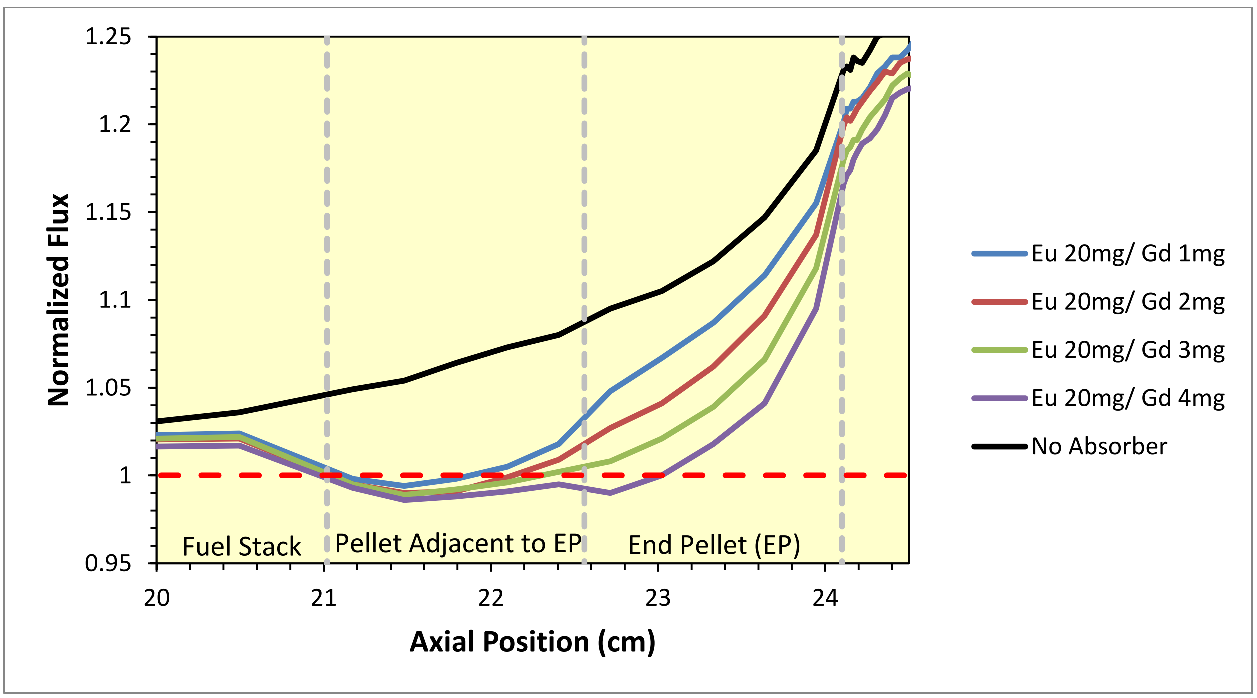

Figure 7: Absorber trials with europium placed within the pellet adjacent to the end pellet and gadolinium placed within the end pellet.

In the preliminary single pellet gadolinium trials, 5mg was the maximum amount that could be added before the axial flux profile dropped below the ideal case. Therefore, for the mixed trials the amount of gadolinium was taken from a range of one to four milligrams. To maintain results that does not drop below the centreline value. As for the amount of europium added, it was held constant at a value of 20 mg. This value was chosen as twice the largest amount added in the preliminary trials, since significant mitigation was not observed in the preliminary trials.

Figure 7 shows the results for the mixed trials as well as the case where no absorber is added to the pellets. This comparison indicates that by adding absorbers into the end pellets, significant mitigation of EFP could occur. The best case shown in Figure 7 is that with 4 mg of gadolinium added to the end pellet. Unfourtunately, there is still significant EFP within the end pellet. This is evident from the peak that occurs in the center of the end pellet. This set of trials confirms the need for more absorber to be placed within the end pellet. To approach better mitigation, europium was chosen to be the absorber placed in both pellets.

3.6 Further Europium Trials

As indicated in the preliminary europium trials, one has not yet reached the point where the flux drops below the ideal line. Europium is the better absorber for smoothing the axial flux profile. Hence europium within both pellets was further optimized.

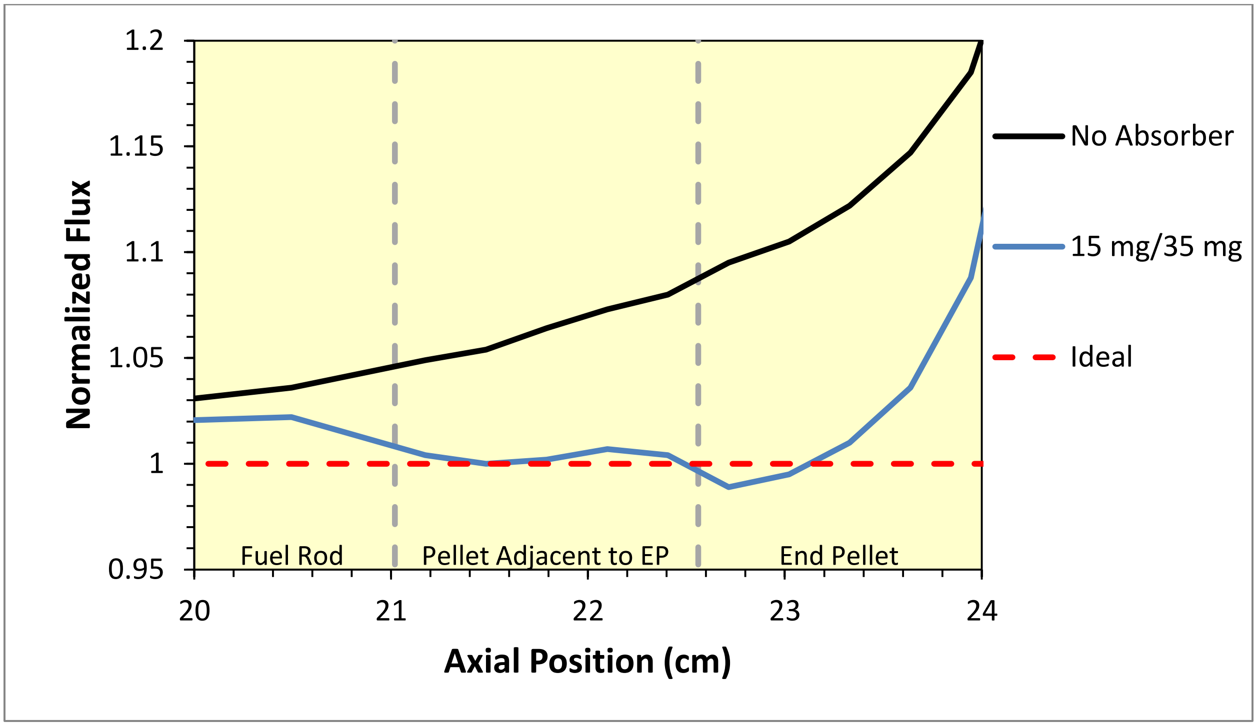

Figure 8: Comparing the ideal europium trials with the case of having no absorber

Figure 8 shows the center element without absorber added and the best absorber case thus far. In the further trials done with europium, the amount of absorber placed within each pellet differed. To provide the best mitigation of EFP without dropping below the centreline value, the amount of absorber placed within the adjacent pellet need to be less than the end pellet. Since the effects of EFP is more significant in the end pellet compared to the adjacent pellet. From Figure 8, the absorber trial represented is the best case trial to date for the center element. Comparing this absorber trial to the no absorber case, significant mitigation of EFP is observed. Another noticeable feature is the peaking which still occurs within the end pellet. This peaking still occurs because of the exponential nature of the EFP within the fuel elements. To better mitigate EFP would require altering the geometry of the end pellet. This would include separating the end pellet into two smaller pellets and having more absorber placed in the half pellet closest to the end region.

4. 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 refuelling and loss-of-coolant 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.

5. Future Work

Continuation of this project should include conditions during various stages of refueling (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, calculations should be performed to ensure the added absorber does not have a negative effect on the power profile as burnup is progressing.

6. References

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