

Chapter 3: Technical evaluation

“For your thought about something is creative, and your word is productive, and your thought and your word together are magnificently effective in giving birth to your reality...”

~ Mariaan Kotzé ~

Overview

The different thorium-based fuel designs for PWR cores are discussed and resulting difficulties and solutions are given. These suggestions are compared and critically evaluated (in terms of advantages and disadvantages). A process of elimination selects the best option for each strategy and results in combination of mitigation and optimisation strategies that will form a starting point for the roadmap.

3.1 Fuel options

Different fuel designs on thorium-based fuels exist, depending on the shape and arrangement (section 3.1.2) of material and the type- and concentration of the fissile element (section 3.1.3). This section discusses the proposed thorium-based fuel designs, specifically inside PWR cores. Note that ThC_2 fuels (pebbles or blocks) also have been used in HTRs, but are not discussed in this section. All the fuels discussed in this section are in the form of oxides. The different thorium-based fuel designs for PWR cores are discussed and resulting difficulties and solutions are given.

3.1.1 Introduction

Due to the fact that naturally occurring thorium only consists of a fertile Th^{232} isotope, one needs to add a fissile component to sustain the nuclear chain reaction. The options for fissile

isotopes are U^{233} , U^{235} , Pu^{239} and Pu^{241} . Thorium-based fuel, for instance $(Th/U^{233})O_2$, $(Th/U)O_2$ or $(Th/Pu)O_2$ (also called TOX), can be used as fuel in unmodified PWRs without negatively influencing the safety features (Schram & Klaasen, 2007). Natural or depleted uranium can be added to any of these fuel options to reduce the weapons material attractiveness of the spent fuel (Waris *et al.*, 2010). The U^{233} is denatured (Puill, 2002) and the spent fuel will be very difficult to chemically separate (IAEA, 2012)

Some modifications are necessary for present LWRs to increase core loading above 33.3% $(Th/Pu)O_2$, to meet reactivity safety limits, but this is also the case with MOX fuel (Trellue *et al.*, 2011). Most modern reactor designs that are capable of using 100% MOX should therefore be capable of using TOX to the same extent (Bjork, 2012). A previous study on the possibility of loading a core with 100% MOX fuel PWRs proved that 100% MOX is possible. With only minor changes, such as the addition of more water rods or the decrease of the fuel pin diameter, 100% MOX is possible. These modifications ensure a highly moderated fuel design, which increases the fissile plutonium consumption rate, within the safety limits (Francois *et al.*, 2002).

Thorium fuel types demonstrate notably higher conversion rates compared with UO_2 -fuel, which allow efficient fuel utilization in a PWRs (IAEA, 2012). Reactors using thorium-based fuel present more stable reactivity (k_{eff}) during long irradiations than in UO_2 , due to the constant thorium conversion to U^{233} (Herring *et al.*, 2001).

Figure 3.1 represents some proposed thorium-based fuels with extended cycles (24-month), due to a more uniform k_{∞} . The red line represents current uranium-only fuel cycles, which starts with a large excess reactivity in the BOC and quickly decreases below 1 (k_{∞}). One can also extend the uranium-only fuel cycle to 24 months, but this will imply shifting the red line much higher. To shift the red line upwards means starting with higher enrichment and more burnable absorbers. All the other lines are thorium-based fuels and show more a slowly decreasing k_{∞} (Bjork, 2012).

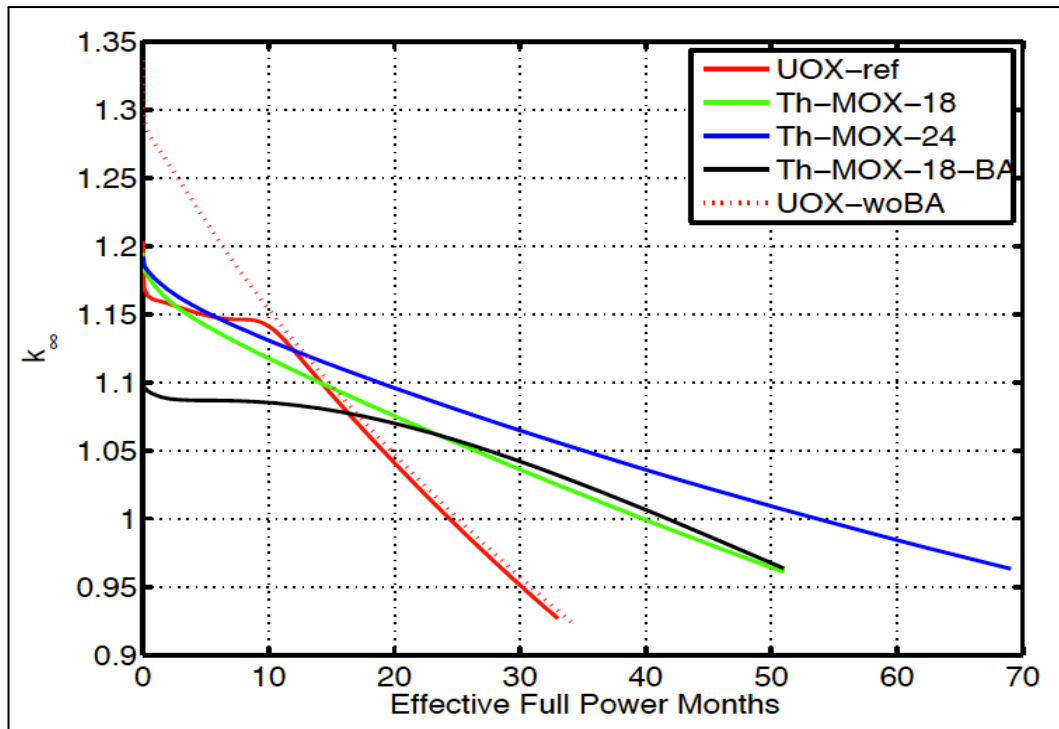


Figure 3.1 K_{∞} vs. effective full power months for uranium and thorium-based fuels (Bjork, 2012)

3.1.2 Geometry

Thorium-based fuel can occur in two forms in a reactor core: discrete (heterogeneous) or integral (homogeneous). Discrete can be discrete fuel rods and/or discrete fuel assemblies. Thorium may exist within its own assemblies (discrete) in portions of the core (like in a blanket). Based on a previous investigation, the discrete design is not beneficial in terms of fuel conversion and breeding. The reactivity of the discrete fuel is extremely low in the beginning, and it will therefore present challenges in controlling the power distribution (Si, 2009).

Seed-blanket assemblies exhibit several thermal design issues that need attention. The seed is highly loaded, which will increase the power density. Using metallic fuel in the high energy density region reduces the thermal energy stored in the fuel and enhances the safety response (Kazimi *et al.*, 1999). Seed-blanket designs show hot spots and thermal properties difficulties (Waris *et al.*, 2010). Seed-blanket assemblies are more complicated to insert and would require some core modifications.

Integral means thorium is homogeneously scattered or mixed with other fissile isotopes, which results in identical composition fuel. Homogeneous thorium-based fuel enhances the breeding of U^{233} , which in turn simplifies the control of the core power distribution (Si, 2009). There seem to be no reports on problems with homogeneous fuel assemblies. The seed-blanket design will be eliminated as a thorium-based fuel option, due to the prevailing thermal design issues. Homogeneous, identical composition, integral thorium-based fuels look the most promising and are the choice for further consideration.

The performance of thorium in tighter pitch fuel lattices and intermediate neutron spectra was investigated, to enhance discharge burnups and cycle lengths, while saving enrichment requirements (Kim & Downar, 2001).

The hydrogen to heavy metal ratio (H/HM) is adjusted by changing the water density in the cell (Weaver & Herring, 2002). Water holes can also be added to increase the H/HM ratio (Trellue *et al.*, 2011). It was also proposed to modify the fuel assembly by increasing the fuel rod thickness resulting in a decreased H/HM ratio (Bjork, 2012). Annular fuel pellets containing burnable poison in the central zone were suggested to reduce the beginning of cycle (BOC) reactivity (Xu, 2003).

3.1.2 Composition

Thorium is mostly mixed with uranium (U^{233} & U^{235}) and plutonium (Pu^{239} & Pu^{241}). The different combinations are discussed in the following section.

3.1.2.1 (Th/U)O₂

Fertile thorium is mixed with enriched uranium (U^{235}). The amounts of fertile thorium and enriched uranium can vary depending on burnup requirements, fuel cycle lifetimes and enrichment constraints. For this study the enrichment is limited to less than 20% enrichment in U^{235} to adhere to the LEU anti-proliferation limit (Weaver & Herring, 2002). The enrichments can also vary depending on the core pattern loading, and if seed-blanket assemblies are used. The uranium used in mixed (Th/U)O₂-fuel is more highly enriched, but the total UO₂ content is only 25–35% of the total composition (Herring *et al.*, 2001). Figure 3.2 shows the composition of a typical homogeneous (Th/U)O₂-fuel for PWRs.

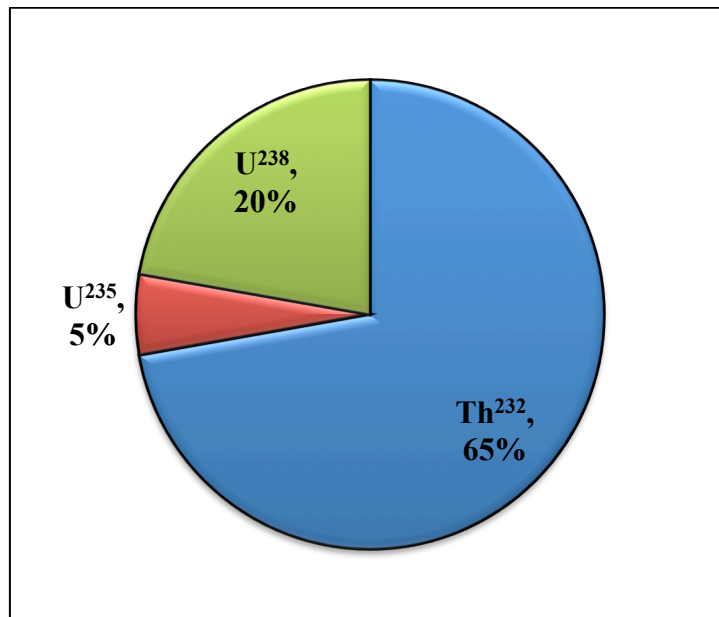


Figure 3.2 Typical isotopic composition of (Th/U)O₂-fuels (Herring *et al.*, 2001)

Strengths

(Th/U)O₂ is subject to corrosive attack in air or oxygenated water, but considerably less than UO₂. This makes (Th/U)O₂ a better type of waste than UO₂. Reactors using (Th/U)O₂-fuel present more stable reactivity (k_{eff}) during long irradiations than in a UO₂, due to thorium conversion to U²³³. (Th/U)O₂ combinations have notably higher thermal conductivity at low temperatures, lower fission gas release rate with a higher melting temperature (Herring *et al.*, 2001).

(Th/U)O₂-fuel can operate in slightly cooler conditions and preserve more fission products (gases) in the fuel during normal operation. This means that (Th/U)O₂-fuel can achieve higher burnups, which will extend fuel cycles, improve plant capacity factors and reduce the number spent fuel bundles to handle (Herring *et al.*, 2001).

(Th/U)O₂ cores designed for long cycles and high burnup might require less enrichment, less separation, and less total heavy metal feedstock than a traditional UO₂ core. High burnup (Th/U)O₂-fuels will improve the weapons material proliferation-resistance in three aspects. Less separable weapons material will be generated due to the fact that the major fertile material will be thorium and not U²³⁸. Extended refuelling periods will make diversion less

probable and the isotopic content of the plutonium will be much less attractive for use in weapons (Herring *et al.*, 2001).

Weaknesses

As U^{233} builds into a Th/LEU system, recoverable energy per fission decreases. Smaller recoverable energy per fission of U^{233} results in slightly more fuel to maintain the same power level as conventional UO_2 -fuel (Waris *et al.*, 2010). (Th/U) O_2 -fuel requires a higher initial enrichment to achieve acceptable burnups, which makes it more expensive than UO_2 -fuel (Weaver & Herring, 2002).

(Th/U) O_2 combinations have slightly higher decay heat, lower thermal conductivity at very high temperatures and exhibits higher fission gas production. During accident conditions like a large break loss-of-coolant accident (LOCA), (Th/U) O_2 -fuel will have less stored energy, but a somewhat higher internal heat production rate compared with UO_2 -fuel. This will change the settings for the maximum cladding temperature and the timing of fuel rod rupture (Herring *et al.*, 2001). One study showed that MEU is not a suitable seed to mix with thorium and that it is difficult to support sustainable thorium-based fuel cycle (Si, 2009).

The effective delayed neutron fraction of (Th/U) O_2 and UO_2 fuels is similar due to the same main fissile isotope, U^{235} . As the cycle progresses the fuel composition changes and β_{eff} is reduced, due to the production of the fissile nuclide U^{233} from the fertile nuclide Th^{232} . This is also the case with UO_2 fuels, due to the production of Pu^{239} from U^{238} (IAEA, 2012).

Suggestions

The method of spectrum shift control like the use of annular (Th/U) O_2 pellet designs is proposed to mitigate the negative effects and optimise the use of (Th/U) O_2 -fuel. Figure 3.3 illustrates the structure of an annular fuel pellet.

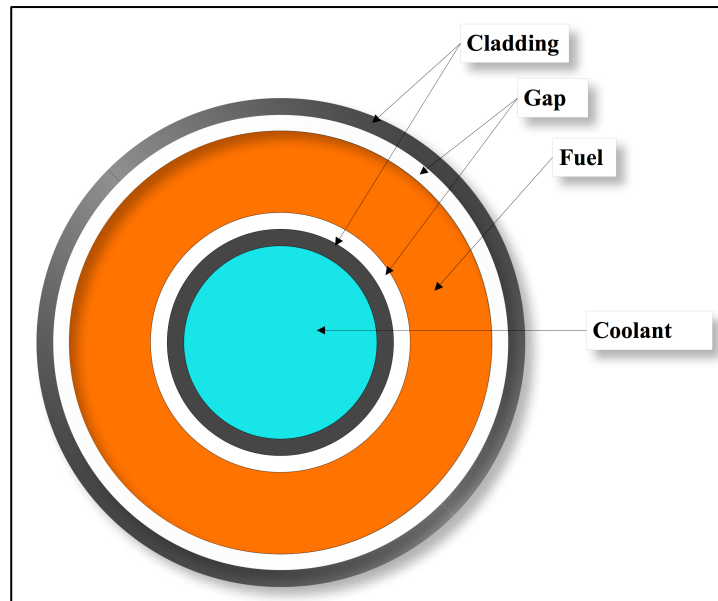


Figure 3.3 Cross-section of annular fuel pellet

3.1.2.2 (Th/Pu)O₂

Fertile thorium is mixed with fissile plutonium (Pu^{239} , Pu^{241}). The amounts of fertile thorium and fissile plutonium to be mixed with thorium can vary depending on burnup requirements, fuel cycle lifetimes and enrichment constraints. The enrichments can also vary depending on the core pattern loading, and if seed-blanket assemblies are used. Figure 3.4 show the composition of a typical homogeneous (Th/Pu)O₂-fuel for PWRs. The uranium oxide fuel was exchanged for a mixture of thorium- and plutonium-oxides. Th^{232} and the fertile plutonium isotopes (Pu^{238} , Pu^{240} , Pu^{242}) replace U^{238} and the fissile plutonium isotopes (Pu^{239} , Pu^{241}) and bred U^{233} replace U^{235} .

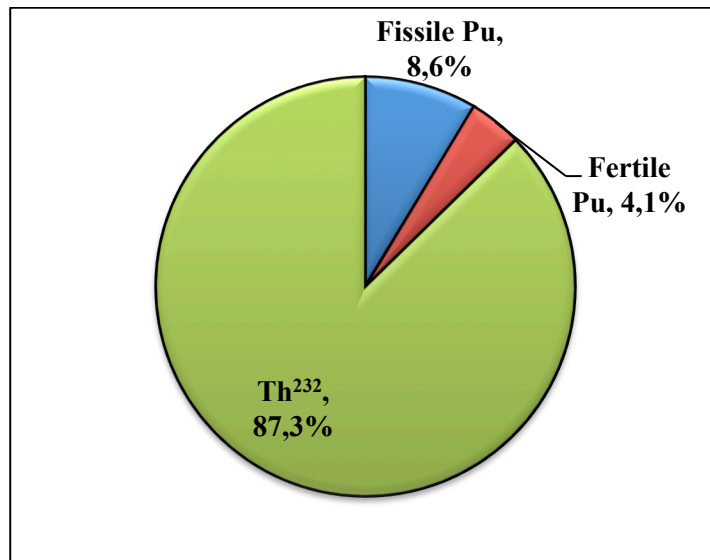


Figure 3.4 Typical composition of (Th/Pu)O₂-fuels (Bjork, 2012)

Strengths

(Th/Pu)O₂-fuel can achieve a plutonium destruction rate more than two times that of MOX at a burnup of 47GWd/Mt. The materials attractiveness of plutonium in the spent (Th/Pu)O₂-fuel is reduced as the burnups are increased. Higher burnups result in longer reactor life spans, excellent plutonium consumption rates, and downgraded material attractiveness (Trellue *et al.*, 2011). One study on (Th/Pu)O₂-fuel pins showed no significant decrease in the cladding diameter, due to increased burnup. The total actinide formation and spent fuel radiotoxicity for (Th/Pu)O₂ cores are considerably less than UO₂ or MOX cores (Schram & Klaasen, 2007).

The lower thermal expansion coefficient will make the in-core behaviour of (Th/Pu)O₂-fuel superior to MOX. The radial core power peak is likely to be more pronounced for UO₂ cores than in (Th/Pu)O₂ and MOX cores. (Th/Pu)O₂ cores have a more negative DC, due to the very strong neutron absorption resonance of Pu²⁴⁰ at 1eV (Fridman & Kliem, 2011). (Th/Pu)O₂ showed an increased thermal conductivity compared with UO₂ up to 14% Pu content. Increased thermal conductivity results in a lower fuel pellet temperature, less swelling, less PCMI (Pellet Cladding Mechanical Interaction) and a larger margin for fuel melting (Bjork, 2012).

Weaknesses

(Th/Pu)O₂ cores involve higher initial plutonium loading than MOX cores to reach the same fuel cycle length (Fridman & Kliem, 2011). A slight increase in the production of minor actinides (MAs) can be noticed, when using (Th/Pu)O₂-fuel (Schram & Klaasen, 2007).

The temperature reactivity coefficients of the (Th/Pu)O₂ core were noted to be always negative, though slightly less reduced than UO₂ cores but still within adequate shutdown margins. β_{eff} in (Th/Pu)O₂ cores is two times smaller than in UO₂ cores and also smaller than in MOX cores, which may cause issues during reactivity-initiated accidents (RIAs). Nonetheless the more negative Doppler coefficient (DC) may potentially compensate for this effect (Fridman & Kliem, 2011).

A significant design challenge of plutonium bearing cores is the reduced reactivity worth of the control rods and soluble boron. The reactivity worth is reduced due to spectrum hardening and the existence of high amounts of thermal absorbers (plutonium). This can possibly complicate the reactivity control and lower the shutdown margin (SDM). The boron worth of the (Th/Pu)O₂ and MOX fuels is about one half of that of conventional UO₂-fuel (Fridman & Kliem, 2011).

Suggestions

Cladding that is less oxidizing than zircaloy, like oxide dispersion strengthened steels (ODSS) or silicon carbide (SiC) could be candidates that manage lengthier irradiation cycles (Trellue *et al.*, 2011). Zirlo (Westinghouse) and M5 (Framatome) claddings have also been suggested (Xu, 2003).

Small amounts of natural uranium are added to decrease the weapons attractiveness of the U²³³ product after irradiation (Waris *et al.*, 2010).

The reduced reactivity worth is a familiar phenomenon for MOX-fuelled cores and does not lead to any operational limitations in modern LWRs. One study suggests increasing the moderation (Bjork *et al.*, 2011). It is also proposed to use soluble boron (SB) enriched in B¹⁰ and B₄C as material in control rods (Bjork, 2012).

Integral Fuel Burnable Absorber (IFBA), which is an advanced burnable absorber, is also suggested for (Th/Pu)O₂ cores. IFBA is a thin layer of zirconium boride applied to the surface of the fuel pellets (Bjork, 2012). Figure 3.5 A illustrates the position of the IFBA coating on a fuel pellet. Wet Annular Burnable Absorber (WABA) rods were also suggested (Fridman & Kliem, 2011). See Figure 3.5 B.

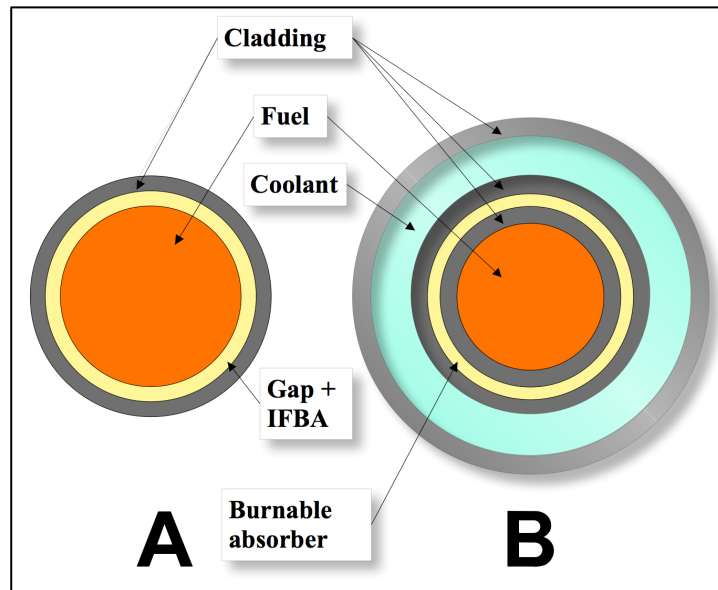


Figure 3.5 Cross-section of IFBA rods (A) and cross-section of WABA rods (B)

Proliferation Resistant Advanced Transuranic Transmuting (PRATT) fuel is a modified thorium-based fuel design. PRATT assemblies are similar to that of a typical 17x17 PWR assembly, only differing in enrichment and pin position with the addition of MA pins. The first inner region comprises of (Th/U²³⁵/U²³⁸)O₂ pins with slightly higher than normal U²³⁵ enrichment and a 75% thorium make-up.

The second outer region consists of (Th/Pu)O₂ pins with variable Pu (reactor grade) enrichment and variable burnable absorber density. IFBA coatings were used as the burnable absorber in both regions. Pins composed of minor actinides from spent fuel in an oxide form are placed throughout the assembly, to act analogous to burnable absorber pins (Haas *et al.*, 2005).

3.1.2.3 Conclusion

The different thorium-based fuel compositions have been discussed with regards to strengths, weaknesses and suggestions. The weaknesses and suggestions will be taken into account when comparing the mitigation strategies in section 3.2. Homogeneous, identical composition, integral thorium-based fuels look to be the most promising and are the choice for further consideration.

Reactors using (Th/U)O₂ and (Th/Pu)O₂-fuel present more stable reactivity (k_{eff}) during long irradiations than in a UO₂, due to thorium conversion to U²³³. (Th/U)O₂- and (Th/Pu)O₂-fuel can achieve higher burnups, which will extend fuelling cycles, improve plant capacity factors and reduce the number spent fuel bundles to handle, store. Higher burnups result in longer reactor life spans and downgraded material attractiveness. Thorium fuel types demonstrate notably higher conversion rates compared to UO₂-fuel, which allow efficient fuel utilization in a PWRs (IAEA, 2012).

The temperature reactivity coefficients of the (Th/Pu)O₂ core were noted to be always negative, but not as negative as in UO₂ cores, although still within adequate shutdown margins. β_{eff} (the delayed neutron fraction) in (Th/Pu)O₂-cores is two times smaller than in UO₂-cores and also smaller than in MOX-cores, but the more negative Doppler coefficient may compensate for this effect. A significant design challenge of plutonium-bearing cores is the reduced reactivity worth of the control rods and soluble boron. This is a familiar phenomenon for MOX-fuelled cores and does not lead to any operational limitations in modern LWRs.

There are no vital technical differences between (Th/U)O₂ and (Th/Pu)O₂-fuels and a choice between (Th/U)O₂ or (Th/Pu)O₂ cannot be made at this point in the investigation. Strategic and economic considerations will shed more light on the subject to assist in making a choice.

3.2 Thorium-based fuel options

The main requirements and suggestions for thorium-based fuels in PWRs are:

- To use more effective burnable absorbers:
 - IFBA coatings,
 - WABA rods.
- To compensate for the reduced control materials worth with stronger and more effective control materials:
 - Soluble boron enriched in B^{10} ,
 - B_4C as absorbing material in control rods,
 - Additional control rods.
- To use spectrum shift moderation control:
 - Increased water density,
 - Annular fuel pellets,
 - Additional water holes,
 - Tight pitch lattices.
- To use advanced cladding:
 - Oxide dispersion strengthened steels (ODSS),
 - Silicon carbide (SiC),
 - Zirlo (Westinghouse),
 - M5 (Framatome).

And to use the PRATT fuel design.

These strategies are analysed in the following section in terms of advantages and disadvantages.

3.2.1 Advanced burnable absorbers

Advanced burnable absorbers are beneficial in controlling the core and can extend refuelling cycles. The two types of advanced burnable absorbers are analysed.

Table 3.1 Advantages and disadvantages for different advanced burnable absorbers

	Advantages	Disadvantages
IFBA coatings	Extend the fuel cycle length (Bjork, 2012).	Need to reach high burnups of 73MWd/kgHM to extend cycle lengths (Bjork, 2012).
	Would not displace moderating water like discrete burnable absorbers (Westinghouse, 2006a).	
	Eliminates handling during refueling, which in reduces refueling time and radiation exposure to workers (Westinghouse, 2006a).	
	Provides exact reactivity control, limits power peaking and maximise neutron efficiency (Westinghouse, 2006a).	The production of helium gas due to the B^{10} reaction increases the cladding pressure. Westinghouse restricts the IFBA loading to below 3,09 mgB ¹⁰ /in (Xu, 2003).
	Have been commonly used in current nuclear power plants (Xu, 2003).	
WABA rods	Helps with radial power flattening (Fridman & Kliem, 2011).	The utilization of WABA rods would reduce the cycle length by about 20 EFPD (Fridman & Kliem, 2011).
	Reduces the soluble boron requirements (Fridman & Kliem, 2011).	
	Enhanced boron depletion (Westinghouse, 2006b).	

3.2.2 Advanced control materials

Advanced control materials are stronger and more effective to compensate for the reduced control materials' worth in thorium-based cores.

Table 3.2 Advantages and disadvantages of different advanced control material options

	Advantages	Disadvantages
SB enriched in B¹⁰	Mitigates the effect of reduced boron worth.	The soluble boron concentration is limited to 2000ppm.
	Commercially available and utilized by Siemens in PWR's (Fridman & Kliem, 2011).	
B₄C control rods	Mitigates the effect of reduced control rod worth.	B ₄ C is not used as commonly as enriched soluble boron and appears to be more difficult to find.
	Commonly used.	
Additional control rods	Mitigates the effect of reduced control rod worth.	Depends on the core design.

3.2.3 Spectrum shift moderation control

The H/HM ratio can be varied by varying the water density, the fuel rod pitch, the rod diameter, the fuel density and using annular fuel pellets. Of all practical ways of increasing the H/HM the cycle length will decrease, although the burnup is increased. Wetter lattices have higher initial excess reactivity, due to the reduced conversion ratio. Wetter lattices reduce the weapons potential in the spent fuel (Xu, 2003).

Spectrum shift control concerns the changing of the H/HM ratio to increase or decrease the moderation. An increase in the H/HM ratio will result in an over moderated system, which favours the fission reaction. A reduction in the H/HM ratio will result in a under moderated system, which will favour neutron capture in fertile material. With the spectrum shift control, it is always a trade-off between the fission reaction and the capture reaction. Increasing the water density, adding water holes and using annular pellets could increase the H/HM ratio. Increasing the fuel pellet radius and using a tighter lattice pitch could decrease the H/HM ratio. These options are discussed with the related advantages and disadvantages.

Table 3.3 Advantages and disadvantages for spectrum shift moderation control options

	Advantages	Disadvantages
Increased water density	Would increase the H/HM ratio and favor the fission reaction.	The increase of the H/HM ratio would increase captures in the water hinder the fission reaction (Weaver & Herring, 2002a). Varying the water density may have negative practical and physical implications (Xu, 2003).
	Increases the reactivity-limited burnup and discharge isotopes of homogeneous (Th/U)O ₂ -fuel (Weaver & Herring, 2002a).	

Table 3.3 cont. Advantages and disadvantages of different options for spectrum shift moderation control

	Advantages	Disadvantages
Annular fuel pellets	Supplies additional volume for the fission product gasses and smaller internal pressures, which results in smaller pellet clad interaction (Caner & Dugan, 2000).	Not commercially available and a new process would be required to produce annular pellets.
	Could be used in conjunction with thicker fuel pellets to increase the thermal conductivity (Bjork, 2012).	Need more research and development, which would require investment and time.
	Will increase the H/HM ratio and avoid the reduction in thermal conductivity. Annular pellets operate at lower peak and average temps, which makes higher burnups more attainable (Xu, 2003).	The manufacturing of annular fuel pellets may be more expensive than solid fuel (Xu, 2003).
	Internally and externally cooled annular fuel (IXAF) have better thermal hydraulic advantages, such as a better DNBR, lower fuel temperature, which reduces the stored energy in fuel pellets (Xu, 2003).	Annular pellets (10% wetter) have shown a fuel cycle cost decrease of 3% (Xu, 2003).
		Russian VVERs already operate on these 10% void annular fuel (Xu, 2003).
Additional water holes	Would increase the H/HM ratio and favor the fission reaction.	IXAF may have a higher fuel cycle cost, due to the increased parasitic absorption of added cladding (Xu, 2003).
		Would require reactor downtime and precise planning.
		The increase of the H/HM ratio would increase captures in the water hinder the fission reaction.
Tight pitch lattices		Depends on the core design.
	The H/HM ratio is decreased, which hardens the energy spectrum. This results in a more negative void coefficient, a higher fuel conversion ratio, non-proliferation characteristics and a reduced production of long-lived radiotoxic wastes (Kim & Downar, 2001).	The modifications to insert tighter lattices will be complex, time consuming and costly.
	Decreases the fissile enrichment requirement (Kim & Downar, 2001).	

Table 3.3 cont. Advantages and disadvantages of different options for spectrum shift moderation control

	Advantages	Disadvantages
Increase fuel radius	The increase in fuel radius would reduce H/HM ratio, favoring neutron capture reactions.	The increase of the H/HM ratio would increase captures in the water hinder the fission reaction (Weaver & Herring, 2002a).
		Decreased flow area should be compensated for, by increasing the mass flow of the coolant by replacing the pumps.
	Would extend operating cycles beyond the normal 12 months, resulting in the reduction of fuel costs and storage costs (Bjork, 2012).	A higher pressure drop in new assemblies would cause a difference in flow resistance, cross flow and vibrations, which mean that these increased radius assemblies, cannot be used with unmodified assemblies (Bjork, 2012).
		The use of stronger pumps and only modified assemblies would be complicated, time consuming and costly.

3.2.4 Advanced cladding

Oxide dispersion strengthened steels (ODSS), SiC or Zirlo (Westinghouse) or M5 (Framatome) claddings have been suggested for high burnup cores and extended fuel cycles (Xu, 2003).

Table 3.4 Advantages and disadvantages of different advanced cladding options

	Advantages	Disadvantages
Oxide dispersion strengthened steels	Can manage lengthier irradiation cycles and higher burnups (Trellue <i>et al.</i> , 2011).	
SiC	Has a higher yield and ultimate strength than Zircaloy-4 under the same primary stresses, which means a higher primary safety margin. (González, 2011)	Irradiation decreases the thermal conductivity of SiC (González, 2011).
	Expected to operate at higher temperatures and to release less fission gas than zirconium fuel clad (González, 2011)	SiC can be brittle (González, 2011).

Table 3.4 cont. Advantages and disadvantages of different advanced cladding options

Advantages	Disadvantages	Advantages
Zirlo (Westinghouse)	Zirlo has replaced Zircaloy-4 as a cladding in almost all of Westinghouse fuel deliveries since the introduction in the 1990's (González, 2011).	These types of alloys are not that commonly available like Zircaloy and availability depends on the fuel supplier.
	The corrosion resistance and enhanced structural stability of Zirlo cladding enable longer cycle length at higher temperatures without reducing operation margins in a standard PWR (González, 2011)	
	Low corrosion rate, best creep properties under irradiation and good mechanical resistance (González, 2011)	
	Can manage lengthier irradiation cycles and higher burnups (Xu, 2003).	
M5 (Framatome)	Less affected to hydrides than Zircaloy-4 and Zirlo, while still maintaining the same good mechanical properties and low thermal neutron cross-section (González, 2011).	These types of alloys are not that commonly available like Zircaloy and availability depends on the fuel supplier.
	This alloy could resist the long resident time of the fuel element in a harsh environment (González, 2011)	

3.2.5 PRATT

Advantages

PRATT fuel can be used in present commercial reactors, as Westinghouse PWRs. Burning MAs decreases the time requirements for spent fuel storage and increases the volume for on-site SNF (Spent Nuclear Fuel) storage (Haas *et al.*, 2005).

Disadvantages

The PRATT design is a combined strategy that uses IFBA's different fissile isotopes in different core regions. This would be very difficult to implement in SA, which means the fuel would need to be imported, jeopardizing the security-of-supply. If a nuclear fuel cycle facility would be employed in the future, this option would become attractive.

3.3 Elimination

The options discussed above are different strategies to mitigate the negative effects of thorium-based fuels as well as optimising the advantages of thorium-based fuels. The simple and most economical option would be the best choice to start with. It should be noted that the options are used in support of one another. There is no single solution to the different negative effects of thorium-based fuels. For example, a strategy is required to mitigate the reduced control rod worth. Another strategy is required to reduce the higher enrichment requirement and another strategy is required to extend the fuel cycle. Table 3.5 shows the different options under their related categories.

Table 3.5 Different strategies to optimise thorium-based fuel

Advanced burnable absorbers	Advanced control materials	Spectrum shift moderation control	Advanced cladding	Other
IFBA coatings	B ₄ C control rods	Increased water density	Oxide dispersion strengthened steels	PRATT fuel designs
WABA rods	SB enriched in B ¹⁰	Annular fuel pellets	SiC	
	Additional control rods	Additional water holes	Zirlo (Westinghouse)	
		Tight pitch lattices	M5 (Framatome)	
		Increase fuel radius		

The critical evaluation is done on a basis of elimination. Based on the previously discussed disadvantages, the options that are too expensive and complex to employ and need further research and development will be eliminated. The following options are eliminated:

- Annular fuel pellets
- Tight pitch lattices
- Increased fuel radius

This leaves one with the following options shown in Table 3.6

Table 3.6 Options after the first step of elimination

Advanced burnable absorbers	Advanced control materials	Spectrum shift moderation control	Advanced cladding	Other
IFBA coatings	B ₄ C control rods	Increased water density	Oxide dispersion strengthened steels	PRATT fuel designs
WABA rods	SB enriched in B ¹⁰	Additional water holes	SiC	
	Additional control rods		Zirlo (Westinghouse)	
			M5 (Framatome)	

For the category of advanced burnable absorbers, the WABA rod option is eliminated, due to the cycle length penalty. The advantages of the IFBA outweigh the advantages of WABA rods. In the category of advanced control materials, it is apparent that enriched soluble boron is more popular and therefore B₄C control rods are eliminated. The option of additional control rods is not yet eliminated, because it depends on the specific reactor core design.

For spectrum shift control, it is decided to keep both options: increased water density and additional water holes. The insertion of water holes also depends on the specific reactor core. In the category of advanced cladding materials, it is apparent that the information on oxide dispersion strengthened steels (ODSS) and SiC is limited, and ODSS and SiC are eliminated. This leaves two options: either Zirlo (Westinghouse) or M5 (Framatome) depending on the current fuel supplier for SA.

The PRATT fuel design in the last category is eliminated for the time being, but could be employed when SA has its own fuel cycle facility. This option is suggested for future implementation in the roadmap. This combination of strategies is the most attractive case to implement in existing PWRs without any drastic changes to the design of fuel lattice or core internals.

3.4 Conclusion

The final choice to start the thorium roadmap would be homogeneous thorium-based fuel with IFBA coatings and Zirlo/M5 (or similar) cladding, increased water density, additional water holes and enriched B¹⁰ soluble boron. The combined advantages are:

- Increased plutonium destruction rate,
- Higher proliferation resistance,
- Extended fuel cycle length,
- Reduced refuelling time,
- Reduced radiation exposure to workers,
- Increased H/HM ratio to favour the fission reaction,
- Increased reactivity-limited burnup,
- Mitigation of the effect of reduced control materials worth.