Chapter 6: Koeberg case study

"No one who cannot rejoice in the discovery of his own mistakes deserves to be called a scholar."

~ Unknown ~

Overview

A case study is done to investigate the possibility of extending fuel cycle length by using thorium-based fuels in the plant Koeberg, the only two PWRs in South Africa. Preliminary calculations show that thorium-based PWR fuel could extend fuel cycles from 18 months to 24 months. The calculations have been carried out to determine initial fissile content and fractions of the components for the thorium-based fuels using the fuel assembly burnup simulation program CASMO-5.

6.1 Introduction

19,9% Enriched U^{235} and plutonium recycled from spent PWR fuel are blended with thorium to form homogenous mixed oxide pellets. The amount of fissile material was chosen to reach a discharge burnup of around 57MWd/kgHM, the same as Koeberg.

A PWR fuel assembly filled with Th/Pu- and Th/U fuel is simulated under normal PWR conditions of Koeberg, using the fuel assembly burnup simulation programme CASMO-5. CASMO-5 presents accurate evaluations of burndown performance and estimations of changes in the neutronic safety limits.

6.2 The modelled system

6.2.1 Reactor specifications

The PWR in South Africa, Koeberg, was used to model the reactor geometry to study the behaviour of thorium-based fuels. The operating parameters, which are used in this study, are shown in Table 6.1.

Table 6.1 Reactor properties of Koeberg

Parameter	Value	Unit
Thermal power output	2 785	MWth
Reactor pressure	15,5	MPa
Power density	102,8	kW/dm^3
Coolant temperature	296	°C
Average fuel temperature	600	°C

6.2.2 Fuel assembly geometry

The UOX Koeberg fuel assembly with 18-month cycle has been chosen as the reference. It contains 264 fuel pins, organised in a 17x17 lattice, of which 12 contain GdO3 and ZrB2 as burnable absorbers.

Table 6.2 Fuel assembly properties

Parameter	Value	Unit
Number of fuel assemblies in the core	157	-
Cladding thickness	0,57	mm
Fuel-cladding gap	0,017	cm
Fuel assembly pitch	21,504	cm
Lattice pitch	1,26	cm

6.2.3 Fissile components

Thorium is mixed with 19.9% enriched U^{235} for the Th/U fuel option. It is noted that current enrichment plants mainly operate with a licence for up to 5% enrichment. To obtain large

quantities of 19.9% enriched U^{235} may be more challenging. Thorium is mixed with recycled plutonium, extracted from spent uranium fuel. The Pu isotope vector used to calculate the Th/Pu fuel was: 2% Pu^{238}, 53% Pu^{239}, 25% Pu^{240}, 15% Pu^{241} and 5% Pu^{242}. This vector corresponds to LWR spent fuel with a burnup of around 42MWd/kgHM (WNA, 2011b).

6.3 Method

The fraction of the fissile material (Pu or 19.9% enriched U) was adjusted in CASMO-5 until the simulation gave a k_∞ curve corresponding to a 24-month cycle length. The calculations assumed a 30-day reload period.

6.3.1 Neutronic simulation software

The calculations are carried out in 2D, using CASMO-5 (Rhodes *et al*., 2007). CASMO-5 is a multi-group two-dimensional transport theory code, mostly used to perform fuel assembly depletion calculations and to compute homogenized cross-sections for subsequent input to 3D core simulators. The cross-section library used in this study is ENDF-B VII. The calculations omit neutron leakage or spectral interactions between assemblies.

6.3.2 Total energy release

The total energy released from a fuel assembly during its lifetime is the product of its mass M and its discharge burnup D_B. The total energy release required from each fuel assembly during its lifetime can be calculated according to Equation 6.2.

$$E_{tot} = M * D_B = \frac{P_{th} * t_c * n}{N} \tag{6.2}$$

Different fuel types have different densities, and as the same fuel assembly geometry is used in each case, this implies that they also have different total fuel mass per assembly. Lighter fuel types need to be designed to reach a marginally higher discharge burnup, to reach to same total energy release. The discharge burnup for a certain fuel design is calculated from k_N, which is given in the CASMO-5 output data, with the linear reactivity model (Graves, 1979).

6.4 Results

2D lattice calculations with CASMO-5 were performed and are presented in this section.

6.4.1 Initial fissile content

The initial fissile content for each thorium-based fuel was calculated to produce the same energy as the reference UO_2 assembly in Koeberg. The resulting fuel compositions are given in Table 6.2. The natural uranium requirements are higher in the Th/U case than with LEU. No uranium savings can be achieved for the Th/U case, under assumed discharge burnup limits.

Table 6.3 Calculated isotopic compositions of fuels

	$(Th,Pu)O_2$	**$(Th,U)O_2$**	**UO_2**
Th^{232}	87%	63,11%	-
U^{233}	-	-	-
U^{235}	-	7,34%	4,95%
U^{238}	-	29,55%	95,05%
Pu^{239} & Pu^{241}	8,83%	-	-
Pu^{238} & Pu^{240} & Pu^{242}	4,16%	-	-

The calculated composition values for the Th/Pu correspond to other examples in literature (Bjork, 2012). The composition values for Th/U differ from those in literature, specifically the high uranium fraction in the fuel (37%). Other studies reported uranium (enriched to 19,9%) fractions between 25% and 35% (Herring *et al*., 2001). The higher uranium fraction demands more natural uranium, which means that there are no uranium savings. The difference can be ascribed to different simulation programs, different fuel assembly geometries and different cross-section libraries used.

6.4.2 Infinite multiplication factor

The infinite multiplication factor calculated at hot, full-power conditions and its change with time is shown in Figure 6.1. In the Th/U, Th/Pu cases, k_∞ decreases rather slowly with burnup, making it possible to reach the discharge burnup demanded in each case without having a high k_∞ at BOL. The use of burnable absorbers in both these cases is no longer required.

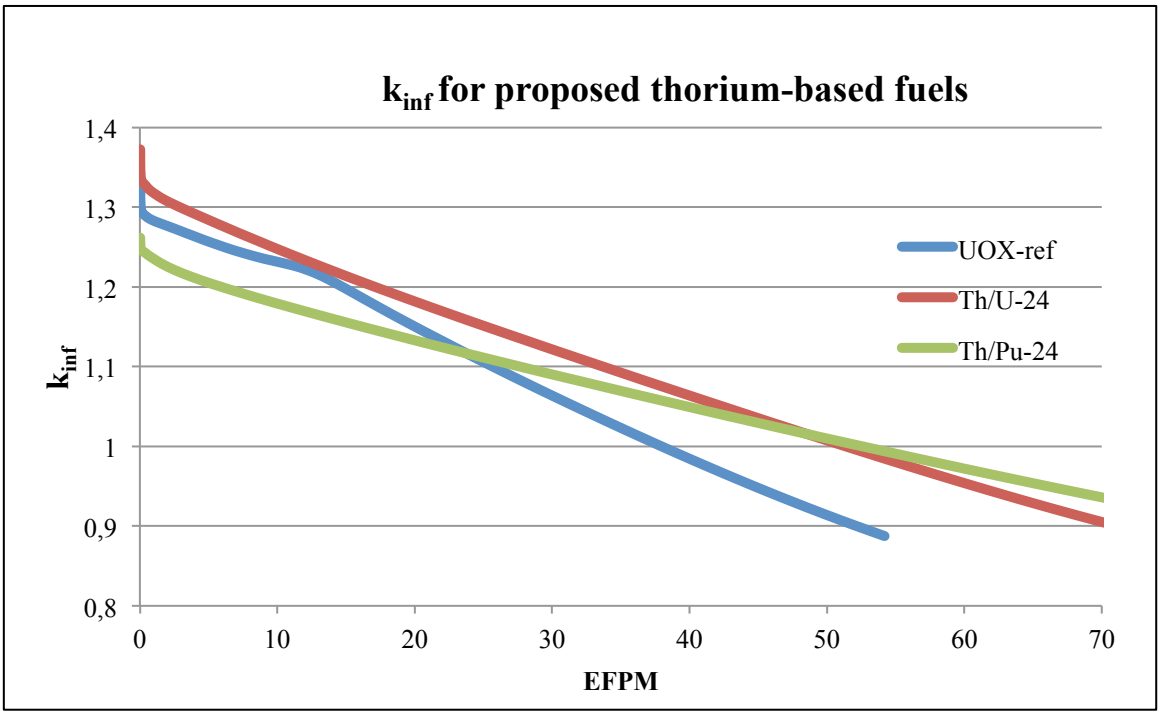

Figure 6.1 k_∞ vs effective full power months for thorium-based fuels and UOX

Th/Pu requires less excess reactivity, because k_∞ decreases more slowly in this case. K∞ decreases more slowly due to the fact that the optimal hydrogen-to-heavy-metal ratio is higher for Th/Pu than for the other two fuel cases. The fuel assembly design used for this calculation, results in a hydrogen-to-heavy-metal ratio further away from the optimal for the Th/Pu case. This results in more conversion of Th^{232} to U^{233} and less fissions, which explains the slower decrease.

The slight bump in the blue line near 10 months is a change in the rate at which k_∞ decreases. The reason why k_∞ has a slower decrease before the bump is that a burnable absorber (BA) is used, for the UOX case. This BA lowers k_∞ by absorbing neutrons, but burns out in the process, and around 10 months the BA is gone and k_∞ starts decreasing, as it would have without BA.

6.5 Conclusions

Thorium was combined with fissile components (Pu or 19.9% enriched U) to see whether Th/U fuel and Th/Pu fuel could reach a 24-month cycle and whether the calculated fuel fractions correspond to other values in literature. The calculated composition values for the

Th/Pu correspond to other examples in literature. The uranium fraction for Th/U fuel is higher than reported in literature.

Results indicate that thorium-based fuels (Th/U & Th/Pu) improve the economy of a nuclear power plant by allowing for longer operating cycles and hence a higher availability of the reactor. The slow depletion of Th/Pu and Th/U makes it possible to achieve high burnups without having an excessively high initial multiplication factor. Mixing reactor-grade plutonium with thorium yields a neutronic performance very similar to corresponding MOX.

It was concluded that it is challenging to achieve natural uranium savings by mixing 19,9% U^{235} with thorium and that mixing reactor grade plutonium with thorium leads to more effective Pu consumption than MOX fuel.