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A scenario analysis of once-through thorium fuel cycles with pressure tube HWRs in Canada

D. Wojtaszek *, A.V. Colton, B.P. Bromley, G.W.R. Edwards, A. Levinsky

Canadian Nuclear Laboratories, 286 Plant Road, Chalk River, ON K0J 1J0, Canada

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A B S T R A C T

Thorium-based fuel cycles offer many potential benefits, including greater long-term energy sustainability and improved waste management, relative to uranium-based fuels. The purpose of this study was to analyze the potential impacts associated with deploying thorium-based fuels in Pressure Tube Heavy Water Reactors (PT-HWRs) in a once-through fuel cycle in Canada, and to compare them with the use of conventional Natural Uranium (NU) fuel. This study analyzed a medium-burnup (~19.1 MWd/kg) Slightly Enriched Uranium-based fuel augmented by small amounts of thorium (SEU + Th) and a high-burnup (~40.6 MWd/kg) fuel made with Low Enriched Uranium mixed with thorium (LEU/Th).

The deployment of the medium-burnup SEU + Th in Canada reduced resource consumption by 23% relative to the low burnup NU fuel. The medium-burnup fuel required 3% to 60% fewer Deep Geological Repository (DGR) Used Fuel Containers (UFCs) relative to the low burnup fuel, depending on the decay time (10–70 years) of the Used Nuclear Fuel (UNF). Extending the decay duration of UNF decreases its decay power per unit mass, and hence the required number of DGR UFCs per mass of UNF, at the expense of requiring more above-ground dry storage capacity.

1. Introduction

Thorium-based fuel cycles offer many potential benefits, including greater long-term energy sustainability and improved waste characteristics, relative to pure uranium-based fuels (IAEA, 2005). Pressure-Tube Heavy Water Reactors (PT-HWRs), (see Fig. 1) are well-suited to exploit the energy potential in thorium-based and thorium-augmented nuclear fuels due to their fuel irradiation flexibility and high neutron economy (IAEA, 2002).

The purpose of this study was to analyze the potential impacts (such as impacts on resource utilization and long-term storage of spent fuel) associated with deploying a number of thorium/uranium fuel concepts in PT-HWRs in a once through fuel cycle, instead of using Natural Uranium (NU) fuel. The fuels that were analyzed are listed below.

- Reference low-burnup, ~7.2 MWd/kg Initial Heavy Elements (IHE), natural uranium oxide (NU) fuel.
- Medium-burnup, ~19.1 MWd/kg IHE. fuel composed of 1.2 wt% $^{235}U/U$ slightly enriched uranium (SEU) oxide combined with small amounts of thorium oxide (95 wt% SEU, ~5 wt% Th), (SEU + Th).
- High-burnup, ~40.6 MWd/kg IHE, fuel composed of 5.0 wt% $^{235}U/U$ low enriched uranium (LEU) oxide mixed with thorium oxide (~50 wt% $LEUO_2$, ~50 wt% ThO_2), (LEU/Th).

Each scenario involves the gradual deployment of one of the above fuels in a fleet of PT-HWRs with a nominal capacity of approximately 13,512 MWe, which is equal to that of all PT-HWRs in Canada in 2014 (Garamszeghy, 2014). It is assumed that all Used Nuclear Fuel (UNF) will be placed in a Deep Geological Repository (DGR). The postulated DGR for storing thorium-based UNF is modelled based on the Canadian DGR concept for all PT-HWR UNF in Canada (CTECH, 2002). UNF is placed in dry storage if, upon being removed from wet storage, it cannot be immediately loaded into the DGR.

The fuel cycle parameters that were analyzed include:

- NU, thorium, and enrichment requirements to produce fuel;
- Radioactivity of UNF;
- UNF wet and dry storage capacities; and
- DGR loading.

* Corresponding author.
E-mail address: daniel.wojtaszek@cnl.ca (D. Wojtaszek).

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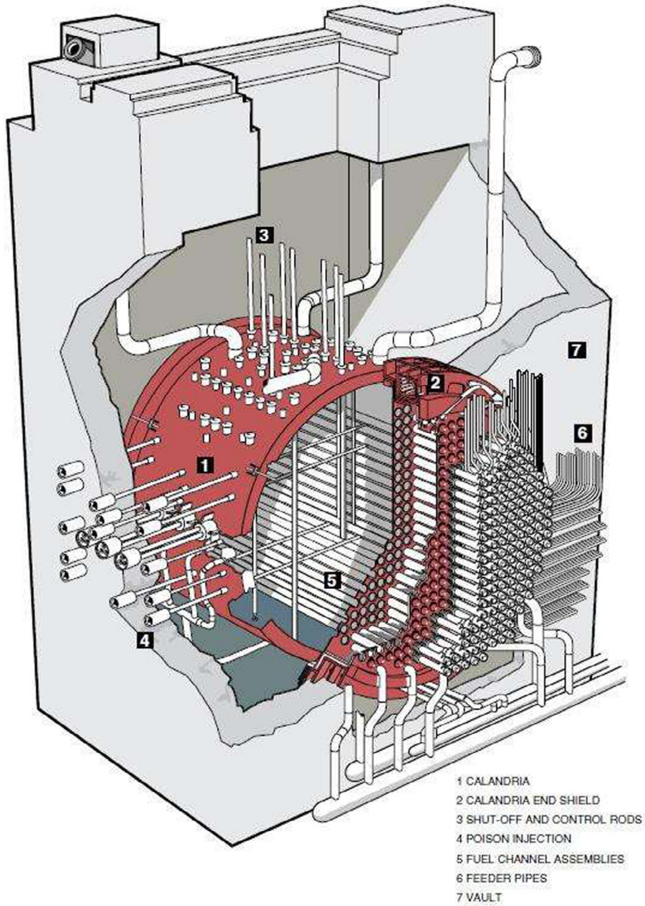

Fig. 1. Illustration of a Pressure Tube Heavy Water Reactor (from IAEA, 2002).

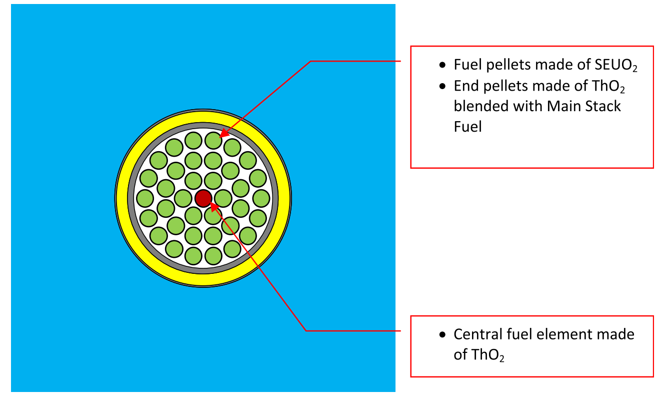

Fig. 2. BUNDLE-37 Fuel Bundle for Med-SEU + Th.

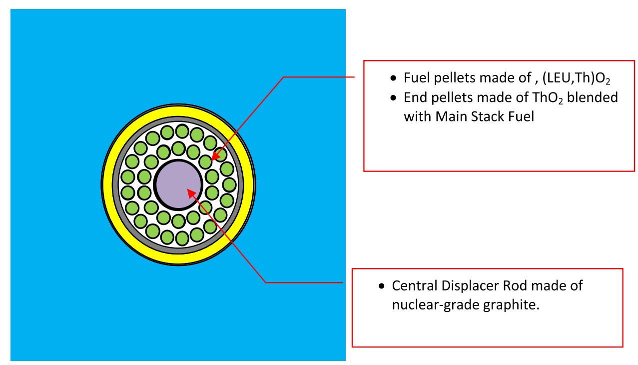

Fig. 3. BUNDLE-35 Fuel Bundle for Hi-LEU/Th.

2. Fuel concepts

The PT-HWR fuel concepts studied in this work have two possible fuel bundle geometries. The standard BUNDLE-37 geometry consists of a 37-element fuel bundle with uniformly sized cylindrical fuel elements that comprise the four fuel rings (1/6/12/18) in a cluster geometry (see Fig. 2). This type of fuel bundle geometry is being used in currently operating PT-HWRs The BUNDLE-35 geometry consists of a 35-element bundle with uniformly sized cylindrical fuel elements divided into two fuel rings (14/21) surrounding a large central graphite displacer rod (see Fig. 3). Both fuel bundle types have fuel sheaths made of Zircaloy-4, and every fuel studied is in oxide form (NUO_2, $SEUO_2$, ThO_2, $(LEU,Th)O_2$).

The first lattice concept, Low-NU, is a pure NU fuelled bundle with BUNDLE-37 geometry.

The second lattice concept studied, Med-SEU + Th, is SEU (1.2 wt% $^{235}U/U$) with BUNDLE-37 geometry and some fuel heterogeneity. The SEU enrichment was chosen due to the results of a prior study (Boczar et al., 1988), which found that a pure SEU fuel that is enriched to 1.2 wt% resulted in the lowest NU consumption in a PT-HWR. The Med-SEU + Th bundle has a central fuel element that is made up entirely of thorium with the intent of reducing coolant void reactivity (CVR) and of breeding ^{233}U. Each of the other fuel elements contains SEU and thorium, where 3 cm of the fuel at each end of these elements contains thorium blended with SEU, and the remainder contains pure SEU. Thorium is used to axially grade the fissile concentration in the end regions to help mitigate the effects of axial power peaking due to higher flux near the ends of each fuel bundle. The thorium used in the end region of the Med-SEU + Th bundles is approximately 2% of the volume in each fuel element.

Lattice concept Hi-LEU/Th is composed of LEU (5 wt% $^{235}U/U$) mixed with thorium with a total composition of ~50 wt% UO_2, ~50 wt% ThO_2 using the BUNDLE-35 geometry. The LEU enrichment and the proportion of LEU and Th in this fuel was chosen based on prior experience to achieve a high burnup. Similar to the Med-SEU + Th fuel, the Hi-LEU/Th fuel uses additional thorium to axially grade the fissile concentration in the last 3 cm at each end of the fuel stack in the fuel bundle, in order to reduce axial power peaking due to end flux peaking. The added thorium in the end regions amounts to approximately 4.2 vol% of the fuel in each fuel element. Specific details on the PT-HWR lattice design and operating conditions, as well as the fuel bundle materials and geometry can be found in earlier studies (Colton et al., 2017).

Table 1 shows data for each fuel concept that is relevant to this study. The total reactor thermal power of the Low-NU concept was less than the other concepts due to the absence of reactivity control devices, which are used to help achieve several safety and performance targets set for the full core analysis, in the full core model for each concept. These safety and performance targets included maximum bundle power, maximum channel power, maximum number of fuelling operations per day and the target k-effective value. In the case of Low-NU fuel, de-rating the core power was required to stay within full core analysis safety targets as described in prior studies (Colton and Bromley, 2016), whereas this was not required for the fuels that include thorium.

3. Scenario parameters and assumptions

Three scenarios were analyzed in this study, each being identical to the others except for the fuel concept being deployed. Each scenario involved the deployment of one of the fuel concepts in a