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Optimal Neutron Absorber Location to Mitigate End Flux Peaking in CANDU Fuel Bundles

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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 neutron absorbers strategically within various locations within the fuel bundle. This paper will present results on the optimal absorber location.

1. Introduction

End flux peaking (EFP) is a phenomenon which affects the flux profile of a fuel bundle occurring in the end region separating two individual bundles. The geometry in the end regions consist of D_2O coolant, Zircaloy endplate and end caps, helium gas, and a uranium dioxide fuel pellet [1]. As shown in the figure below,

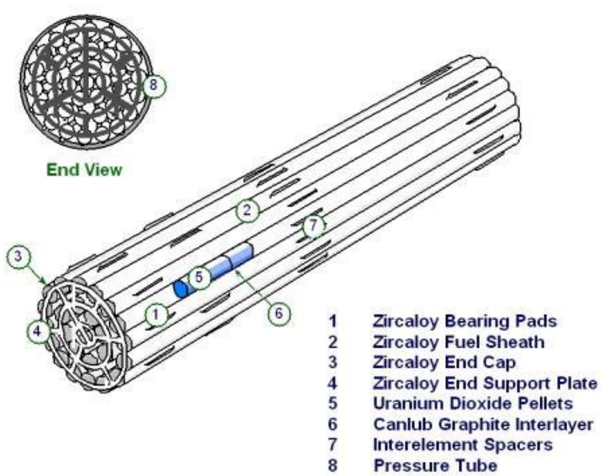


Figure 1 CANDU fuel bundle design, including the 37 element pattern [2]

Due to the heavy water coolant and Zircaloy structural material having a much lower absorption cross section, σ_a, for thermal neutrons than the uranium dioxide, thermal neutrons tend to not be absorbed as much as they would in the fuel [3]. The lack of absorption of thermal neutrons in these regions leads to peaks in neutron flux around the end regions. The occurrence of EFP leads to higher fission rates, leading to more heat being produced and therefore higher overall temperatures within the pellets adjacent to these end regions. Higher temperatures lead to an increased risk for sheath strain, corrosion and fuel centerline melting. All of which have significant impact on the integrity of the sheath and fuel pellets during over-power of loss of coolant accident (LOCA) conditions [3].

1.1 Burnable Neutron Absorbers (BNAs)

Burnable neutron absorbers (BNAs), have seen regular use within Light Water Reactors (LWRs) for some time now. Yet, their implementation in CANDU type reactors has not been used in operating CANDU reactors, due to various concerns such as the absorbers effect on the neutron economy of the reactor. Therefore, an appropriate absorber must be chosen which both mitigates unwanted behaviours such as xenon free effects (refueling transients) while having minimal impact on the neutron economy [3].

Neutron absorbing materials could exist within the reactor for an extended period of time and undergo various transformations. A good absorbing material will therefore have a high initial absorption cross section, with interaction products which also have high absorption cross sections. It is therefore important to analyze the effectiveness of an absorbing material by analyzing the interaction products.

In Chan et al. [3], it was determined that gadolinium oxide (Gd_2O_3) and europium oxide (Eu_2O_3) meet the criteria discussed 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. Eu_2O_3 was used to mitigate plutonium peaking since it has a long chain of stable isotopes that have relatively large thermal absorption cross sections. Using these two absorbers it was concluded by Chan *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 plutonium peak. The combined mass of the absorbers, ~300mg of Gd_2O_3 plus~700 mg of Eu_2O_3 equalling 1000 mg of absorbing material, to the total mass of the fuel bundle, roughly 24-kg, is on the order of ~10^{-3} weight % , [3].

1.2 End Flux Peaking (EFP)

To quantify the phenomenon of EFP, 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 [2]. PF^{flux} is defined for a single element in each element ring. Meaning there is a representative PF^{flux} for each ring.

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

In the following figure, EFP is shown in terms of how thermal neutrons pass through the end regions readily without much being absorbed. This is caused by a discontinuity in absorption cross section of the uranium dioxide fuel and heavy-water and Zircaloy structural components. Since the absorption cross section of the heavy-water and Zircaloy components is lower than that of the UO2 fuel, more thermal neutrons are able to pass through these materials, leading to an increase in neutron flux in the end regions. Figure 2, demonstrates the increase in thermal neutron flux which occurs in the contact region between two fuel bundles. The coloured curves represent the axial flux curves from an element in each ring of the CANDU fuel bundle. The blue curve represents the center element, the red curve represents the inner elements, the green curve represents the intermediate elements and the yellow curve represents the outer elements. This indicates that the flux peak in a single fuel element is dependent on the ring in which it resides.

Also in Figure 2, the black areas on the right hand side of the figure are there to depict the UO2 fuel clad in Zircaloy metal. The red arrows simply represent how thermal neutrons pass through the end cap/plate with a low probability of interacting.

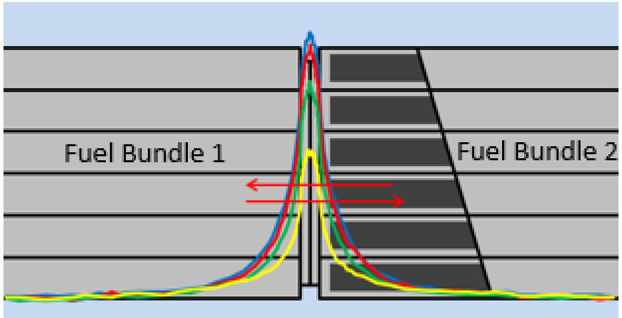


Figure 2 Illustration of End Flux Peaking

2. MCNP Model Specifications

Monte Carlo N-Particle Code (MCNP) 6.1 was used to simulate the addition of a small amount of neutron absorbers strategically at various locations within the CANDU fuel bundle. In the MCNP 6.1 model, see Figure 3, two separate half fuel bundles are modelled, with the end region of each half bundle in contact with the other. The fuel within each element is simplified and modelled as a solid rod, opposed to a fuel stack of individual pellets, with the exception to the last two pellets, closest to the end cap. The last two pellets are defined separately for neutron absorbers to be located. As part of the CANDU fuel bundle design, as well as those being modelled in this project, each fuel element is coated with a roughly 20 micron thick layer of CANLUB coating, a feature which was replicated in the MCNP model. CANLUB is a protective graphite coating added to each fuel element to help mitigate the effects of stress corrosion cracking. Calandria and pressure tubes are included in the MCNP model, although these features are excluded in Figure 3 such that the 37 half-fuel elements can be easily. To mimic the existence of multiple fuel channels, reflective boundary condition is applied to all external surfaces of the simulated bundles.

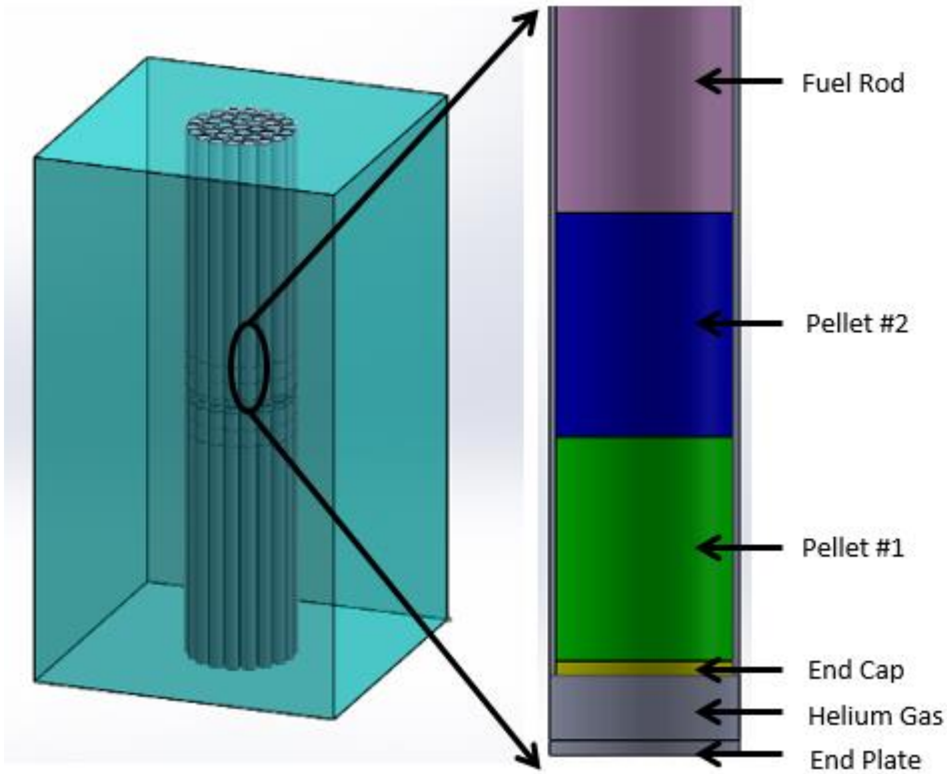


Figure 3 Two-half–CANDU-bundle model, including blown up cross section of a fuel element

The neutrons in the model are generated using the KCODE module. The KCODE module is run using 2400 cycles, each with 100000 neutrons being simulated in a single cycle. Results were calculated after the first 200 cycles were completed. The source guess locations was taken as the mid points of the fuel portion of the fuel element. Since the MCNP model simulates the contact region between two half-bundles there is a total of 74 initial guess source point for neutrons. Running the KCODE module under these parameters was determined through sensitivity analysis, fixing all parameters except the number of cycles. The objective of the sensitivity analysis was to minimize both the simulation error and the time of a single trial.

3. Results

3.1 Model Validation

The goal of this project is to use neutron absorbers to reduce the peaking factor within the end pellets to 1.0, based on Equation 1, this means that the thermal neutron flux in the end region would equal the flux at the center of the fuel bundle. To ensure that the model was able to predict the correct values for the peaking factors, comparison was done to both experiments done at the ZED-2 reactor at Chalk River Nuclear Laboratories (CNL), and to a similar model performed with DRAGON 3.03a. It should be noted that the DRAGON model makes use of the 89-group ENDF/B-V library, while the MCNP 6.1 model uses the more up to date ENDF/B-VII.1 library. The MCNP model is making use of a more up-to-date material library which may help account for its improved performance in predicting the peaking factors when compared to the DRAGON model. 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 represent the percent difference from the experimental results for each simulation. From Table 1, the model in MCNP is able to accurately predict the peaking factors of each fuel ring, within 1%. Using this model, trials were done to determine the amount of neutron absorber to be placed within several location within the fuel bundle deemed the most likely to demonstrate significant mitigation of EFP. Another relevant conclusion drawn from Table 1 is the peaking factors for fuel elements in each fuel ring have different values. This indicates that the amount of absorber need to successfully mitigate EFP in each fuel ring will like differ on a ring by ring basis.

3.2 Absorber Location Testing

EFP is a highly localized phenomenon. For absorbers to be effective, they need to be placed strategically in the end region. The absorbers need to be located closely to the locations most affected by EFP, but with minimal impact to the fuel bundle design. To determining the optimal location for the neutron absorber to be placed, various locations were investigated, with various amounts of absorbing material, either gadolinium or europium oxide. The locations of interest include; the end pellets, thin disks located in the gap between the end pellet and the end cap, layer of CANLUB, and the endplate itself. For all locations except the endplates, the absorbing materials place in their oxide forms, whereas the absorbing material in the endplates was taken as the pure metallic form of europium or gadolinium to form a doped Zircaloy-4 alloy.

3.2.1 Thin Disks

The first absorber location is in thin disks which occupy the gap between the end of the fuel pellet stack and the end cap. The thickness of the disks is roughly 0.1 mm. The benefit of having the neutron absorbing material located in thin disks is that it allows for the introduction of the absorbing material without having to alter existing bundle materials. A drawback to using thin disks as the method of mitigating EFP is they take up physical space in the gap between the end of the fuel stack and the end cap which was designed to accommodate pellet expansion during reactor operation.

Trials were done using 5mg, 10mg, 15mg, 20mg and 25mg of either europium or gadolinium oxide. These results are summarized in Figure 4, in which the field of view is limited to the end region of a center element.

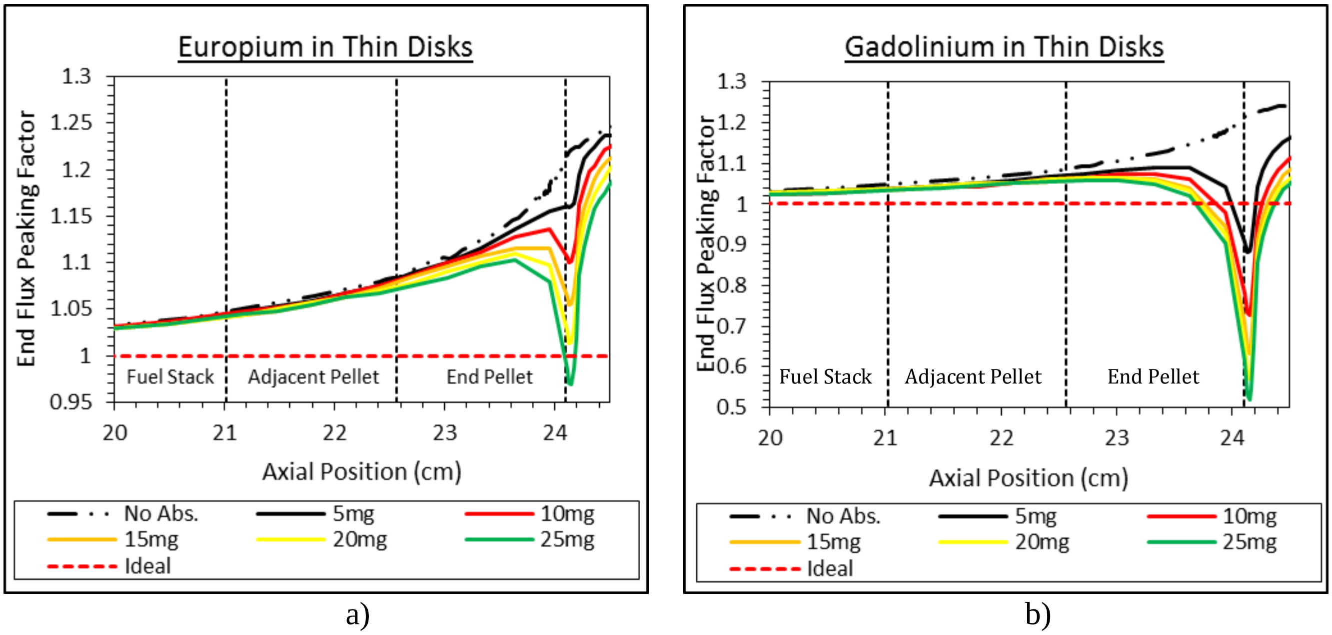


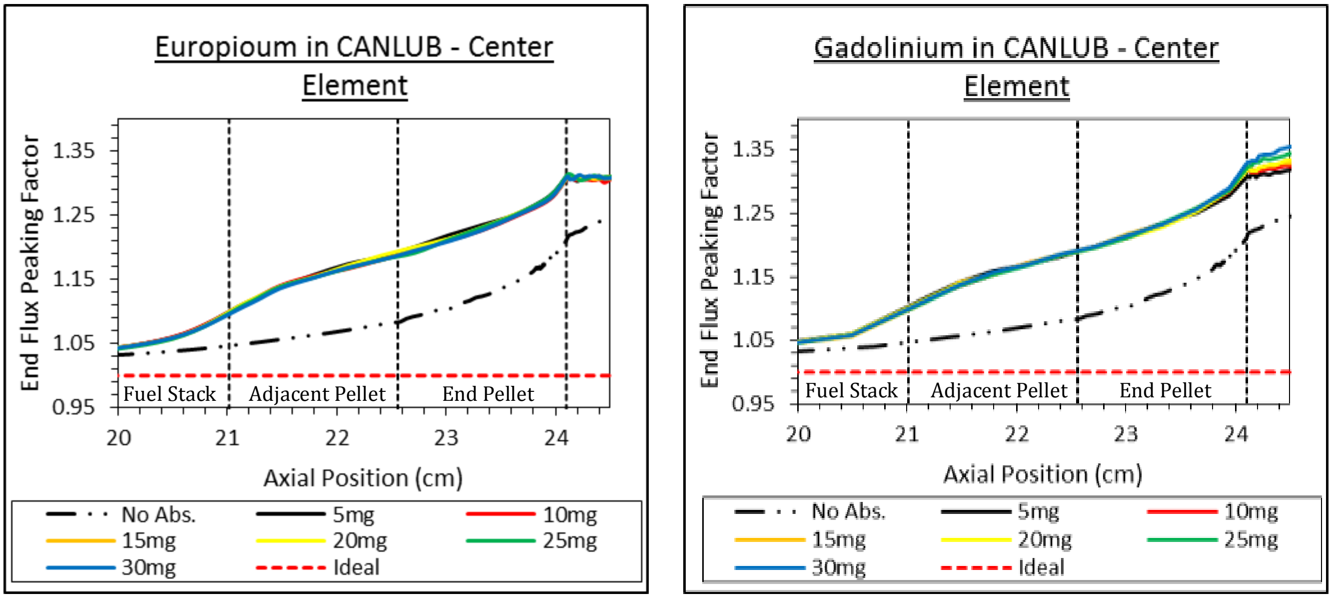
Figure 4 Summary of thin disk trials using a) europium oxide (Eu_2O_3), or b) gadolinium oxide (Gd_2O_3) as the neutron absorbing material

Even though thin disks seem like the easiest location to implement, having neutron absorbers located in a compact volume causing the dipping of the flux at the location of the thin disks, regardless of the absorbing material, as shown in the above figure. As expected this flux dipping is more severe when gadolinium oxide is chosen as the absorbing material. There does appear to be a slight improvement in the end flux peak when compared to having no absorber in the fuel bundle. The flux dipping caused by the implementation of absorbing material as thin disks leads to a more complex flux profile, while not mitigating EFP to the desired magnitude. This excludes thin disks from further trials.

3.2.2 CANLUB

The neutron absorber was assumed to be distributed uniformly throughout the entire fuel bundle. The absorbing material was mixed into the CANLUB of all 37 fuel elements.

Trials were done using 5mg, 10mg, 15mg, 20mg, 25mg and 30mg of either europium or gadolinium oxide, per element. These results are summarized in Figure 5, in which the field of view is limited to the end region of a center element.



a) b)

Figure 5 Summary of thin disk trials using a) europium oxide (Eu_2O_3), or b) gadolinium oxide (Gd_2O_3) as the neutron absorbing material

Since the CANLUB exists along the entire length of the fuel elements most of the absorbing material does not exist within the end region. Meaning that the flux along the length of the fuel bundle is reduced, but the end regions remain unaffected because there is very little absorber at the ends to provide mitigation. This coupled with the fact that Equation 1, relies on taking a ratio of the flux in the end region over the flux at the center of the fuel bundle leads to the end flux peaks appearing larger than the case where there no absorber in the fuel bundle. Since CANLUB has the effect of enhancing the appearance of EFP it is excluded from further trials.

3.2.3 End Pellets

The third absorber location investigated was having the absorbing material doped into the end pellets. This means that the absorbing material will be integrated into the fuel matrix. As shown in Figures 3 and 4 the no absorber curve starts prior to the very end of the fuel element. Since it is the fuel pellets in the end region which are most effected by EFP. Therefore, by adding material into the end pellets which absorbs neutrons, and itself does not undergo fission, will provide the most direct method to combat EFP within the end pellets. End pellets are either short, chamfered or smaller in diameter than other fuel pellets, these design features help to distinguish end pellets from other fuel pellets thereby mitigating the risk associated with doped end pellets being loaded into the fuel stack prematurely.

The trials were done using a single end pellet and doping it with 1 to 10 mg of the respective absorbing material, incremented by 1 mg. Figure 6 summarizes these results.

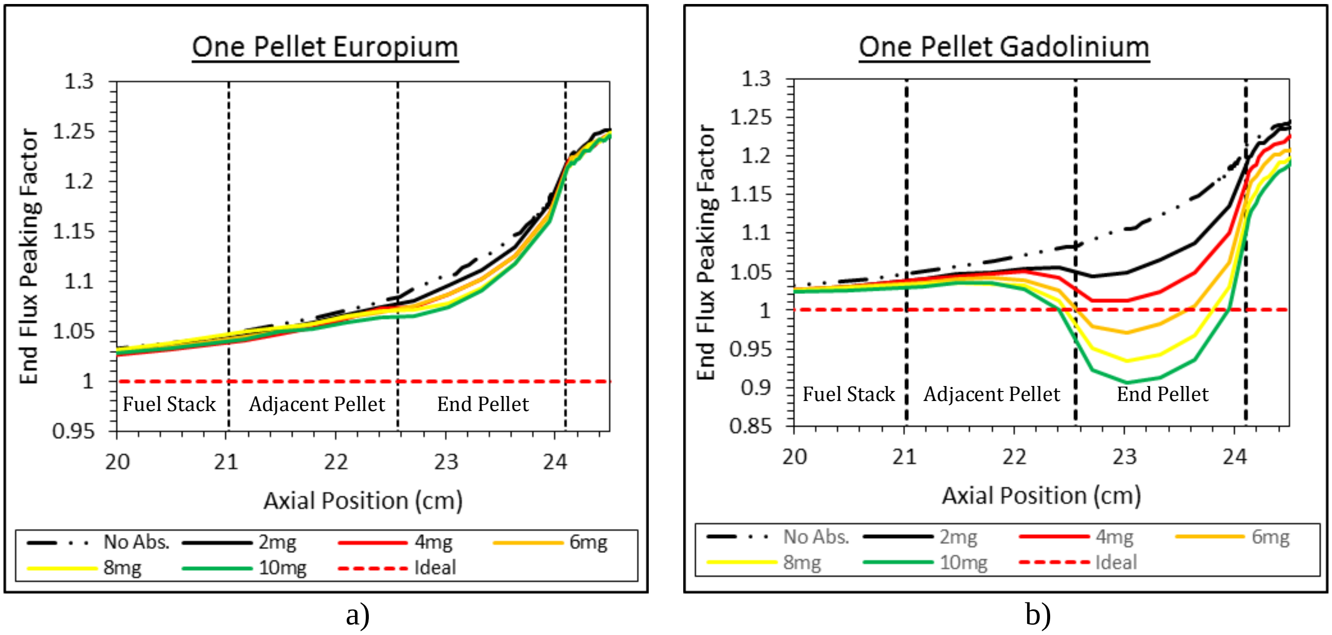
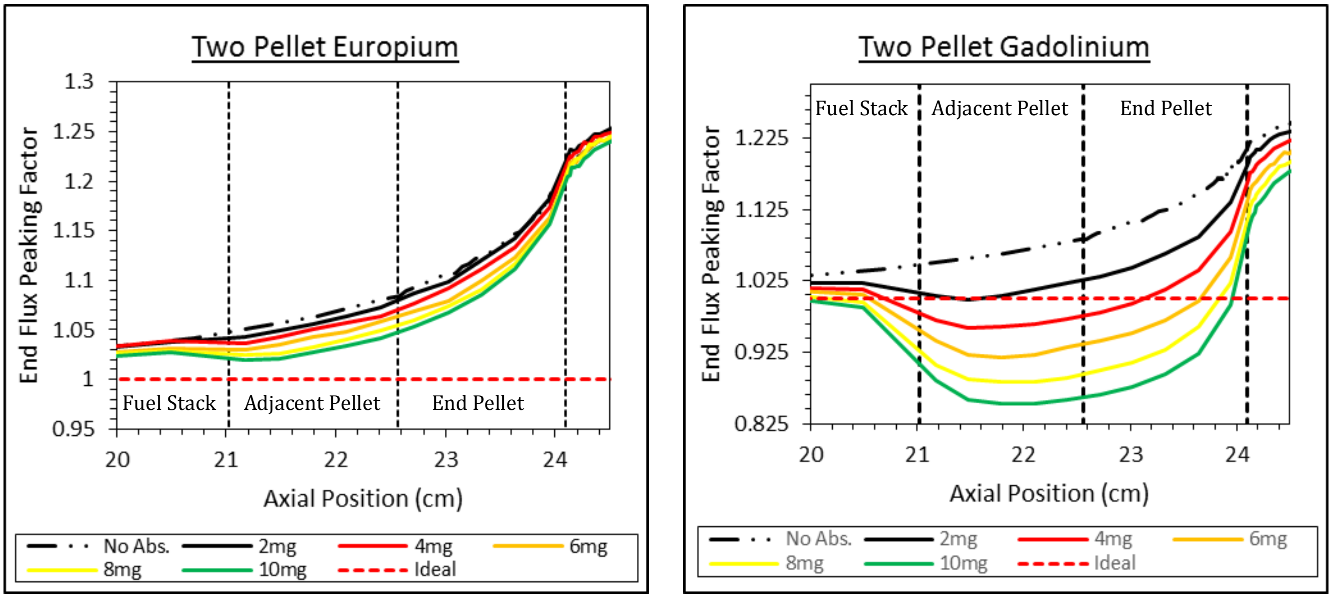


Figure 6 Summary of single end pellet trials using, a) europium oxide (Eu_2O_3), or b) gadolinium oxide (Gd_2O_3) as the neutron absorbing material

As shown in Figure 6a, the europium in the single end pellet is able to bring the flux peak to the ideal line. The mitigating potential does seem to be limited to the single end pellet, with little benefit being provided to the fuel pellet next to the end pellet, henceforth referred to as the adjacent end pellet. This observation is strongly emphasized in Figure 6b, where the absorbing material was Gd_2O_3. Gadolinium has such a high absorption cross section that only a small amount can cause the flux curve to be drastically altered. As shown in Figure 6b, any amount greater than roughly 4 mg will cause the flux curve to drop below the center flux curve value, which is the ideal line. As with the europium doped end pellet, the mitigating effect of the absorbing material is for the most part isolate to the location in which it is placed. Therefore, by doping a single end pellet significant mitigation of the flux peak within the doped end pellet is observed with little benefit beyond the end pellet. As shown in in Figures 4, 5 and 6, there is still significant peaking in the adjacent end pellet. To address this issue, trials were conducted where the absorber was still placed into fuel pellets, but now placed into both the end and adjacent end pellet.

Similar to the single pellet trials, the two trials were done each pellet with 1 to 10 mg of the respective absorbing material; incremented by 1 mg. Figure 7 summarizes these results.



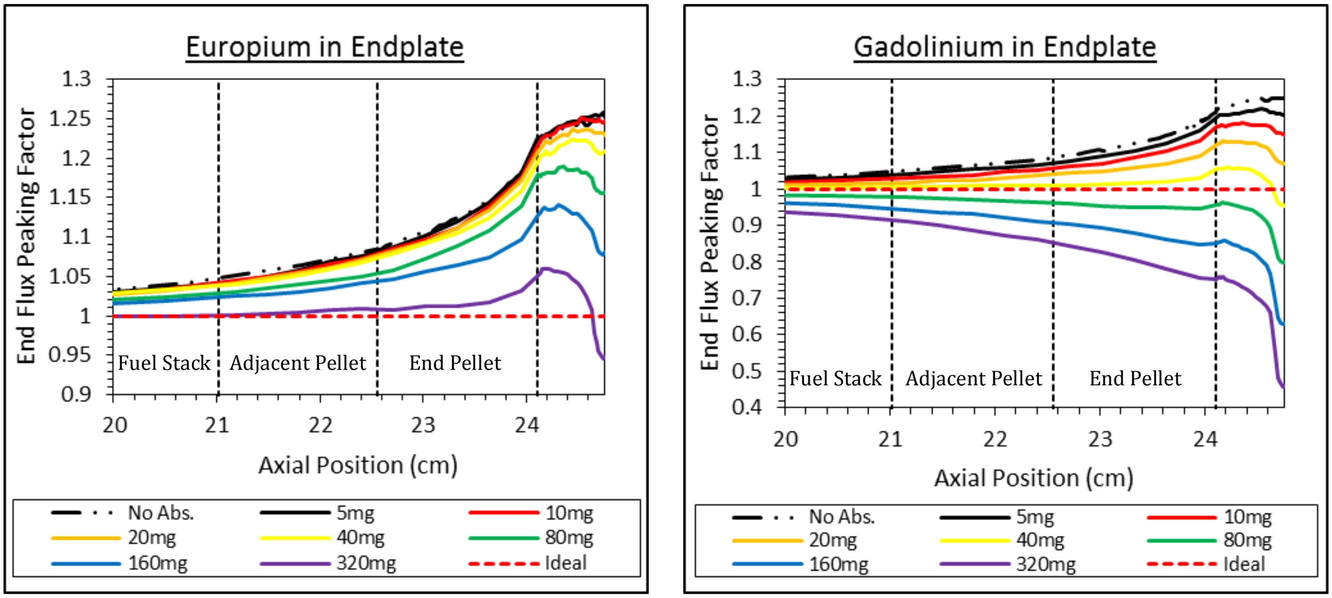
a) b)

Figure 7 Summary of double end pellet trials using, a) europium oxide (Eu_2O_3), or b) gadolinium oxide (Gd_2O_3) as the neutron absorbing material

Similar to Figure 6, it is clear that of the two absorbing material investigated the europium is able to provide a more controllable mitigation potential, as the flux curve approaches the ideal line more steadily as the amount of absorbing material is increased. Also similar to Figure 6, is the ability of gadolinium to drastically alter the flux curve. Now that the absorbing material has been spread to two pellets the flux peak is being mitigated more completely than it was with the single end pellet trials. Even increasing the number of doped end pellets to two, flux peaking still exists beyond the last end pellet. However, the amplitude of flux peaking is smaller than that occurs in the adjacent and end locations. Once may need to consider that the amount of absorbing material in the adjacent and end pellet will likely be different, as the flux peak is stronger in the end pellet than the adjacent pellet.

3.2.4 Endplates

Unlike the previous locations, the endplates do not involve the addition of oxide materials. Instead pure europium or gadolinium was included to form either a Zircaloy-4-Europium or –Gadolinium alloy material. This absorbing material location was included due to the fact that trials were conducted in the past at Canadian Nuclear Laboratories (CNL) in the past where different alloys were investigated to try and mitigate EFP. Using the endplates as a location for gadolinium and europium is highly discouraged as a practical method. Since during operation the gadolinium and europium in the alloy would constantly be changing through neutron capture reactions, this might raise a concern over the structural integrity of the endplate during reactor operation. Since the endplates are structural components of the fuel bundle this location is not recommended in this study. Regardless, Figure 8 demonstrates the ability of absorbing material alloyed endplates ability to mitigate EFP.



a) b)

Figure 8 Summary of endplate trials using, a) europium oxide (Eu_2O_3), or b) gadolinium oxide (Gd_2O_3) as the neutron absorbing material

Similar to all locations up to this point the europium seems to provide the more controllable option of absorbing material when compared to gadolinium. The drop in flux in the endplate is not a concern since the material here is Zircaloy-4 and heavy water, and no fission therefore occurs here. So no loss of power will be seen due to these flux drops in this region. However as mentioned, endplates are a structural component of the fuel bundle and therefore adding absorbing materials are highly discouraged.

3.2.5 Optimal Location

From the preliminary gadolinium and europium trials done thus far, the following conclusions can be obtained. Firstly, the best location for mitigating EFP is the double end pellet configuration. Secondly, gadolinium has too large a neutron absorption cross section to smoothly mitigate EFP by itself. Therefore, the best absorber and absorber location is to have europium placed into the adjacent and end pellets. From Figure 7a, it is clear that the amount of europium in the pellets investigated thus far needs to be optimized. Likely, the amount of europium will need to be larger in the end pellet than in the adjacent pellet.

Using an optimization routine, the optimal amount of europium oxide added to both pellets in fuel elements from each fuel ring was determined. The optimal results are summarised in Figure 9. Note that the first number in the absorber curves indicates the amount of europium added to the adjacent pellet and the second number represent the amount of europium added to the end pellet.

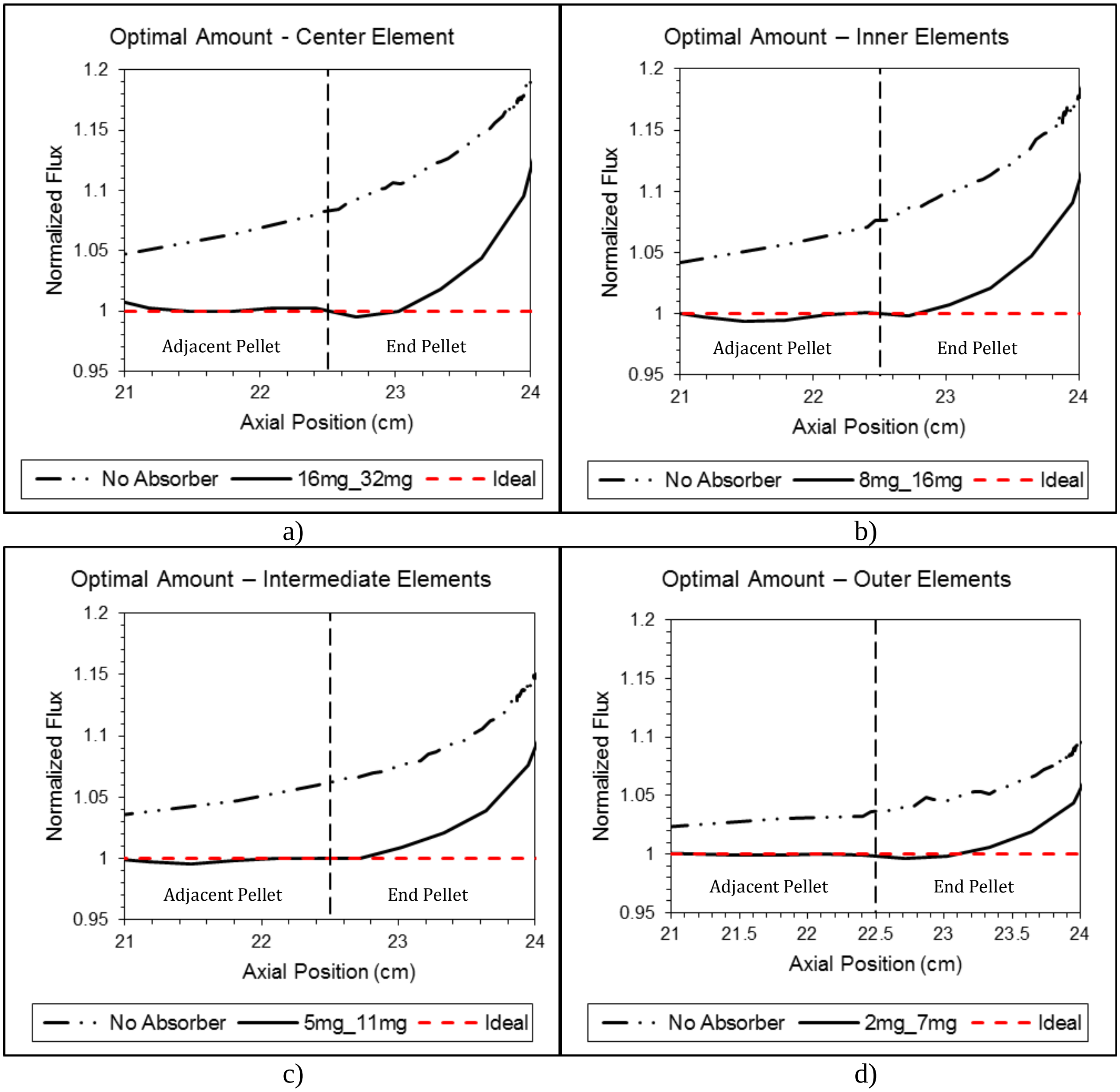


Figure 9 Optimized results for the amount of europium placed into the adjacent and end pellets within, a) the center fuel element, b) an inner fuel element, c) an intermediate fuel element, and d) an outer fuel element

When comparing the results for the doped fuel bundle to the non-doped, it is apparent that by adding specific amount of europium can successfully mitigate EFP, but not to eliminate it. This is due to the fact that the structural material remains the same so there will still exist some peaking regardless of the amount of europium placed into the fuel pellets. As mentioned prior the amount of europium needed in the end pellet is larger than the amount in the adjacent pellet. Also, since the EFP is different in each fuel ring, the amount of europium added to the elements in each ring is different. The largest amount of europium being added is to the center element and the smallest amount being added is to the fuel elements in the outer ring. This is expected since the peaking factor is largest for the center element and decreases radially towards the outer elements, as shown in Table 1.

4. Conclusion

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 various locations in which the absorbing material was investigated and both the optimal location and concentration of absorbing material was determined. A model using MCNP 6.1 was developed and used to simulate the addition of a small amount of neutron absorbers strategically within a CANDU fuel bundle. Two important conclusions derived from this work. The first conclusion being that the addition of neutron absorbers affect the flux profile even in small quantities. The second conclusion is that based on certain criteria the optimal location and amount of absorber can be determined through the use of various optimization techniques. Even though endplate alloyed with absorbing material could provide the best mitigation potential there exist several concerns with this method of implementing absorbers into the fuel bundle. Therefore, the optimal technique chosen was by doping the adjacent and end pellets, with various amounts of europium oxide depending on which ring the fuel element belonged too. This change would have significant changes to the natural uranium fuel manufacturing system and increasing the cost of fuel bundles, design study is on-going at RMCC as a project funded by COG and NSERC.

6. References

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