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Modeling and mitigation of bundle end power peaking in pressure tube heavy water reactor advanced fuels using thorium dioxide

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ABSTRACT

Fuel bundle end power peaking in pressure tube heavy water reactors (PT-HWRs), particularly considering advanced reactor fuels (such as thorium-based fuels), was evaluated and a mitigation method was assessed. For bundles containing all the same fuel pellets, power is greatest at the bundle ends due to higher thermal neutron flux there. A method to achieve a flatter axial power profile along a bundle by downblending the fissile content in the end pellets with thorium dioxide was evaluated. The method was shown to be effective, and only a slight reduction in fresh fuel reactivity was observed.

1. Introduction

Pressure tube heavy water reactors (PT-HWRs) (International Atomic Energy Agency, 2002) are refueled online, and they have high neutron economy due to the use of heavy water moderator and coolant. These properties make PT-HWRs well suited for exploiting the energy potential in natural uranium and in various types of advanced nuclear fuels, including thorium-based fuels (Bromley, 2014). PT-HWRs, such as CANDU reactors, typically use a dozen short fuel bundles (~50 cm long each) in each fuel channel to enable partial online refueling of each channel. Each fuel bundle is a separate assembly, completely enclosing the fuel with cladding and having endplates to hold all of the fuel elements in place. The end caps and end plates at bundle ends, when placed end-to-end in a reactor's fuel channel, cause regions of high thermal flux between fuel bundles due to a lack of fuel there to absorb those neutrons. The high thermal neutron flux at the ends of fuel bundles causes the power in the fuel to peak at the bundle ends. Thus, the power in the fuel at the ends of bundles is the most limiting in terms of allowable fuel power density.

A method to mitigate the end power peaking of fuel bundles in pressure-tube heavy water reactors is considered, with a focus on the application to higher-burnup thorium-based fuels. As the fissile content of fuel increases, as would be required to increase burnup, the end power peaking effect becomes more pronounced. Hence, mitigation of end power peaking becomes more important for high-burnup fuels.

2. Methodology

To reduce end power peaking in fuel bundles, the relative amount of fission occurring at the bundle ends must be reduced. One option for reducing the fission rate at the bundle ends is to add neutron absorbers to the end pellets, as was investigated previously by (Pierce et al., 2015). Neutron absorbers however have the downside of having non-productive neutron captures, reducing the reactivity of fuel and achievable burnup. Another option is to reduce the fissile content of the end pellets by mixing with non-fissile material (downblending). As the focus of this work has been to enable advanced thorium-based fuels, it was decided to use thorium to reduce the fissile content. Thorium is also a weak neutron absorber, breeding ^{233}U as the fuel is burned; hence, blending thorium into the end pellets also has the benefit of increased late bundle reactivity.

To evaluate how effective thorium would be in mitigating end power peaking, computational fuel bundle models were simulated with MCNP5 (X-5 Monte Carlo Team, 2003). Specifically, MCNP5

Abbreviations: PT-HWR, pressure tube heavy water reactor; NUO_2, natural uranium dioxide; RUO_2, recycled uranium dioxide; $SEUO_2$, slightly enriched uranium dioxide; $(^{233}U, Th)O_2$, uranium-233/thorium mixed oxide; $(LEU, Th)O_2$, low-enriched uranium/thorium mixed oxide; $(Pu, Th)O_2$, plutonium/thorium mixed oxide; ThO_2, thorium dioxide.

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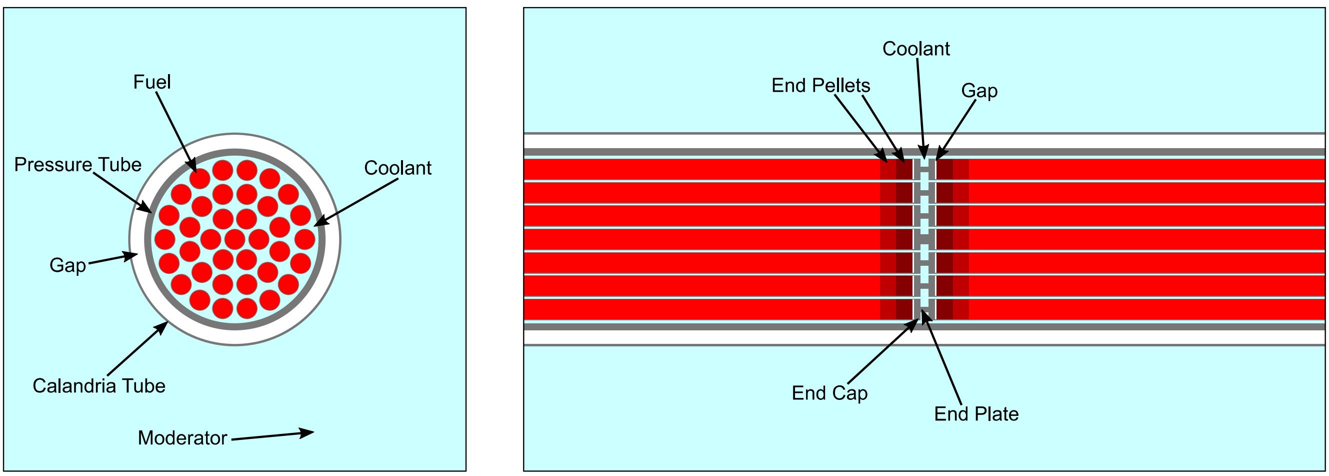
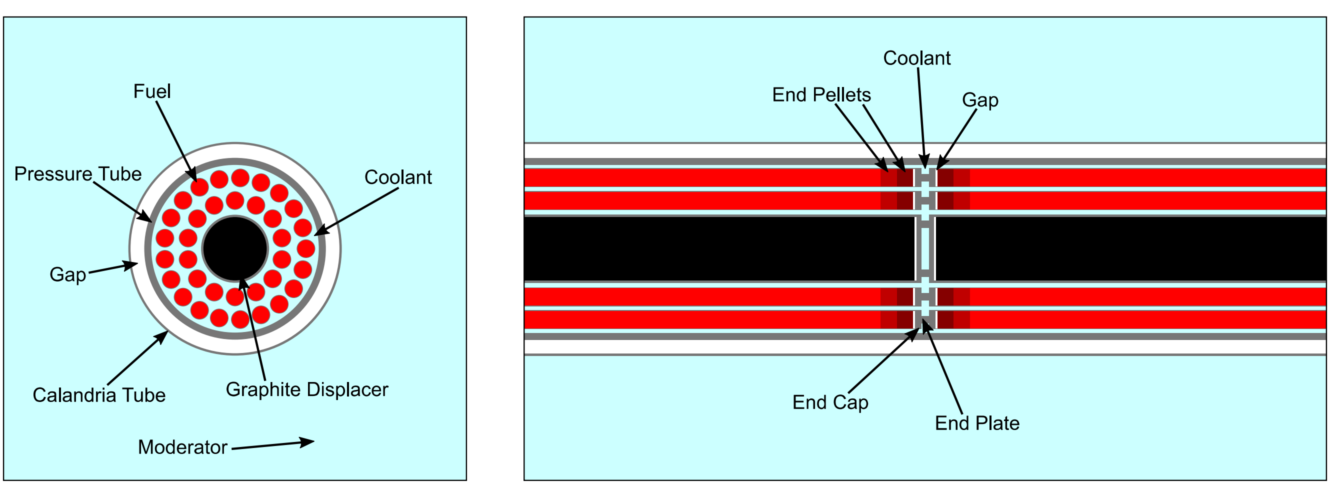
1.40 with internally generated nuclear data based on ENDF/B-VII.0 (Altiparmakov, 2010) was used. The models consisted of one lattice element with reflective boundary conditions—effectively an infinite lattice. Two geometrically differing bundle concepts were used: a 37-element bundle similar to existing CANDU-type bundles, and a conceptual 35-element bundle with a central graphite displacer. The remainder of the lattice site remained the same between the two bundle concepts, with a pressure tube and calandria tube similar to that of existing CANDU reactors. The two bundle types are depicted within lattice sites in Fig. 1 and Fig. 2 for the 37-element bundle and the 35-element bundle, respectively. The fuel discontinuity along the channel that gives rise to end power peaking is clearly visible in both figures. For both bundle types, the end plates, which hold the elements in place, were approximated as annuli, maintaining the same volume as the corresponding detailed end plate construction. The single-element fuel stack volume was 56.17 cm^3 for the 37-element bundle and 42.40 cm^3 for the 35-element bundle. Additional details for materials and dimensions can be found in (Colton et al., 2017). From the outside of each bundle, the rings of fuel elements are denoted as outer, intermediate, inner (if applicable), and center (if applicable).

Six different bundles types were selected for this work; the seven fuel types used in those bundles are presented in Table 1. Natural uranium dioxide, NUO_2, recycled uranium dioxide, RUO_2 (0.95 wt% $^{235}U/U$), and slightly enriched uranium dioxide, $SEUO_2$



(a) Slice Through Fuel Channel (b) Slice Along Fuel Channel

Fig. 1. The lattice cell with a 37-element bundle. Perpendicular to the fuel channels, the lattice is square with a pitch of 28.575 cm. In the axial direction, bundles are 49.53 cm long. In (b), the junction of two half-bundles is shown; the angular offset of each ring of elements has been removed for clarity.



(a) Slice Through Fuel Channel (b) Slice Along Fuel Channel

Fig. 2. The lattice cell with a 35-element bundle. Perpendicular to the fuel channels, the lattice is square with a pitch of 28.575 cm. In the axial direction, bundles are 49.53 cm long. In (b), the junction of two half-bundles is shown; the angular offset of each ring of elements has been removed for clarity.