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Thorium as an additive for improved neutronic properties in boiling water reactor fuel

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ABSTRACT

This article treats the replacement of burnable absorbers with a fertile absorber in boiling water reactor fuel. The target is to improve the fuel economy while meeting the same safety demands as the currently used conventional uranium oxide (UOX) fuel. A candidate fertile absorber is Th-232, and this work investigates the impact of replacing part of the U-238 in UOX fuel with Th-232.

Computer simulations have been carried out and comparisons made for fuel assemblies with fertile and burnable absorbers, loaded in the boiling water reactor Oskarshamn 3, using the tools and methods that are normally employed for reload design and safety evaluation for this reactor. The results show that power balance and shutdown margins can be improved at the cost of higher enrichment needs. Alternatively, the fuel can be designed to just fulfil the relevant safety criteria, giving slightly lower uranium needs, which may compensate for the increased enrichment costs.

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1. Introduction

The objective of the work described herein is to investigate how thorium can be used to replace part of the U-238 and burnable absorbers in normal uranium oxide (UOX) fuel assemblies in a boiling water reactor (BWR). As will be described in Section 2.2, thorium can in this context only be used as a minor component in the fuel, i.e. as an additive. We therefore choose the term *thorium additive* (Th-Add) to describe this fuel type. Given the small amount of thorium used (approximately 10% on assembly average, and maximum about 40% in a few rods per assembly), the impact on the core dynamics and most thermal–mechanical properties of the fuel is small.

We here present and discuss the simulation of a standard BWR fuel assembly loaded with Th-Add fuel, and of a core loaded with such fuel. The fuel assembly design is developed using the fuel assembly burnup simulation program CASMO (Rhodes et al., 2009, 2007) and the core simulations are carried out with SIMULATE-3 (Dean, 2007.) As a reference, we also simulate a normal UOX fuel assembly and reactor core. The Th-Add assembly and the reference assembly are designed to release the same amount of energy, i.e. the cycle length, core power and number of loaded fuel assemblies are kept unchanged.

The objective of the nuclear design of BWR fuel and core is to optimize the fuel economy while fulfilling the necessary safety requirements. Burnable absorbers (BA) are used in order to fulfil the demands on power distribution and shutdown margins (SDM) at the cost of a worse fuel economy, so the BA usage is minimised under the strict condition that the safety requirements are fulfilled. By using thorium, these safety parameters can be improved and BA usage reduced, which however leads to an increased need of uranium enrichment.

The optimization of a nuclear fuel assembly design is complex, partly due to the large number of parameters that can be varied (the uranium enrichment and burnable absorber content of each fuel pin) and partly due to the many demands that must be fulfilled (e.g. reactivity, SDM, power distribution). The same is true for core loading patterns. At commercial power plants, these processes are normally conducted by skilled and experienced core physicists. Several attempts have been made at designing algorithms for the optimization of fuel assembly designs (e.g. Lin and Lin, 2012; del Campo et al., 2007) and core loading patterns (e.g. Rahmani, 2017; del Campo et al., 2009), however the design still requires much craftsmanship to be acceptable for use. Thus, the design processes in this work are carried out manually.

Assuming that the current demands on power distributions and SDM warrant safe core operation, there is no need to design a fuel assembly for achieving higher margins. The Th-Add fuel assembly design is therefore designed to give the same safety performance

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as the reference assembly, thus targeting improved fuel economy instead of increased margins. This also facilitates comparison of Th-Add with the UOX reference, since all the different properties of the fuel assembly are kept constant, allowing for a direct comparison of reactor feedback parameters, fuel economy and power distribution.

The use of thorium as a fertile absorber has previously been investigated for pressurized water reactors (PWR) (Lau et al., 2012, 2014, 2013; El-Sheikh et al., 2010), and the use of thorium in initial VVER cores has been modelled (Dwiddar et al., 2015), but to our knowledge, this manner of using thorium as an additive in BWRs has not yet been investigated.

The fuel assembly design and the simulated reactor system are described in Section 2 and the calculation tools used in this study in Section 3. The results in terms of depletion behaviour and neutronic safety parameters are presented in Section 4 and conclusions are drawn in Section 5.

2. Description of the modelled system

2.1. Reactor

The reactor simulated in this study is the Swedish Oskarshamn 3 reactor, which is a 3900 MW_{th} BWR, operating with one-year cycles. In the reference case, which is a typical operation cycle, the Oskarshamn 3 core is loaded with 150 fresh fuel assemblies. The core design is shown in Fig. 1 and the fuel assemblies will be discussed in more detail in Section 2.2.

2.2. Fuel assemblies

The reference fuel is a UOX fuel assembly designed for a standard 12-month cycle in Oskarshamn 3, which requires an average enrichment of 3.9%. The assembly comprises 96 fuel rods, arranged in a standard 10-by-10 lattice with a water cross and a central moderator channel for improved neutron moderation, as shown in Fig. 2. As is normal for a BWR fuel assembly design, pins closer to the water-filled inter-assembly gaps and moderator channels have a lower enrichment in order to compensate for the higher thermal neutron flux in these parts of the fuel assembly. Eight rod types with different fuel composition are used in the present UOX reference design for achieving an even power distribution.

Gadolinium (Gd) in the form of Gd_2O_3 is used as a burnable absorber in each assembly to reduce the reactivity of the fresh fuel assemblies, thus improving power balance and SDM. The Gd is distributed in eight rods with 5.5 wt% Gd_2O_3 and three rods with 4.5 wt% Gd_2O_3. The reference fuel design is shown in Fig. 2.

The Th-Add fuel assembly design uses the same mechanical structure as the reference fuel, but the uranium oxide fuel is exchanged for a mixture of uranium and thorium oxides. The fuel assembly design strategy is to let the amount of U-235 in each fuel rod remain the same in the Th-Add assembly as in the UOX refer-

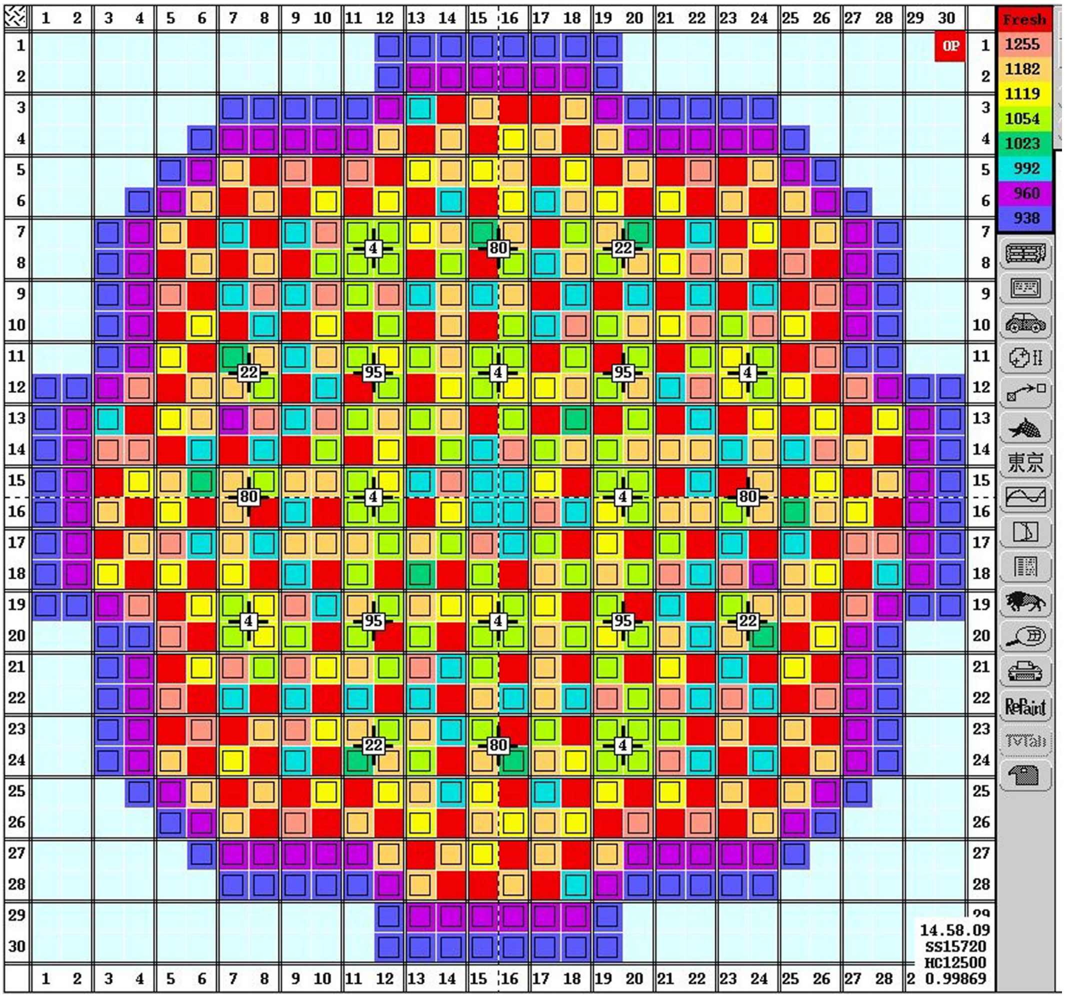

Fig. 1. The UOX reference core. Fresh fuel assemblies are red/dark grey with no square. Other assemblies are colour coded, according to the legend in the top right corner of the image, where the numbers denote $k_\infty \cdot 1000$ of the assembly, i.e. lower numbers denote older and less reactive assemblies. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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