

Review

Review of thorium-containing fuels in LWRs

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ABSTRACT

Stemming from a renewed interest in the suitability of thorium as fertile isotope, this study presents an extensive survey of some of the recent advances on the use of thorium in light water reactors, with the view of informing researchers and policy makers. The isotopic properties of fertile and fissile material are discussed, with an emphasis on the suitability and unique characteristics of thorium. The overview is categorized in terms of fuel design, moderation, neutronic behaviour, thermal-hydraulics, fuel performance, radiotoxicity and proliferation. A brief scoping of varying perspectives on the economics of thorium in various fuel designs and applications in open and closed cycles, long residence fuel and fleet applications is presented. In conclusion, a high-level explanation of dominating factors, rendering various (often divergent) outcomes, is attempted, based on first principles.

1. Introduction

Thorium is a nuclear fuel candidate for various reactors, such as the pressurised water reactor (PWR), boiling water reactor (BWR), heavy water reactor (HWR), and molten salt reactor (MSR). The MSR is particularly suitable for the ²³²Th-²³³U fuel cycle, which produces less minor actinides (MAs) than the uranium-plutonium fuel cycle (Lecarpentier, 2011). MSRs that use thorium are best described as catalytic nuclear reactors due to the transmutation of thorium to uranium (Weinberg and Hammond, 1970). The thorium molten salt reactor (TMSR) employs fissile ²³³U, which can be practically converted from all the ²³²Th isotopes without the need for enrichment (Juhász et al., 2009). Due to the attributes of online post-processing and continuous feeding, MSRs seem promising for transmutation and conversion/breeding (LeBlanc, 2010). Furthermore, unlike traditional reactors, TMSRs circumvent the safety issues associated with fuel meltdown of typical solid fuel reactors (Furukawa et al., 2008; Juhász et al., 2009). However, MSR technology is still under development.

Since the early 1970s, light water reactors (LWRs) have dominated the nuclear power market. Recently, many research efforts have focused on adding thorium to existing LWRs (Benrhnia et al., 2022; Lkous et al., 2023; Zuhair et al., 2022). One of the factors spurring a resurgence of attention to thorium in the USA and Western Europe is that its use can lead to higher burn-ups in LWRs operating on a once-through fuel cycle (IAEA, 2000).

There are various ways in which thorium can be employed in LWRs, such as in a homogeneous or heterogeneous fuel arrangement, in an oxide or nitride composition, with and without recycling, and mixed with various fissile isotopes. Fig. 1 shows various permutations for Thorium-containing (Th-containing) fuels in LWRs—these are discussed further in the sections that follow.

This paper presents an overview of the potential of Th-containing fuels in LWRs, in terms of in-core neutronic behaviour, fuel performance, thermal hydraulics, waste, proliferation resistance, feasibility, safety, economics and manufacturing. Recent advances are highlighted and topics for further investigation are identified. An attempt is made to link general trends in Th-containing fuel characteristics to underlying fundamental principles.

2. Isotope properties

To understand the behaviour of Th-containing fuels in LWRs, one first needs to understand the individual properties of the fertile and fissile isotopes related to Th-containing fuels. Three fissile isotopes primarily sustain reactor criticality in Th-containing fuel cycles: ²³³U, ²³⁵U and ²³⁹Pu, with a small contribution from ²⁴¹Pu. ²³⁵U depletes over the lifetime of the fuel and should be substituted with ²³³U and ²³⁹Pu bred throughout the fuel lifetime. When choosing ²³⁵U as fissile fuel, the initial concentration of ²³⁵U must be sufficient to achieve the BOL (beginning of life) criticality of the reactor (García et al., 2013). ²³⁵U can

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Acronyms			
ABWR	Advanced boiling water reactor	LEU	Low-enriched Uranium
AP1000	Advanced pressurised water reactor	LOCA	Loss-of-cooling accident
ARI	All rods in	MA/s	Minor actinide/s
ARO	All rods out	MFR	Moderator-to fuel ratio
BOC	Beginning of cycle	LWR	Light water reactor
BOL	Beginning of life	MOX	Mixed oxide
BW	Boron worth	MSR	Molten salt reactor
BWR	Boiling water reactor	MTC	Moderator temperature coefficient
CR	Conversion ratio	NoXe	No xenon
CRW	Control rod worth	PCMI	Pellet cladding mechanical interaction
CZP	Cold zero power	PPF	Power peaking factor
DNB	Departure from nucleate boiling	PWR	Pressurised water reactor
DTC	Doppler temperature coefficient	RMBWR	Reduced moderation boiling water reactor
EFPD	Electric full power days	RMPWR	Reduced moderation pressurised water reactor
EOC	End of cycle	RTF	Radkowsky thorium fuel
EOL	End of life	SBU	Seed and blanket unit
EPR	European pressurised reactor	SFR	Sodium-cooled fast reactor
EqXe	Equilibrium xenon	SWU	Separative work unit
FA	Fuel assembly	TMSR	Thorium molten salt reactor
HFP	Hot full power	TPUC	Heterogeneous fuel assembly
H/HM	Hydrogen to heavy metal ratio	TRU	Transuranics
HWR	Heavy water reactor	VC	Void coefficient
HZP	Hot zero power	VVER	Water–water energetic reactor
IFBA	Integral fuel burnable absorber	WASB	Whole assembly seed and blanket
		WATU	Whole assembly heterogeneity

be replaced by ^{233}U or ^{239}Pu in closed-cycle systems.

2.1. ^{232}Th

Thorium is found naturally as ^{232}Th . ^{232}Th has a higher thermal neutron capture cross section than ^{238}U , hence its use in a reactor requires more fissile enrichment (Kim and Downar, 2002). This has a

strong influence on the conversion ratio (IAEA, 2002). However, it may also be considered an advantage because ^{232}Th acts as a burnable absorber which reduces excess reactivity at BOL. Neutron spectrum hardening can be observed due to thorium's large thermal neutron capture cross section (Lau et al., 2014). The capture cross section and capture resonance integral of ^{232}Th is approximately three times smaller than that of ^{238}U (Kim and Downar, 2002), which may weaken the

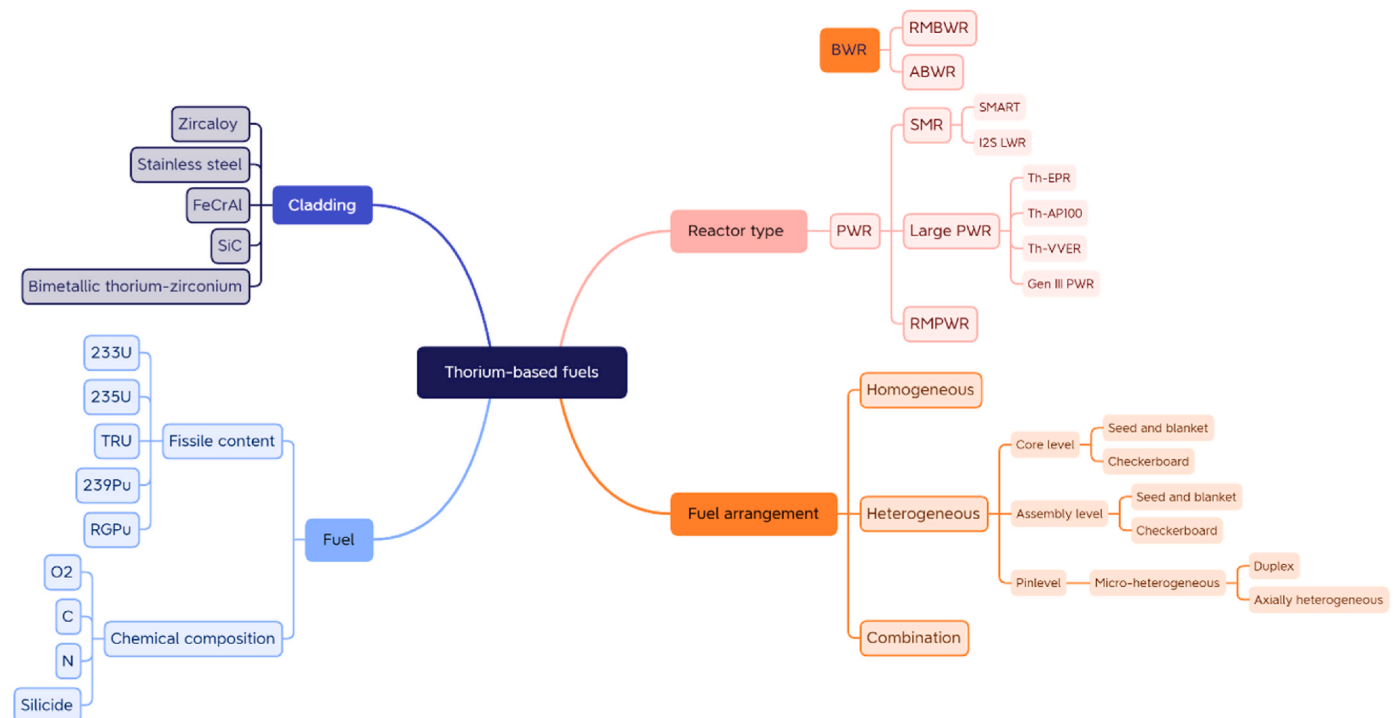


Fig. 1. Th-containing fuel options.

negative Doppler temperature coefficient (DTC) feedback in overpower transients (Perry and Weinberg, 1972). The fast fission cross section of ^{232}Th is lower than that of ^{238}U . The fast fission of ^{238}U produces between 7% and 8% of total energy, while ^{232}Th contributes only 2% (IAEA, 2002).

2.2. ^{233}U

The delayed neutron fraction of ^{233}U is smaller than that of ^{235}U (see Table 1) (Trellue et al., 2011). As the fuel burns, the composition of the fissile isotopes in the fuel changes due to transmutation of ^{232}Th to ^{233}U , and for example from ^{238}U to ^{239}Pu . A shorter reactor period stems from a smaller delayed neutron fraction, indicating an increased chance of prompt criticality, which results in a more delicate reactor when reactivity varies (more so than systems where the delayed neutron fraction is larger). As a result, control systems must be more responsive (Kazimi et al., 1999).

The cross sections of ^{233}U vary the least among fissile isotopes at epithermal neutron energies. This decreases the reactivity impacts of neutron spectrum changes caused by coolant transients. Consequently, when the neutron spectrum moves to more epithermal energies, ^{232}Th – ^{233}U fuels are less affected by spectrum hardening (Perry and Weinberg, 1972). This is because the nuclear characteristics of ^{233}U , such as cross sections and η (number of neutrons produced per fission), are significantly less dependent on power and temperature than those of ^{235}U . More constant properties (such as cross sections) with varying neutron spectrum lead to improved reactor safety when moving from cold to hot conditions (Greneche et al., 2007).

^{233}Pa is present in the transmutation chain of ^{232}Th . ^{233}Pa has a longer half-life (27 days) than ^{239}Np (2.3 days) in conventional uranium fuel. This longer half-life of ^{233}Pa increases the reactivity after the reactor is shut down because of the breeding of ^{233}U . Therefore, a reactivity surge after shutdown must be accounted for in the safety of Th-containing reactor designs (Herring et al., 2001; Lung and Gremm, 1998). ^{233}Pa is also a strong neutron absorber, considerably stronger than ^{232}Th . This in turn decreases ^{233}U production (Lung and Gremm, 1998) and can result in a decrease in the conversion/breeding ratio over the lifetime of a reactor (Greneche et al., 2007). It should be noted that in the case that ^{233}Pa absorbs a neutron to form ^{234}Pa , it would beta decay to ^{234}U to form either ^{233}U or ^{235}U , following $+n-2n$ or $+n$ reactions, respectively, from ^{234}U .

^{232}U is also present in the transmutation chain of Th-containing fuels that have daughters with high-energy gamma emission (Hania and Klaassen, 2012). Due to the lower recoverable energy per fission of ^{233}U , more fissions per unit of energy generation are required, which implies that somewhat more fuel (or more enrichment) is required to sustain the same power level as with conventional uranium fuel (Trellue et al., 2011).

At thermal neutron energies, ^{233}U has the highest neutron yield of any fissile isotope (Trellue et al., 2011). ^{233}U has a high neutron fission

cross-section and low neutron capture cross-section, lower than ^{235}U . This low neutron capture cross-section of ^{233}U limits unwanted transmutation” (du Toit, 2017). The production to absorption ratio of ^{233}U by fission is 2.29 (higher compared to other fissile isotopes), which suggests the possibility of a thermal breeding reactor (IAEA, 2002). This high value of the number of fission neutrons released per absorbed neutron allows ^{232}Th – ^{233}U fuel to achieve self-sustainable breeding in thermal spectrum LWRs (Baldova et al., 2014a).

Van der Walt et al. (2023) illustrated the superior fuel characteristics of ^{233}U by comparing neutrons generated per fission, multiplied by the microscopic fission cross section, as a fraction of the total microscopic cross section for ^{233}U , ^{235}U , ^{239}Pu and ^{241}Pu . ENDF/B-VIII data (Brown et al., 2018) (using the generic Janis PWR spectrum (Soppera et al., 2014), five groups per decade on an energy log scale) was used for calculations. The suitability of thorium for thermal breeders/converters was demonstrated.

Compared to ^{235}U and ^{239}Pu , the production of important fission products (e.g., Xe, Sm) is significantly lower for ^{233}U . This indicates that the absorption cross sections for ^{233}U fission products decline by approximately 25%–30%, resulting in reduced reactivity losses and longer core lifetimes (Greneche et al., 2007). ^{233}U produces more fission gases, but these gases are better retained in the fuel matrix (Perry and Weinberg, 1972).

The properties of singular isotopes have been addressed. The real behaviour of the Th-containing reactor will be the combined effect of the different isotopes (composition) as well as the neutron spectrum, the fuel configuration, etc. Therefore, each reactor system will have to be analysed individually and evaluated on its own merit. Various studies of specific systems are discussed in Section 4.

3. Fuel

Th-containing fuel in LWRs can be used in various forms, either in oxide form, nitride form or carbide form. Recently, Th-containing fuels were investigated with alternative cladding for the development of accident-tolerant fuels (Bouassa et al., 2023; Rabir et al., 2022). These and other important material properties are discussed in Section 3.1. The composition can also vary in terms of various fissile and fertile isotopes used in the Th-containing fuel, the different permutations of which are discussed in Section 3.2. Different fuel options, in terms of arrangement (spatial separation of thorium and other fissile isotopes) are utilised—these are most commonly referred to as homogeneous or heterogeneous designs, as addressed in Section 3.3. Altering the conventional neutron spectrum enhances certain properties of Th-containing fuels, as addressed in Section 3.4.

3.1. Material properties

ThO_2 has a 10% lower density than UO_2 , which might be considered a disadvantage due to the lower accompanying number of heavy nuclei for the same volume (Lau et al., 2012). (If Th-containing fuel achieves a better burn-up in terms of fuel burn-up comparisons, the difference in fuel density should be accounted for). Analysing Electric full power days (EFPD) for judging cycle improvement is recommended in addition to burn-up. On the other hand, a decreased density can improve fission product retention within thorium fuel (Perry and Weinberg, 1972).

In the early 2000s, it was common practice to use a lower thermal conductivity value for ThO_2 (lower than for UO_2) with the expectation that mixing ThO_2 with UO_2 would cause a decrease in thermal conductivity to values lower than for pure UO_2 (Yang et al., 2003). However, more recently it was proven that the thermal conductivity of ThO_2 is substantially higher than that of UO_2 . The thermal conductivity of $(\text{ThU})\text{O}_2$ decreases with an increasing share of UO_2 . At $\geq 60\%$ UO_2 share, the conductivity of the $(\text{ThU})\text{O}_2$ fuel approaches that of UO_2 (Saoudi

Table 1

Fissile isotope properties.

	^{233}U	^{235}U	^{239}Pu	^{241}Pu
Recoverable energy per fission, MeV (Ogujiuba et al., 2022)	191.02	193.42	199.01	202.00
Average number of neutrons produced (Galahom et al., 2022)	2.4968 ± 0.0036	2.4355 ± 0.0023	2.8836 ± 0.0047	2.9479 ± 0.0055
Delayed neutron fractions (β), pcm (Fridman and Kliem, 2011)	271	665	226	546

et al., 2018).

Ševeček et al. (2018) found that although it could be expected that the higher conductivity for Th-containing fuels would aid in the reduction of the maximum fuel temperature, the high thorium content (>80%) in homogeneous fuels offers negligible conductivity enhancement. Hence, the authors proposed the use of metal thorium plates between uranium dioxide pellets (axially heterogeneous), which reduced the maximum fuel temperature significantly, leading to an increase in reactivity, thus further extending fuel utilisation and burn-up rendered by conversion/breeding. The proposed solution can be incorporated in fuel geometry modifications to enhance the safety of the fuel or increase the output power of a reactor.

From a metallurgical and chemical point of view, ThO₂ is more stable and robust than UO₂ (Caner and Dugan, 2000). ThO₂ is the highest oxide of thorium and it does not deviate much from its stoichiometric composition when exposed to air or water at temperatures up to 2000 K (Herring et al., 2001). Understanding the macroscopic behaviour of ThO₂ and other actinides requires understanding the microscopic behaviour which was investigated by means of hybrid density functionals and other computational methods (Mo et al., 2016; Pegg et al., 2017). Recent literature have confirmed with experiments and density functional theory that ThO₂ will not accommodate a significant oxygen excess (Murphy et al., 2014). This lattice stability of ThO₂ can also be seen as a drawback. Fission products become trapped within the lattice structure of ThO₂ and as they accumulate, the energy of the lattice increases which could lead to significant changes the structure, such as phase change, or the formation of precipitates. This means that extended burnups in ThO₂ fuel can become an issue, especially in terms of the spent fuel. On the other hand, UO₂ can be oxidised from 4+ and 5+ providing a low energy charge compensating mechanism for aliovalent fission products without triggering a phase change (Wang et al., 2014).

Pure ThO₂ has a higher melting point than UO₂. A higher melting temperature could result in higher safety limits and high thermal efficiency (IAEA, 2012), which may justify increasing specific power and burn-up for pure ThO₂ reactors (Trellue et al., 2011). ThO₂ is stable and with its high melting point (3300 °C) it could prove to be a good fuel that can allow higher burnups and temperatures. However, the melting point of homogeneous mixtures of (ThU)O₂ is lower than that of pure ThO₂. (ThPu)O₂ and mixed oxide (MOX) fuel have similar physical properties and are present in the face-centred cubic crystalline form. This feature is fundamental for the manufacture and stability of mixed oxide fuels and could allow for high burn-up fuels (Lung and Gremm, 1998). Long et al. (2004) noted that Th-containing oxide fuels have higher thermal conductivity, lower density and volumetric heat capacity, less thermal expansion, a higher melting point and a lower gas diffusion coefficient than pure uranium oxide fuel.

Gorton et al. (2019) examined the accident tolerance benefits of mixed thorium mononitride (ThN) and uranium mononitride (UN) fuels in PWRs under normal operating conditions. ThN has significantly greater thermal conductivity than UO₂ and UN, providing an additional margin to the melting temperature. An admixture with fissile UN is required with ThN prior to conversion. For enhanced internal breeding, ThN was used to achieve lower fuel temperatures and thus increased thermal margin. ThN has a higher heavy metal density of 11.2 g/cm³ (Peterson and Curtis, 1973) than 8.8 g/cm³ for ThO₂ (Peterson et al., 1965), and a 4–20 times greater thermal conductivity over the temperature range 100–1200 °C (Rahman and Franceschini, 2012). It should be noted that as thorium undergoes transmutation to form protactinium and uranium, the thermal conductivity will decline (Parker et al., 2019). The enhanced thermal conductivity in nitride-based fuels could possibly reduce fission product release. A reduced temperature gradient in the fuel could result in less thermal stress and a smaller probability of fuel pellet cracking (Van Brutzel et al., 2015).

Rouf and Su'ud (2016) modelled (ThU)O₂ and (ThU)C fuel in a three-ring radial geometry, with each region having a different

enrichment of uranium of between 30% and 40%. The optimum core design was achieved at a simulated thermal power of 600 MWt, with 35% uranium and a ²³⁵U enrichment of 11%–13% (it was inferred to be vol%, but the authors did not specify this), which rendered 14 years operation, and axial and radial power peaking factors (PPFs) at 1.5 and 1.2, respectively. They found that the carbide fuel had better cycle lengths than oxide fuel due to the higher density of the carbide fuel.

Vaidyanathan (2020) studied Th-containing fuel PWRs using bimetallic thorium-zirconium cladding as part of the fuel rod design. Although the proposed cladding design achieves heterogeneity, thermo-hydraulic considerations pose a disadvantage. Liu et al. (2020) and Qiu et al. (2021) investigated two-layer SiC cladding in combination with Th-containing fuels under normal and accident conditions. The two-layer SiC cladding comprised an inner SiC/SiC composite layer and an outer monolithic SiC layer. Advanced steel cladding FeCrAl and baseline fuel U₃Si₂ were used by Kotlyar et al. (2017) to withstand longer exposure periods. The degradation rates were significantly lower than with traditional Zr-based alloys, especially at higher burn-ups.

3.2. Fuel composition

Th-containing fuels can be employed in various ways. Thorium alone includes only fertile material, yet it can be mixed with ²³³U, ²³⁵U, ²³⁹Pu or ²⁴¹Pu as the fissile driver material. Fissile content is the sum of all fissile material as a percentage of fuel. It is important to note that the conventional definition of enrichment no longer applies here, but rather the ratio of fissile elements to the total fuel elements.

The ²³⁵U enrichment is restricted to <20 wt% to comply with the definition of low-enriched uranium (LEU) (Weaver and Herring, 2002). Therefore, adding thorium to 20 wt% enriched uranium will reduce the fissile content. For example, mixing 35 wt% UO₂ enriched to 20 wt% ²³⁵U and 65 wt% ThO₂ will result in an initial fissile content of 7 wt%. Longer fuel cycles require a 2.7 wt% higher fissile content, than ordinary uranium cycles of 4.5 wt% (i.e. of ~7.2 wt%). To achieve 24-month cycle lengths which corresponds to ~77.5 GWD/MTM burn-up, the initial fissile content should be between 6.5 and 8 wt%. Du Toit and Naicker's (2018) Th-containing fuel for the European pressurised reactor (EPR) is homogeneous, with the total fissile content of the average fuel assembly (FA) being 2.54 wt% ²³⁵U. The features of ²³⁵U are expected to dominate the cycle at first, but when ²³²Th breeds ²³³U the properties of ²³³U will become more evident. Th-containing fuels have significantly higher conversion rates than uranium-only fuel, allowing for more efficient fuel utilisation in PWRs (IAEA, 2012). According to Saglam et al. (2004), thorium-uranium fuel cycles are technically feasible in modern PWRs and can replace traditional UO₂ fuel without requiring significant mechanical modifications (Joo et al., 2004).

²³⁵U can be replaced with isotopes of plutonium, which promotes plutonium incineration. According to Morrison and Parks (2020), thorium-plutonium MOX fuels may be preferable to uranium-plutonium MOX fuels for plutonium management in LWRs.

3.3. Fuel arrangement

Th-containing fuel can be used in reactors in various arrangements. In homogeneous fuel, the thorium is mixed with uranium and plutonium at the molecular level. In this case, thorium and other isotopes are mixed to the point that they can no longer be distinguished from each other.

Thorium can also be employed in a heterogeneous manner, where the thorium is separated from the fissile isotopes in fresh fuel. This separation can be within a single pin ('micro-heterogeneous'), such an example being the duplex design. Separation can also be on a pin level, with discrete thorium and fissile pins inside an assembly. Finally, the separation can be executed at the assembly level with discrete thorium and fissile assemblies, and specific arrangements in seed and blanket or chequerboard patterns. The various permutations for homogeneous and

heterogeneous fuel arrangements are depicted in Fig. 2. Researchers have investigated various combinations of homogeneous and different levels heterogeneous designs.

The use of ThO_2 in heterogeneous arrangements does not always increase burn-up, since thorium is not fissile but a strong neutron absorber (Galperin et al., 2002; Nuttin et al., 2012). However, improved cycle performance depends on improved conversion and neutron economics, which depend on geometry, composition, fissile content and the neutron spectrum. Schwageraus et al. (2008) and Yun et al. (2010) suggested the use of a heterogeneous configuration in which the fissile part of the fuel containing ^{233}U is separated from the fertile isotope ^{232}Th to promote conversion in a Th-containing PWR. Homogeneously mixed thorium-uranium fuel performed more poorly than micro-heterogeneous fuel in terms of burn-up. The spatial separation of uranium and thorium improved the achievable burn-up of thorium-uranium fuel designs by more effective breeding of ^{233}U from ^{232}Th (MacDonald et al., 2002; MacDonald and Lee, 2004; Schwageraus et al., 2004). The spatial separation between the fissile ^{235}U and the fertile ^{232}Th in duplex fuel promoted moderation of freshly fissioned neutrons before reaching ^{232}Th (Li et al., 2021).

Massachusetts Institute of Technology investigated $(\text{ThU})\text{O}_2$ micro-heterogeneous duplex fuel designs, where discharge burn-up is increased, compared to homogeneous $(\text{ThU})\text{O}_2$ fuel (Joo et al., 2004). Van der Walt et al. (2023) proposed the implementation of in-rod axially micro-heterogeneous thorium-uranium fuel pins in a typical PWR. They introduced fuel denaturing, which reduced power peaking and peak-to-peak flux differences. Vaidyanathan (2020) proposed a uranium PWR with bimetallic thorium-zirconium cladding in a radial micro-heterogeneous design to reduce transuranics (TRU) generation.

Subsequently, he further developed his concept by adding new rods to the core, where the fissile part of the fuel consists of thorium and uranium oxide pellets (instead of uranium oxide only) (Vaidyanathan, 2021).

The EPR thorium utilisation concept has a heterogeneous seed and blanket thorium-uranium design. Despite reduced discharge of spent fuel during the lifetime of the reactor, the decay heat for the seed and blanket assemblies was higher than for the reference EPR assembly (Ashley et al., 2014). Bae and Kim (2005) proposed a heterogeneous Th-containing seed and blanket assembly design with discrete thorium pins in the blanket assembly and some discrete thorium pins present in the seed assembly. Their design gave the same neutronic performance as conventional PWRs, but a slightly higher PPF. Raites et al. (2009) investigated the Radkowsky thorium fuel (RTF) concept, where the utilisation of the seed and blanket unit (SBU) FA consists of a fissile enriched uranium region, known as the seed, and a fertile thorium region, known as the blanket—it is direct replacement for a conventional FA in a Russian-type Water–Water Energetic Reactor (VVER) or a Western PWR.

Lindley et al. (2013) ameliorated the possibility of a positive moderator temperature coefficient (MTC) associated with a Western PWR of TRU by adding thorium to the fuel. To improve neutronic performance, heterogeneous fuel design with spatial separation of thorium and uranium (called Th-U3) and thorium and transuranics (called Th-TRU) is achieved in the heterogeneous FA (called TPUC) or in the whole assembly heterogeneous fuel (WATU). The heterogeneous FA loading entailed positioning Th-TRU pins in the center of the assembly and Th-U3 pins in the periphery (TCUP). To achieve satisfactory discharge burn-up, while ensuring a negative MTC, the authors had to increase the standard pin diameter. This design change caused a loss in

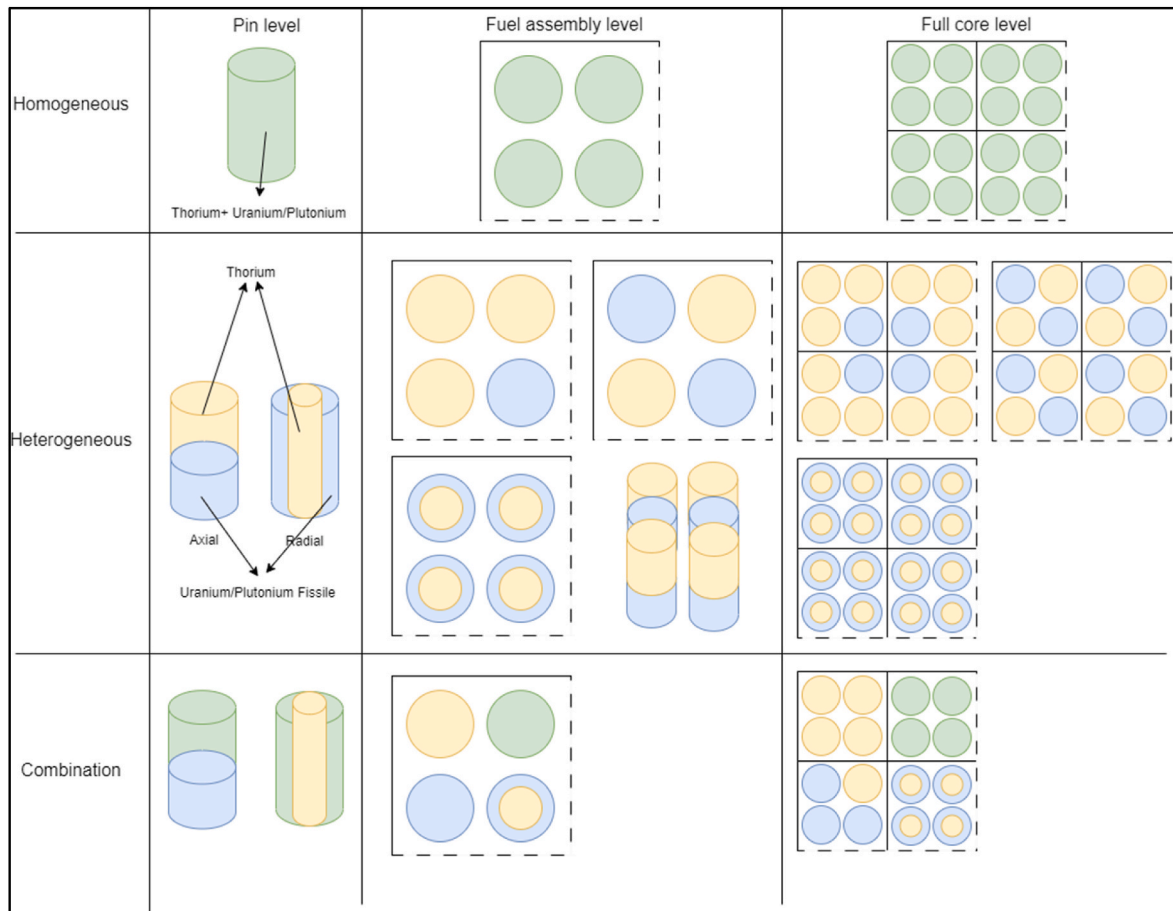


Fig. 2. Thorium-containing fuel arrangements.

shutdown margin (in a postulated accident scenario) and led to additional design requirements (Lindley et al., 2014a).

Oettingen (2019) investigated thorium fuel in the Westinghouse four-loop PWR to investigate the time evolution of fissile ^{233}U , ^{235}U , ^{239}Pu , ^{241}Pu and fertile ^{232}Th and ^{238}U . Thorium was introduced as SBU and the whole assembly seed and blanket (WASB). In the Westinghouse four-loop PWR, the WASB approach was used; the blanket comprised of 90 wt% ThO_2 and 10 wt% UO_2 . Oettingen performed analyses over several fuel cycles in a new feasible reloading scheme. The heterogeneous design was found to result in a more effective conversion of ^{232}Th into fissile ^{233}U . The decrease of both isotopes in the blanket showed linear behaviour, in contrast to the much faster increase in the ^{232}Th region.

Although heterogeneous seed and blanket arrangements give better conversion, they do not meet the thermal hydraulic requirements when the coolant flow rate and fuel channel dimensions remain unchanged, due to higher PPF (de Stefani et al., 2020). Heterogeneous designs are more adaptable but require more complex fuel management and reloading (Bae and Kim, 2005; Du Toit and Naicker, 2018; Todosow and Kazimi, 2004). Homogenous Th-containing fuel will result in simpler fuel management and conventional PPFs, although the penalty (when compared to heterogeneous fuel) is a reduction in burn-up and conversion.

3.4. Moderation

At thermal neutron energies, Th-containing fuel presents a good conversion/breeding ratio. Because ^{232}Th has a larger absorption cross section than ^{238}U , high conversion from ^{232}Th to ^{233}U can be reached at thermal neutron energies (Bae and Kim, 2005). The ratio of fertile absorption to parasitic absorption (neutron loss in the material) for ^{232}Th is higher than for ^{238}U (IAEA, 2012), making thorium fuel for conversion more effective. The conversion of ^{232}Th to ^{233}U is dominated by epithermal neutrons, which could increase the conversion ratio in Th-containing fuel (Shengyi, 2011). Breeding ^{238}U - ^{239}Pu in a uranium-fuelled reactor, as reported by García et al. (2013), is only probable with a fast neutron spectrum. Breeding ^{232}Th - ^{233}U in Th-containing fuel is probable in any type of neutron spectrum.

Numerous studies have examined the alteration of the moderation of the core to improve various characteristics that are affected by the neutron spectrum (Björk, 2012; Fridman and Kliem, 2011; Mozafari and Faghihi, 2013; Sidik et al., 2008; Todosow and Kazimi, 2004; Trellue et al., 2011; Waris et al., 2010; Xu, 2003). In these instances, the neutron spectrum is changed primarily by altering the hydrogen to heavy metal ratio (H/HM) or moderator-to-fuel ratio expressed as MFR or V_m/V_f . It can also be referred to as neutron spectrum shift moderation control. A typical conventional PWR has an MFR value of 1.95–2.00 (Sidik et al., 2008; Todosow and Kazimi, 2004) and H/HM ratio of 3.4 (Weaver and Herring, 2002). Low MFR, V_m/V_f ratios or H/HM ratios can also be used to represent reduced moderated systems, typically by using a tighter fuel rod pitch or thicker fuel pellets.

The ^{232}Th - ^{233}U conversion reaction is favoured when the system moderation is decreased to increase the epithermal neutron spectrum (i. e., when the spectrum hardens)—hardening the neutron spectrum benefits the conversion of ^{232}Th - ^{233}U . In resonances of ^{232}Th , more neutrons will be absorbed, resulting in a more negative MTC (Lau et al., 2012; Todosow and Kazimi, 2004). A prerequisite to achieve breeding of ^{232}Th - ^{233}U is that the number density ratio of $^{233}\text{U}/^{232}\text{Th}$ must be less than the lattice's conversion/breeding performance index ($\sim 2\%$ for a standard 17×17 FA) (Shengyi, 2011). Reduced moderation can lead to increased discharge burn-ups and cycle lengths, and decreased production of MAs, while saving on enrichment requirements (Kim and Downar, 2002; Lindley and Parks, 2012). Due to the lower resonance integral and the higher fast fission threshold of ^{232}Th compared to

conventional uranium fuels, Th-containing fuel can potentially improve safety features in reduced moderated systems (Kim and Downar, 2002).

Ganda et al. (2012) designed a core concept similar to the 4000 MWth reduced moderation boiling water reactor (RMBWR), with modifications: thorium replaces depleted uranium as fertile fuel, the internal blanket and absorbers are removed from the axial reflectors and the fissile region length is increased. They reported that a Th-containing self-sustaining (breeding) RMBWR with stationary fuel and radially uniform FA composition is feasible.

Brown et al. (2015) investigated the potential of continuous recycling of uranium and thorium with a feed containing thorium only. They evaluated the Th-RMBWR reactor with axially heterogeneous seed and blanket configurations in a hexagonal array. The aim was to compare the feasibility of intermediate neutron spectrum systems with fast neutron spectrum systems. They found that the fuel cycle performance for both these systems was comparable and that the limiting factor for intermediate neutron spectrum systems is the number of fission neutrons emitted per neutron absorbed.

Vaidyanathan (2020) examined a potential scenario for transitioning to a thorium fuel cycle in PWRs using bimetallic thorium cladding as a means to provide radial heterogeneity. The low MFR and requirement of heterogeneity are known requirements for significant ^{233}U conversion from thorium. They determined that the MFR is a strong determinant of sustainable operation of a thorium cycle. After the first fuel cycle, reactor models with a low MFR (e.g., 0.954) achieve a significantly higher thorium conversion than models with a higher MFR (e.g., 1.91). Such an improvement was found to lead to further improvements in subsequent cycles, due to the accumulative improvements over several cycles. (The formation of fissile elements in the cladding via conversion and the impact on reactor safety were not considered.)

Wojciechowski (2016) found that for a sufficiently hard neutron energy spectrum a conversion ratio (CR) comparable to that of the fast breeder reactor (FBR) can be achieved, reaching a CR and burn-up of 1.4 and 360 GWd/MTHM respectively. To achieve a conversion/breeding ratio larger than 1, Bi et al. (2013) increased the outer fuel radius to 0.5 cm and added 24 solid zirconium rods in the guide tubes to replace water and decrease the MFR.

Lindley et al. (2013) also reduced the moderation to evaluate TRU incineration. They achieved a harder neutron spectrum by keeping the fuel rod pitch constant but increasing the fuel rod radius from 4.75 to 5.75 mm, to enable full TRU recycling, while achieving sufficient discharge burn-up (40 GWd/MTHM) and a negative MTC. According to them, it would be easier to retrofit exiting cores to reduced moderation pressurised water reactors (RMPWRs), however, for RMBWRs, more substantial changes are required and retrofitting is unlikely.

A summary of some of the most recent studies of Th-containing fuels is listed in Table 2 indicating the reactor type, fissile content, burnup and fuel arrangement and corresponding safety parameters. The table serves to illustrate the wide range of applications and variations in state parameters considered. It is important to note that even though there are general trends that can be expected from Th-containing fuel as discussed before, each design must be evaluated on its own merit in detailed analyses. It is clear that the safety parameter results can vary significantly depending on the fuel composition and arrangement, level of neutronic analysis (pin, FA or Core), stage in the fuel cycle (BOC, EOC, equilibrium cycle), control rod and shim composition, reactor state (HFP, HZP, CZP, ARI, ARO, NoXe, EqXe) and refuelling scheme. Another conclusion that can be drawn from the table is that even though the studies have reported some of the safety parameters as listed, not all are necessarily included in the analysis or the scope of a single research paper. It is therefore recommended to initially evaluate new fuel concepts on a pin and fuel assembly level with neutronic and reactivity coefficient evaluation. If the design is feasible it needs to be expanded to a full core level with thermal hydraulic feedback and fuel performance evaluation.

Table 2
Summary of some Th-containing fuels considered in various studies (2003–2022).

Ref	Reactor	Fissile content	Burn-up (GWd/ MTHM)	Arrangement	Cycle length (EFPD)	Level	BOL/EOL	DTC (pcm/K)	MTC (pcm/K)	β_{eff}	CRW (pcm)	BW (pcm)
Castro et al. (2020)	Agra 2 PWR	15, 18, 23% fissile TRU	33 per cycle	3 homo-geneous FAs	868.5	Full core and FA	BOL EOC	−1.7/-1.5/-2 TRU19/ TRU25/ TRU32 −0.9/-2.7/- 2.2 TRU19/ TRU25/ TRU32	0.4/-1.9/ 0 TRU19/ TRU25/TRU32 −0.1/0.1/-1.4 TRU19/ TRU25/TRU32		19619 TRU19 19842 TRU25 19922 TRU32	−6.5/-4.1/- 5.4 TRU19/ TRU25/ TRU32
Du Toit and Naicker (2018)	EPR	2.54 wt% ²³⁵ U	75	Homo-geneous	730	FA	BOL EOL	−2.85 −4.44	−14.84 −34.14	0.0067 0.004	15218 –	−10.32 −12.1
Galahom et al. (2022)	Westinghouse PWR	4.7 wt% ²³⁵ U 4.7 wt% ²³³ U	70 70	Homo-geneous FA Homo-geneous FA		FA FA	BOC BOC	−1.885 −2.035	– –	0.00656 0.0032	68500 72600	– –
de Stefani et al. (2020)	AP1000	3.2, 4.8, 6.4 wt% ²³⁵ U	60	3 homo-geneous FAs	1360	1/4 core	BOC EOC	−2.45 to −0.91 (various burn- up levels)	−28.38 to −3.52 (various burn-up levels)	0.00683 0.00539	8427 HZP	−8.1 CZP −6.4 HZP −6.5 HFP
Kotlyar et al. (2017)	I2S-LWR	Th–Pu 17 vol% enrichment 64.35 wt% fissile Pu	>90	Homo-geneous		Full core	BOC EOC	−2.68 −2.94	−3.4 −35.2			−6.5 −7.8
Gorton et al. (2019)	AP1000	7.8 wt% ²³⁵ U 20 wt% ThN 80 wt% UN	41.81	Homo-geneous	471	Pin cell	Various burn-up levels	−4.3 to −3.7	−68.5 to −57.5		~23000 BOC	−3.9 to −2.9
Bi et al. (2013)	RMPWR	1.94 wt% fissile (mainly ²³³ U) for U3ThOX FA	27.9 per cycle	Homo-geneous	2646 (6 cycles of 442)	1/4 core	BOC EOC		−4.07 ARO/ NoXe −9.1 HZP/ EqXe −26.8 HFP/ EqXe −38.9 HZP/ EqXe −68.5 HFP/ EqXe	0.00586 0.00501		−6.2 −7.3
Tucker et al. (2015)	Westinghouse PWR	5.5 wt% PuO ₂ 56.35 wt % ²³⁹ Pu, 8.02 wt% ²⁴¹ Pu)		1/3 homo-geneous FAs in hetero-geneous blanket core arrangement		Core	BOC	−3.693		0.00607	10574	
Li et al. (2021)	RM-AP1000	4.64 wt% ²³⁵ U	36.5 per cycle	Radial hetero-geneous duplex pin with thorium in centre and uranium periphery		FA	BOC EOC	−2.3 −1.7	−42 −27		~28700 ~19500	
Baldova et al. (2014b)	Westing-house PWR	8.86 wt% ²³³ U in seed 0.5 wt % ²³³ U blanket	48.7 seed, 8.1–8.9 blanket	Hetero-geneous seed and blanket FAs with larger blanket pins	330 per cycle	Core	BOC EOC	−4.2 −4.4	−26.7 −33			−5.1 −5.2
Lindley et al. (2014a)	Westinghouse RMPWR	Equilibrium fuel at 3.59 at% ²³⁹ Pu 1.07 at% ²⁴¹ Pu 1.96 at % ²³³ U 0.42 at% ²³⁵ U 7.04 at % total fissile	Th-TRU: 57.8 Th-U3: 31.8 Core: 41	WATU: homo-geneous assemblies in hetero- geneous checkerboard loading	346 per cycle	Core	BOC EOC	−3.8 ARO -2.7 ARI −3.9	−8.8 ARO −58.4 ARI −17.4			
		Equilibrium fuel 3.65 at% ²³⁹ Pu 1.14 at% ²⁴¹ Pu 2.03 at % ²³³ U 0.46 at% ²³⁵ U 7.28 at % total fissile	Th-TRU: 60.8 Th-U3: 30.1 Core: 41.2	TPUC: TRU pins at the periphery of the FA with U3 pins at the centre			BOC EOC	−3.6 ARO -2.7 ARI −3.8	−12.1 ARO −68 ARI −19.6			

4. In-core neutronic behaviour

The properties of the most significant isotopes were discussed in Section 2. However, the real behaviour of the Th-containing reactor will be a result of the combined effect of the different isotopes (composition) as well as the neutron spectrum, the configuration, etc. Therefore, each system should be analysed on a case-by-case basis. This section addresses the burn-up, delayed neutron fraction, reactivity coefficients and reactivity management in such studies. Table 2 presents a summary of some of the most recent studies carried out to compare delayed neutron fractions, RCs and control rod worth (CRW).

4.1. Burn-up

Homogeneous (ThU)O₂ has a slightly lower burn-up than UO₂ fuel with the equivalent ²³⁵U initial loading in short-cycle-length fuel reloading strategies (Joo et al., 2004). (When enrichment remains unchanged in Th-containing fuel, in comparison with conventional fuel, the total fissile content is reduced). To obtain acceptable burn-ups, (ThU)O₂ requires a higher initial enrichment (Weaver and Herring, 2002). A higher enrichment may necessitate the addition of more burnable absorbers to counteract the excess reactivity at BOL. The addition of thorium decreases reactivity at the BOL (and the need for neutron burnable absorbers) and the reactivity swing during life due to the larger thermal neutron capture cross section of ²³²Th (Galperin et al., 2002; Lau et al., 2013; Tucker et al., 2015). Lower reactivity swings simplify the operation for the thorium cycle (Kok, 2009).

Due to the conversion of ²³²Th to ²³³U, reactivity in (ThU)O₂ reactors is more stable during long burn-ups than in UO₂-fuelled reactors (Herring et al., 2001). According to Zhao et al. (2001), self-shielding is responsible for the initial 'burnable poison' effect and the reactivity gain near the EOC. Changes in self-shielding appear to contribute most to the burn-up extension; they also hinder the production of ²³⁹Pu. Since the reactivity vs. burn-up gradient for thorium fuel is flatter than that of UO₂, less ²³⁵U is required in the (ThU)O₂ to achieve the same discharge burn-up. At the EOL, the k_{∞} (eigenvalue) may be higher, potentially increasing the power (Galahom et al., 2022) or the cycle length. (ThU)O₂ cores with high burn-up may require reduced enrichment, separation and total heavy metal feedstock than a UO₂ core with the same cycle length.

Because ²³³U has a lower recoverable energy per fission than ²³⁵U (see Table 1), the recoverable energy per fission decreases as ²³³U breeds into the fuel. Consequently, a slight increase in fissions is required to sustain the same power level as the ²³³U contributions increase (Trellue et al., 2011). "This may be more complicated due to other competing reactions and becomes prominent at later stages in the fuel-cycle when sufficient amounts of ²³³U are present" (du Toit, 2017).

The evolution of the multiplication factor for the Th-TRU assemblies as developed by Castro et al. (2020) decreases more slowly than for UO₂. This is anticipated because the creation of ²³³U balances out the fissionable and fissile isotope burn-up in the reactor when using a Th-containing fuel. Due to its 27-day half-life, the concentration of ²³³Pa increases during the first few days of irradiation in all TRU cases, before levelling off over time. The TRU core has a conversion ratio that is substantially higher than that of the typical UO₂ core.

Shwageraus et al. (2004) observed an increase in burn-up of micro-heterogeneous thorium-uranium fuel, with a concomitant improvement in economics. The observed PWR operating cycle improvements of up to 15% (compared to the reference fuel) were mainly attributed to neutron spectral shift and, to a lesser extent, to mutual resonance shielding of uranium and thorium.

A neutronics comparison of micro-heterogeneous duplex fuel with UO₂ fuel in a PWR reveals that a (ThU)O₂ duplex fuel can match the discharge burn-up of UO₂ fuel with ²³⁵U enrichment of 5%–20% (Li

et al., 2021).

Homogeneous Th-containing fuel in the inherently safe light water reactor was investigated (IS-LWR) by Kotlyar et al. (2017). Higher discharge burn-ups (20% above 100 GWd/MTHM) and thus deeper plutonium and transuranic elements incineration (up to 62% of plutonium burnt) and improved utilisation (by 22%) were achieved by increasing the number of batches in various refuelling strategies. To withstand longer exposure periods, with significantly lower degradation rates compared to traditional Zr-based alloys, advanced steel cladding, FeCrAl and baseline fuel U₃Si₂ were used. The most favourable loading pattern with respect to cycle length performance was achieved through their simulated annealing optimisation technique.

Long et al. (2004) studied the thermal, mechanical and chemical behaviour of (ThU)O₂ and (ThPu)O₂ during in-service and under hypothetical accident conditions in LWRs. They found that these fuels can be designed to perform safely, to burn-ups equivalent to burn-ups achieved with 100% UO₂ fuel.

To achieve 24-month fuel cycles for a Th-containing EPR core, the EOL eigenvalue of (ThU)O₂ fuel should be greater than or equal to the eigenvalue of the uranium-only EPR. Compared to uranium alone, the eigenvalue for the Th-containing FA begins at a lower value, implying lower soluble boron needs and less neutron captures in Gd₂O₃. The total reactivity swing is significantly lower compared to uranium cores. "The reduction in the reactivity swing can be explained by the better breeding properties of ²³²Th/²³³U as well as the lower initial excess reactivity due to captures in ²³²Th" (du Toit, 2017). ²³³U is bred in the pure ²³²Th axial sections. The fissile content of Th-containing fuel decreases at a slower rate with time, implying that longer fuel cycles are possibly due to improved conversion. The initial fissile content for the Th-EPR by Du Toit and Naicker (2018) is less than half of what has been reported in previous literature due to the axially heterogeneous design of the EPR.

The Th-AP1000 suggested by de Stefani et al. (2020) has a conversion factor of 0.78, against 0.65 for the standard AP1000, and the evolution of the eigenvalue (k_{eff}) with burn-up is relatively flat (for the first cycle). However, for the second, third and fourth cycles of the Th-AP1000, the slope of k_{eff} is much more pronounced, resulting in the fissile content having to be increased to maintain cycle lengths.

Galahom et al. (2022) compared the neutronic characteristics of UO₂ with (Th²³⁵U)O₂ and (Th²³³U)O₂. Although the fissile content of (Th²³⁵U)O₂, (Th²³³U)O₂ and ²³⁵UO₂ at BOC was the same, the k_{∞} was the highest for (Th²³³U)O₂ at BOC due to the higher average number of neutrons produced for ²³³U (see Table 1). At EOC, both thorium fuels achieved a larger k_{∞} than UO₂; (Th²³³U)O₂ was the highest. The η was compared throughout the cycle. The η increases linearly for UO₂ due to ²³⁹Pu and ²⁴¹Pu being converted from ²³⁸U. ²³⁹Pu and ²⁴¹Pu have significantly higher η values (Table 1). Although both (Th²³⁵U)O₂ and (Th²³³U)O₂ contain the same amount and type of fertile material, (Th²³³U)O₂ has a higher CR than (Th²³⁵U)O₂. This is true because the number of fission neutrons released per neutron absorbed for ²³³U is greater than for ²³⁵U.

Hassan et al. (2020) investigated the use of homogenous (Th²³³U)O₂ to replace conventional fuel in the Russian VVER-1200 PWR without any assembly design modifications. A 9.45% improvement in burn-up and a significant fuel cycle improvement was achieved in the VVER-1200 without any modification of the assembly design or increasing enrichment. Dwidar et al. (2015) evaluated the VVER first core with homogeneous thorium-uranium fuel and found that the amount of thorium and the position of thorium assemblies inside the reactor (where the positioning of thorium on the core-periphery rendered the best results) were key determinants of the core cycle length.

Rouf and Su'ud (2016) evaluated various fuel compositions for providing a higher conversion ratio and long operational cycle length. The fuel composition was adjusted to obtain increased cycle lengths; 14

and 10 years for power levels of 600 MWt and 1000 MWt, respectively, was achieved. The best design had a 45% fuel volume fraction and 0.0125% gadolinium as burnable poison. Lapanporo and Su'Ud (2022) studied the performance of Th-containing fuel with Zirlo cladding in a 300-MWt small modular PWR by varying the percentage of ^{233}U in thorium oxide fuel by 3%–8%, and varying the burnable poison ^{231}Pa by 0.2%–5%. The influence of the fuel volume fraction (40%–60%) was investigated. They found that when using 4–6% of ^{233}U , with a fuel volume fraction of 60% and the addition of 2.5%, ^{231}Pa performed the best. The following were recorded: cycle length up to 19 years, BOL excess reactivity 2.57% dk/k, and excess reactivity at EOL 0.87% dk/k. In both studies, the burn-up was not quantified, but rather expressed in terms of time, which makes it quite difficult to make comparisons with findings of other studies; it was also unclear whether the units at% or wt % or vol% were used.

Gorton et al. (2019) investigated the reactor performance and safety characteristics of ThN and UN fuels in PWR under normal operating conditions, in comparison with UO_2 fuels. The discharge burn-up was lower for the UN and (ThU)N (mixed thorium uranium nitride) fuels compared with UO_2 due to the increased heavy metal loading (because of the increased density of nitrides) and increased absorption from ^{14}N .

4.2. Delayed neutron fraction

If ^{235}U is used as fissile material for Th-containing fuels, the effective delayed neutron fraction will be similar for Th-based fuels and conventional uranium fuels at BOL. The fuel composition varies as the cycle progresses and β_{eff} decreases due to the production of the fissile isotope ^{233}U (^{233}U has lower β_{eff} fractions than ^{235}U , see Table 1).

The effect of decreasing β_{eff} is also common for UO_2 fuels, as ^{239}Pu and ^{241}Pu (with lower β_{eff} fractions) are converted from ^{238}U . A smaller β_{eff} later in the cycle will be more difficult to control during a reactivity-initiated accident (Björk, 2012) (especially the rod ejection accident (Bi et al., 2013). Cores with lower β_{eff} have a smaller safety margin to prompt criticality than conventional cores (Björk et al., 2013). Nonetheless, as described in Section 4.3, the more negative DTC may potentially compensate for this effect (Björk, 2012).

Long et al. (2004) noted that Th-containing fuels performed more poorly than conventional fuels by a smaller delayed neutron fraction. The drawback of the most promising micro-heterogeneous Th-containing fuels is the reduced delayed neutron fraction. However, this parameter is still within normal LWR safety limits. Castro et al. (2020) found that for Th-TRU fuels the delayed neutron fraction increases slightly over the cycle. However, the delayed neutron fraction in the conventional UO_2 fuel maintains a higher value throughout the cycle. The reason is the low β_{eff} of ^{233}U and the large amount of ^{239}Pu in the TRU fuel also having a low β_{eff} (see Table 2). Tucker et al. (2015) was also interested in the delayed neutron fraction and reported that, at all the time steps of interest, the β_{eff} value of the Th-MOX configuration is lower than that of the UO_2 configuration.

Du Toit and Naicker (2018) also noticed a reduced delayed neutron fraction for their homogeneous thorium-uranium assembly at EOL. When they compared the same uranium and thorium-uranium fuel on a full-core level, the delayed neutron fraction, calculated for the Th-EPR, was 4.2% less than the result for the U-EPR at BOL. Nonetheless, it will be reduced with burn-up as ^{233}U is bred. De Stefani et al. (2020) compared the delayed neutron fraction of their Th-AP1000 with the AP1000 at BOL and EOL. The Th-containing core has values of β_{eff} 0.00018 and 1E-05 lower at BOC and EOC, respectively. This is expected, as the first cycle is mainly driven by ^{235}U . Further analysis is required to calculate the β_{eff} of the second, third and fourth cycles.

4.3. Reactivity coefficients

The reactivity coefficients of Th-containing cores are comparable to those of the conventional PWRs (Raites et al., 2009; Tsige-Tamirat, 2011). The DTC and MTC were more negative, but nonetheless within acceptable ranges (Du Toit and Naicker, 2018; Dziadosz et al., 2004; Joo et al., 2004; Long et al., 2004). Additional resonance peaks resulted from the simultaneous presence of ^{232}Th and ^{238}U , leading to a decrease in the resonance escape probability, which enhances the DTC, in comparison with ^{238}U only fuel. This lower consequent resonance escape probability and the higher total neutron capture cross section rates resulting from the ^{232}Th contribute significantly to the more negative DTC (Lau et al., 2014). (The enhanced DTC is not only attributed to additional resonance peaks but arises from the increased resonance integral due to the addition of ^{232}Th .)

For Th-containing fuel cores, a lower fast fission cross section results in a more negative void coefficient (VC) (Kim and Downar, 2002). Morrison and Parks (2020) found that the presence of ^{241}Am in thorium-plutonium fuels is unlikely to result in unpredictable trends in VC with burn-up. They reported that the advanced boiling water reactor (ABWR) had significantly higher full-core fissile masses than the PWR or RMBWR (Morrison and Parks, 2020). ^{232}Th is a suitable fertile isotope, especially when the focus is TRU incineration in LWRs, where the MTC and/or VC tend to become positive; fortunately ^{232}Th has a beneficial effect on the MTC (Lindley et al., 2013).

Ganda et al. (2012) reported negative reactivity coefficients and VCs for the entire fuel life of the RMBWR. The reference design has a too negative VC, making an acceptable shutdown reactivity margin at cold zero power (CZP) impractical. The addition of a small amount of plutonium from used LWR nuclear fuel was found to be effective in reducing the magnitude of the VC, allowing for an adequate shutdown margin under CZP conditions; it also flattens the axial power distribution. A reduction in the coolant mass flow rate or increase in the total power, renders an overall negative VC, while causing a negative VC at the lower axial regions and a positive VC at the upper regions of the seed. This may induce unstable axial power oscillations, rendering the design unfeasible.

Hassan et al. (2020) also found that Th-containing fuel safety characteristics were acceptable, albeit generally lower than in LEU during burn-up; LEU was found to have a more negative MTC. Gorton et al. (2019) investigated the DTC and MTC for the nitride-based thorium fuels and found that they were within the acceptable limits. They also investigated the neutronic impact of ^{15}N enrichment on RCs; however, such enrichment will increase the production cost.

Rahman and Franceschini (2012) assessed the possibility of burning and multi-recycling TRU in a Th-containing fuel PWR for comparison with more typical alternatives such as U-MOX. Although homogeneous assembly designs gave simple loading patterns and the highest rate of TRU transmutation, the rapid increase in the TRU content of the recycled fuel challenges safety coefficients, fuel handling and reactivity control, hence limiting the number of cycles for such fuels.

Morrison and Parks (2020) conducted a study on thorium-plutonium fuel containing 0–30 wt% Am with varying Pu vectors as fuel for the ABWR and observed the same predictable trends in reactivity feedback coefficients as found in PWRs and RMBWRs. Tucker (2016) found that all fuel temperature coefficients for the Th-MOX configuration are lower than those of the UO_2 configuration, and (with the exception of the beginning of third cycle) the Th-MOX configuration's moderator temperature results are also more favourable. The more favourable temperature coefficients could ameliorate the impact of β_{eff} on the controllability of the Th-MOX configuration, however, they also called into question the magnitude of the increase in plutonium content for the third cycle.

The stronger negative feedback of DTC and MTC results in a lower CRW, which reduces the shutdown margin (Galahom et al., 2022) and

makes Th-containing fuel more susceptible to cooldown incidents or changes in water temperature than UO_2 cores (Dziadosz et al., 2004; Lau et al., 2012). On the other hand, a more negative DTC could improve performance during transients (Lindley and Parks, 2012) and, due to ^{233}U cross sections varying the least in the epithermal range, cooldown incidents would be less problematic (Greneche et al., 2007; Perry and Weinberg, 1972). Furthermore, the more negative MTC in $(\text{ThU})\text{O}_2$ results in a lower axial offset of the power compared with the conventional uranium core (Lau et al., 2014).

4.4. Reactivity management

Due to the abundance of thermal absorbers and the hardening of the neutron spectrum in Th-containing fuels (Bi et al., 2013), the reactivity worth is reduced (Björk, 2012; Dziadosz et al., 2004). The latter is a common experience with MOX-fuelled cores and it poses no operational restriction in modern LWRs (Björk, 2012). The higher the plutonium content in the Th-containing fuels, the harder the neutron spectrum, which results in reduced reactivity worth (Kotlyar et al., 2017).

The lower boron worth (BW) requires more dissolved boron at the BOL. However, because of the possibility of the MTC becoming positive, the maximum boron concentration is restricted (Dziadosz et al., 2004). This may cause a reduction in shutdown margin and complicated reactivity control. That is why Kotlyar et al. (2017) increased their boron enrichment up to 90%. However, Saglam et al. (2004) noted that $(\text{ThU})\text{O}_2$ fuel cycles have a lower soluble boron concentration and burnable poison requirement than conventional uranium fuel cycles. One of the concerns pertained to the Th-containing FA developed by Du Toit and Naicker (2018), is the lower BW at the EOL; nonetheless, the BW is most likely within acceptable limits. The new design was created by reducing, and eventually eliminating, the burnable poison requirements, as well as slightly reducing the overall initial fissile content whilst maintaining a 24-month fuel cycle.

Various burnable absorbers for Th-containing fuel have been proposed in several studies. Björk et al. (2013) suggested the integral fuel burnable absorber (IFBA) concept, which involves coating the surface of the fuel pellets with a thin layer of zirconium boride. Wet annular burnable absorber rods were also proposed, in which cladding and water surround a tiny burnable poison ring (Björk, 2012). To assist in controlling reactivity and radial power peaking, Saglam et al. (2004) suggested discrete burnable poison rod assemblies. Galahom et al. (2022) proposed the use of erbium instead of gadolinium as an integral burnable absorber for Th-containing fuels. The effect of gadolinium is much more pronounced at the very beginning of the cycle, whereas erbium depletes more slowly. Large reactivity swings can result in power and temperature fluctuations, which in turn can negatively affect the thermomechanical and physical properties. They also suggested using erbium to manage the radial power distribution for the FA.

Due to the high capture cross section of ^{232}Th , the burnable absorber requirement in Th-containing fuels could be reduced (Lau et al., 2012). TRU fuel also behaves like a neutron absorber. It is for this reason that the core results of Castro et al., (2020) indicated that the insertion of burnable poison rods is not required if reprocessed fuel spiked with thorium is used. The Th-AP1000 described by de Stefani et al. (2020) had a higher initial excess reactivity than the AP1000, however, fewer burnable absorbers were required due to increased thermal absorption in thorium. They eliminated the use of IFBAs and used Pyrex burnable absorbers in selected FAs. However, to modify the AP1000 for thorium, they had to replace the grey control banks with black control banks.

The CRW will be significantly influenced by the enrichment, composition and anticipated cycle duration of the thorium-containing fuel, and it will vary from case to case. According to Greneche et al. (2007), because the reactivity swing and power peaking are less pronounced, greater controllability in Th-containing PWRs than in reactors with conventional uranium cores can be expected. Achieving a high rod

worth is difficult in a hard neutron spectrum. It is for this reason that Lindley et al., 2014d employed solid pellets of B_4C with 95% ^{10}B enriched boron. The CRW for Th-TRU cores at BOL was comparable at 50% insertion; however, at 100% the average of the three Th-TRU cores had a CRW that was 26% lower (Castro et al., 2020). According to du Toit and Naicker (2018), the total CRW shows that the Th-EPR fuel has a much higher CRW than the U-EPR due to the use of B_4C at BOL. Galahom et al. (2022) compared the CRW for $(\text{Th}^{235}\text{U})\text{O}_2$, $(\text{Th}^{233}\text{U})\text{O}_2$ and $^{235}\text{UO}_2$ at hot full power (HFP). $(\text{Th}^{233}\text{U})\text{O}_2$ had a reduced worth of 400 pcm, while $(\text{Th}^{235}\text{U})\text{O}_2$ had a more significant reduced worth of 4500 pcm. The reactivity worth of the control rod in the case of UO_2 is greater than in $(\text{Th}^{235}\text{U})\text{O}_2$ and $(\text{Th}^{233}\text{U})\text{O}_2$ because the thermal neutron absorption cross section of ^{232}Th is larger than in ^{238}U .

According to Gorton et al. (2019) the shutdown margin is insufficient due to reduced soluble BW and CRW, which warrants the control system change. The Th-MOX fuels investigated by Tucker (2016) showed that the shutdown margins were lower than those of the UO_2 composition, however, they were well above the required USA Nuclear Regulatory Commission value of 1300 pcm.

5. Thermal-hydraulics and fuel performance

$(\text{ThU})\text{O}_2$ fuel cycles tend to have lower PPFs (Saglam et al., 2004) and power peaking problems are easier to handle with Th-containing fuels (Kok, 2009) in comparison to conventional fuel. During normal operation, $(\text{ThU})\text{O}_2$ can operate under colder conditions and have better fission product retention. This means that $(\text{ThU})\text{O}_2$ could reach higher burn-ups, increase fuel cycle lengths, improve plant capacity factors and decrease spent fuel (Herring et al., 2001). Lower fuel pellet temperature, less swelling, reduced pellet cladding mechanical interaction (PCMI) and a larger margin for fuel melting are all advantages of increased thermal conductivity in Th-containing fuels (Björk, 2012).

Lau et al. (2012) devised a thorium-uranium design (requiring less gadolinium) that reduced the pin peak power at BOL. Because the margin to reach the departure from nucleate boiling (DNB) is greater, operation and safety were improved. They established that an equilibrium $(\text{ThU})\text{O}_2$ core could reduce the maximum axial offset by a third “due to the stronger MTC and an 8% lower minimum AO compared with a standard uranium core, due to a more homogenous radial power distribution” (improving core thermal margins and core stability). The use of thorium-containing fuel in PWRs could improve thermal hydraulics due to a flatter axial distribution and the reduction in pin power peaking. Improved thermal margins could potentially be used to increase reactor power or can allow for more adaptive core designs with reduced neutron leakage, whilst maintaining safety margins (Lau, 2014).

The combinations of $(\text{ThU})\text{O}_2$ compared with those of UO_2 have somewhat higher decay heat, lower thermal conductivity at very high temperatures, higher fission gas production per fission, but a lower rate of release of the fission gas and a higher melting temperature. During an accident, such as a major break loss-of-coolant accident (LOCA), $(\text{ThU})\text{O}_2$ has less stored energy but a slightly higher internal heat generation rate than UO_2 . This will alter the maximum cladding temperature and the timing of fuel rod rupture (Herring et al., 2001).

Ganda et al. (2012) studied a RMBWR with seed and blanket containing thorium. The reactor had a maximum linear heat generation rate significantly lower than that of the RMBWR core at power levels of ~ 4000 MWth. Preliminary estimates indicated that safe operation of the proposed Th-containing RMBWR core is possible at higher power, even if the ABWR core diameter is not increased.

Shwageraus et al. (2004) showed that some micro-heterogeneous fuels exhibit challenges to meet thermal-hydraulic design requirements, but that it could nevertheless be viable to meet or exceed conventional fuel burnup. In their investigation of fuels, Long et al., (2004) determined that Th-containing fuels performed more poorly than conventional fuels—there was a higher production of fission gas and

decay heat.

Liu et al. (2020) evaluated fuel performance by investigating two-layer SiC cladding in combination with Th-containing fuels under normal conditions. They evaluated both the zircalloy and two-layer SiC cladding for three compositions: (ThU)O₂, (ThPu)O₂ and conventional UO₂. They found that mixing thorium with uranium reduced the fuel centreline temperature by 100 K (compared with traditional and thorium-plutonium fuels with the zircalloy). A lower centreline temperature reduces the fission gas release and the plenum pressure. However, when applying the two-layer SiC cladding, the centreline temperatures for all three compositions increased by 50–200 K, which can result in a higher fission gas release and plenum pressure. Nonetheless, the two-layer SiC cladding delayed the gap closure time, which points to a delayed PCMI and the probability of improving reactor safety when using the two-layer SiC cladding.

These fuels were investigated further under accident conditions. Qiu et al. (2021) determined that during reactivity-initiated accident conditions the fuel centreline temperature of Th-containing fuels performed more poorly (~100 K) than conventional UO₂, irrespective of the cladding. Nonetheless, SiC and Th-containing fuels have a higher melting point margin and a lower thermal expansion coefficient than those of traditional UO₂-zircalloy fuels, and thus a higher maximum temperature would not affect fuel safety (Carpenter, 2010). During a LOCA, the Th-containing SiC fuels behaved better, with a maximum temperature 200 K lower than that of the UO₂-zircalloy fuel. Further developments should focus on (ThU)O₂ with two-layer SiC cladding, while increasing the fuel thermal conductivity, to reduce the centreline temperature (Qiu et al., 2021).

Loza Peralta et al. (2021) adapted the DIONISIO code for (ThPu)O₂ and (ThU)O₂ fuels in terms of burn-up distribution, thermomechanical behaviour and fission gas release by comparing the predicted data with results of experiments with (ThPu)O₂ in the Obrigheim KWO PWR and BR-2 reactors (Pöml et al., 2015; Somers et al., 2013). It was found that the modification was acceptable, specifically in terms of species distribution and thermomechanical behaviour. However, differences were identified in the release of fission gas in (ThPu)O₂ fuels (Loza Peralta et al., 2021).

Van der Walt et al. (2023) proposed axially micro heterogeneous thorium-uranium fuel pin in a conventional PWR. PPFs became limiting factors at BOL in axially heterogeneous thorium-uranium fuel concepts, leading researchers to introduce fuel denaturation, resulting in reduced and acceptable power peaking and peak-to-peak flux differences.

In the Lapanporo and Su'ud (2022) study of Th-containing fuel in a 300-MWt small modular PWR, with various thorium-uranium combinations and ²³¹Pa, the radial power distribution over the burn-up cycle did not change significantly, whereas changes in power distribution in the axial direction were significant; the radial PPF at BOL was 1.53 and 1.57 at EOL, whereas in the axial direction the PPF at BOL was 1.40 and 1.21 at EOL.

The homogeneous AP-Th1000 core proposed by de Stefani et al. (2020) had a 6% higher PPF than the uranium-only AP1000 at BOC. Nonetheless the AP-Th1000 core presented an acceptable minimum DNB ratio and thermal-hydraulic safety limits were met. Baldova et al. (2014b) attempted a similar thorium-uranium modification of a PWR using heterogeneous seed and blanket regions within a FA. Due to the very high peak power density at BOC, the thermal power had to be reduced from 3358 to 1943 MW to meet thermal-hydraulic safety limits.

Ramdhani et al. (2019) studied two heterogenous core design options for Th-containing fuel cycles in PWRs using the WASB design. The seed units were loaded with UO₂ fuel rods and the blanket with ThO₂-UO₂. Blanket units loaded with 75% ThO₂ and 25% UO₂ (with 15 wt% enrichment) resulted in the lowest peak-to-average power distribution in WASB-I designs, whereas the best results in WASB-II designs were obtained with blanket units loaded with 75% ThO₂ and 25% UO₂ (12 wt% enrichment). The WASB-I core loading pattern had a better

power distribution with smaller peak-to-average power distribution than the WASB-II core loading pattern.

6. Waste and proliferation

ThO₂ is less corrosive in air and oxygenated water than UO₂ making ThO₂ a better type of waste than UO₂ (Herring et al., 2001). Thorium-uranium dioxide spent fuel appears to be a much more chemically stable waste form than uranium oxide spent fuel. This inertness of ThO₂ could help in retarding the migration of fission products and actinides in the repository. ThO₂ will also remain intact for longer periods than uranium, even if groundwater permeates the fuel in deep geological repositories (Elsevier, 2012). The increased robustness of ThO₂ could potentially allow longer in-core residence times (higher burn-ups), thereby also reducing waste (Kazimi et al., 1999). Studies in which use was made of a single enriched fuel showed that Th-MOX fuel outperforms conventional MOX fuel in terms of reducing high-level waste, the burning of stockpiled plutonium and proliferation-resistant spent nuclear fuel (Uguru et al., 2021). Wilson et al., (2009) demonstrated that a fleet of three different water reactors, using mixed uranium-plutonium and thorium-uranium cycles, offers great potential to reduce uranium consumption and produce significantly lower amounts of plutonium and MA waste.

6.1. TRU production

Th-containing spent fuels contain radioactive isotopes that are lower in volume and mass than U-based nuclear waste. Due to the atomic number of ²³²Th being six units less than ²³⁸U, the production of plutonium and MA is reduced, especially if actinides are recycled (Van Gosen et al., 2009). The total production of plutonium from Th-containing fuels is significantly lower (by a factor of three) compared with conventional PWR fuel (Shwageraus et al., 2004). The use of Th-containing fuels in conventional PWRs decreases plutonium generation by 45% (Galperin et al., 2002). The number of TRU isotopes in spent fuel decreases by two orders of magnitude when thorium replaces ²³⁸U as the fertile element (Hania and Klaassen, 2012). Ganda et al. (2012) found that the axial seed and blanket Th-containing BWR, using reduced moderation, provides efficient incineration of LWR-generated plutonium. The fraction of fissile plutonium in the fuel discharged from this RMBWR core is very low and it does not pose additional proliferation concerns. Vaidyanathan (2020) proposed a uranium PWR with bimetallic thorium-zirconium cladding in a radial micro-heterogeneous design that reduced the TRU generation by a factor of four, compared with conventional UO₂ fuels. Subsequently, he suggested a core mixed with the previous micro-heterogeneous design but with the addition of new rods, where the fissile part of the fuel consists of thorium and uranium oxide pellets (instead of uranium oxide only). TRU can be reduced by up to six times. Within c. 200 years, the thorium cycle spent fuel radiotoxicity is expected to fall to acceptable levels, in comparison to the radiotoxicity of TRU waste (from the uranium cycle) will continue for tens of thousands of years (Vaidyanathan, 2021).

6.2. Proliferation resistance

Th-containing spent fuel is significantly more proliferation resistant than UO₂ fuel. The daughter products of ²³²U in Th-containing fuel cycles increase the proliferation resistance. Proliferation resistance requires the denaturation of the thorium sections (in micro-heterogeneous fuels) to evade pure ²³³U production by allowing significant amounts of ²³²U and ²³⁸Pu having high-energy gamma/alpha emitter daughters, respectively, to accumulate during the fuel cycle (Ashley et al., 2012; IAEA, 2003; Rineiski and Kessler, 2010). In addition, ²³⁸Pu has high decay heat and exhibits spontaneous neutron production. High decay heat, high-energy emitters and spontaneous neutron production

complicate the production of nuclear weapons and deter nuclear proliferation (MacDonald et al., 2002).

A non-proliferation fuel, as proposed by Alhaj et al. (2017) for the AP1000, includes a small amount of ^{238}U from enriched or depleted uranium to reduce the attractiveness of the resulting uranium. Thorium-plutonium MOX fuels generate spent fuel with $\sim 90\%$ ^{233}U . Notwithstanding the presence of ^{238}U leading to an increase in the fissile content of plutonium, conversion from reactor-grade fissile material to weapon-grade does not follow. On the other hand, ^{238}U degrades uranium from weapons-grade to non-weapons-grade. Adding uranium to thorium-plutonium MOX results in the production of less attractive uranium. The addition of only 1% uranium to a fresh thorium-plutonium MOX fuel nearly doubles the critical mass. The critical mass increases significantly at higher uranium concentrations—it is about 10-fold greater—reaching about ten times that at 5% additive uranium.

Zhang et al. (2018) investigated Th-containing hydride fuels and found three times higher ^{232}U – ^{233}U ratios in the discharged thorium hydride fuel than in the other blankets, affording an improvement in the proliferation resistance of the thorium hydride blanket. Ganda and Greenspan (2009) assessed the feasibility of plutonium recycling in a PWR in the form of plutonium hydride (PuH_2) mixed with uranium and zirconium hydride ($\text{ZrH}_{1.6}$), referred to as PUZH, uniformly loaded in each fuel rod. Relative to MOX, the discharged PUZH fuel has a reduced fissile plutonium fraction (45% vs 60%), 15% smaller MAs inventory, and more than double the spontaneous fission neutron source intensity and decay heat per gram of discharged TRU.

Kang et al. (2001) investigated HWRs and LWRs fuelled with natural uranium or LEU, or containing thorium mixed with uranium, or in separate target channels. They discovered that at high burn-up (70 GWd/MTHM) the PWRs fuelled with Th-LEU fuel produced ^{233}U , with ^{232}U contamination levels of about 0.4%. However, just as it is possible to produce weapons-grade plutonium from low-burn-up fuel, it is also feasible to use HWRs to produce ^{233}U with only a few ppm of ^{232}U if the thorium is separated in target channels and discharged a few times more frequently than natural uranium driver fuel. As a result, the proliferation resistance of thorium fuel cycles is highly dependent on how they are implemented. On the one hand, gamma radiation from ^{232}U renders ^{233}U from high burn-up ^{232}Th – ^{233}U fuel cycles more hazardous than plutonium. Due to its low rate of spontaneous neutron emission, the requirement for remote handling of heavily ^{232}U contaminated ^{233}U in a closed fuel cycle provides a strong incentive for integration of reprocessing and fuel fabrication. In the integral fast PWR proposal, such integration was envisioned for plutonium breeder PWRs (Wade and Hill, 1997). Nevertheless, no fuel cycle involving the separation and recycling of ^{233}U would approach the proliferation resistance of unprocessed spent fuel, the radiation dose rate of which is in the order of 1000 rem/h at 1 m for decades after discharge (Lloyd et al., 1994).

Greneche (2006) compared the positive and negative radiological/nuclear/chemical characteristics of thorium as a fuel for prototype or commercial nuclear reactors, notably in HTR's, by analysing updated data on world-wide thorium resources, and considering sustainability of nuclear energy. The authors considered open and closed fuel cycles and the impact on waste streams and proliferation issues related to the use of the thorium cycle. Their all-encompassing appraisal of the technical features of various thorium fuel cycle options, shed light on the interest in the thorium cycle for the development of sustainable nuclear energy.

6.3. Radiotoxicity

The radiotoxicity of actinides for thorium-uranium waste can be reduced by about three orders of magnitude in comparison with conventional PWRs (David et al., 2014). For fuel cycles based exclusively on ^{232}Th and ^{233}U , the radiotoxicity of actinides is about one-tenth that of

closed uranium-plutonium fuel cycles over 10,000 years, upon disposal (Gruppelaar et al., 1999).

A multi-recycle system investigated by Yun et al. (2010) burns ^{232}Th – ^{233}U . This is achieved by recycling the total content of the fuel, apart from the fission products and all non-uranium and non-thorium heavy elements. They found that the normalised radiotoxicity and decay heat is higher than in conventional PWR UO_2 fuel at discharge because of the lower burn-up (18 GWd/MTHM). Nonetheless, the normalised radiotoxicity becomes lower than UO_2 after 20 years and the decay heat becomes lower after 50 years. The normalised radiotoxicity of multi-recycled ^{232}Th – ^{233}U spent fuel is dominated by fission products and uranium isotopes (mainly ^{232}U) from 10 to 100 years. Subsequently, ^{233}U slowly decays to ^{229}Th , which is the dominant isotope from 1000 years to roughly a million years after operation. Note that ^{210}Po , a daughter product of ^{234}U (although present in very small amounts), is significant in terms of ingestion toxicity. The radiotoxicity of the multi-recycled fuel reaches natural uranium levels at about 10,000 years, as opposed to 200,000 years for conventional UO_2 PWR fuel.

Mirvakili et al. (2015) compared $(\text{Th}^{233}\text{U})\text{O}_2$ and $(\text{Th}^{235}\text{U})\text{O}_2$ fuel. Their burn-up results revealed that ^{230}Th is only produced in the $(\text{Th}^{233}\text{U})\text{O}_2$ cycle, at insignificant concentrations. ^{230}Th is an alpha emitter and has a long half-life of 7.54×10^4 years. ^{231}Th is produced in both the above fuels. ^{231}Th is a beta emitter that decays to ^{231}Pa (an alpha emitter with a half-life of 3.28×10^4 years). ^{233}Th (a beta emitter) is found in both fuels, but at concentrations of <1 g.

The radiotoxicity of thorium-uranium oxide (mainly recycled ^{233}U) fuel developed by Bi et al. (2013) is drastically reduced (compared with other spent fuel) at the beginning after disposal (due to the reduction of TRU). ^{232}U (~ 69.8 year half-life) and its decay daughter ^{228}Th are the main contributors to the radiotoxicity 500 years after disposal. Whereas ^{233}U ($\sim 1.59 \times 10^5$ year half-life) and its decay daughter ^{229}Th are the main contributors from 500 years to 1 million years after discharge. The presence of ^{208}Tl in the ^{232}U decay chain causes the intensity of gamma rays near 2.6 MeV in Th-containing fuel to be much stronger than that in U-based fuel and reaches a maximum around 10 years after discharge. It is therefore suggested that there be a waiting period of 10 years before starting to reprocess Th-containing fuels (Bi et al., 2013).

6.4. Inventory of long-lived radionuclides

The micro-heterogeneous duplex fuel studied by Li et al. (2021) offered improvements in the proliferation resistance and inventory requirements of long-lived radio isotopes, compared with UO_2 (Li et al., 2021). ^{229}Th , an actinide present in thorium cycles, has a long-term radiological impact because of its 7340-year half-life. ^{229}Th is a daughter of ^{233}U (half-life 159,200 years), which can be easily eliminated if actinides are recycled (Van Gosen et al., 2009). ^{129}I is considered one of the most significant fission products because of its long half-life, absorption by the human body and high mobility in the environment. ^{129}I concentrations in the case of $(\text{Th}^{235}\text{U})\text{O}_2$ and $(\text{Th}^{233}\text{U})\text{O}_2$ are higher than conventional UO_2 , with $(\text{Th}^{233}\text{U})\text{O}_2$ being the highest, which increases the radioactivity of the Th-containing fuel fission products (Galahom et al., 2022). Furthermore, the ^{233}U decay chain heat of the Th-containing fuel increases after 2000 years (Ashley et al., 2014).

Raitses et al. (2009) analysed an RTF concept with improved proliferation resistance and reduced spent fuel requirements. The total plutonium production rate was 30% of a conventional reactor, and the compositions of the spent fuel and standard RGPu differed significantly due to the extremely high burn-up of the RTF spent fuel. The spent fuel had fewer higher actinides, which reduced long-term radioactivity. The main feature of the RTF cycle was the total amount of spent fuel discharged from the reactor core for each cycle. Compared with conventional VVER/PWR, the RTF fuel management scheme could result in a

reduced spent fuel production (at the same energy production).

6.5. Deep transuranic incineration

Rahman and Franceschini (2012) analysed FA configurations containing both homogeneous and heterogeneous thorium mixtures in both oxide and nitride compositions, in multiple recycling schemes (e.g., Pu recycle, TRU recycle, TRU and in-bred U recycle) with the primary aim of considering PWRs for the sustained incineration of TRU, as an interim measure, while fast reactors are being developed. The study compared burning and multi-recycling TRU in a Th-containing fuelled PWR with alternatives such as U-MOX, and variations. Th-containing PWR fuel was found to be a promising option for multi-recycling and burning of TRU in a thermal neutron spectrum, while satisfying the most important operational and safety constraints. While homogeneous assembly designs allow simple loading patterns and result in the highest rate of TRU transmutation, the reactivity control, safety coefficients and fuel handling are complicated by the rapid rise in the TRU content of the recycled fuel, which limits the number of cycles for such fuels. TRU burning in homogenous Th-containing fuels is almost three times as efficient as in U-based fuels, with the same number of MOX assemblies in the core. The heterogeneous FA study aimed to achieve a fully closed thermal cycle, recycling all TRUs, without an external fissile feed from ^{233}U recycled fuel. The design allows for burning an external supply of TRU through multiple cycles of irradiation, enabled through the enhanced conversion/breeding from thorium and reduced residual TRU.

Lindley et al. (2014b) compared a reduced-moderation LWR (RMLWR) to a sodium-cooled fast reactor (SFR) utilising thorium. SFRs, the benchmark for transuranic burning, achieve better discharge burn-up and incineration rates than RMLWRs, and the ensuing reduced fuel reprocessing/fabrication requirements for breeder/burner reactors, respectively, offers savings. Sufficient neutron spectrum hardening in RMLWRs renders repository radiotoxicity and actinide decay heat similar to that from SFRs. Hard gamma sources and spontaneous neutron sources complicate fuel fabrication in both systems. In both reactor systems, thorium outperforms uranium due to improvement in the void fraction. The authors predicted a higher capital cost for SFRs, which may negate the decreased requirements of reprocessing and fuel fabrication (assumptions are however sensitive to reactor size, cost and availability factors).

Long-lived actinides and spent nuclear fuel or high-level nuclear waste storage duration can be significantly reduced by multiple recycling. Since most TRU isotopes have low fission cross sections in thermal reactors, fast reactors are usually considered for such recycling. Reduced-moderation LWRs, which are based on established LWR technology, could also be considered for TRU reduction, especially in cases where thorium fuel, with its significantly improved VC, is considered. Reduced-moderation LWRs that utilise thorium may achieve full actinide recycling while burning an external supply of TRU, and also better waste management and fuel utilisation. In their analyses of RMPWRs and RMBWRs with TRU-bearing thorium fuel, Lindley et al. (2014c) sought to maximise the TRU burning rate by exploiting quick implementation and intrinsically low conversion ratios. Current BWR technology, RMBWR, requires extensive changes and hence more time to implement RMPWR, but gives favourable fuel cycle performance, arising from the harder neutron spectrum. Although implementation in the RMBWR seems best, the authors found it technically feasible to implement the solution in a two-stage TRU burning cycle (first stage for Th–Pu MOX in a PWR, then a second continuous burn stage in a RMPWR or RMBWR).

7. Economics and manufacturing

Based on the lower recoverable energy per fission of ^{233}U , the strong thermal capture cross section of ^{232}Th and the lower density of ThO_2 , Th-

containing fuels require more fissile fuel material to offer the same power levels in line with the levels of conventional uranium fuel (Trellue et al., 2011), which could result in increased fuel costs. According to du Toit and Naicker, fuel costs savings of Th-containing fuel are achieved by keeping the fissile content the same as the enrichment of conventional uranium enrichments. This makes the reactor properties the same as those of the uranium only EPR, with no major changes required. A reduction in neutron poisons and better conversion resulted in an improved fuel cycle with concomitant economic advantages (Du Toit and Naicker, 2018).

Because of the increased burn-up for the micro-heterogeneous thorium-uranium fuel, suggested by Schwageraus, economic improvement was evident. PWR fuel cycle improvements of up to 15% (in comparison with the reference fuel) were possible. However, the costs of the increased separative work unit (SWU) to achieve the 20% enrichment required in the thorium-uranium fuel overshadow this economic improvement in the fuel cycle length (Schwageraus et al., 2004).

It is unlikely that the cost of switching to the thorium cycle (including associated reprocessing) as well as thorium fuel manufacturing costs compare favourably with the cost of waste disposal of \$ 1/MWh in the US as at 2004 (including the disposal of TRU waste from once-burnt uranium fuel) (Vaidyanathan, 2021). Preliminary fuel cycle cost estimates of the RTF and SBU FA showed that the RTF concept has better economic potential than the homogeneous mixture approach, and it is comparable to that of conventional PWRs (Raites et al., 2009).

Du Toit and Cilliers (2014) determined the economic benefit of Th-containing fuels in PWRs by assuming an extension of the Th-containing fuel cycle from 18 months to 24 months. They considered the reactor downtime for refuelling and increased income from higher capacity factors in addition to the fuel cost. The calculations assumed an initial fissile content of 4.88%, which is lower than the assumed values in other studies (see Table 2). They did not account for higher or enriched soluble boron in the O&M costs and the fact that enriching up to 19.5% requires major upgrades at enrichment plants. Nonetheless, a 37% increase in electricity sales per cycle could be achieved with extended cycles. However, on an equivalent six-year time frame (three cycles for Th-containing fuels and four cycles for conventional uranium fuel), the economic benefit reduces to 3%.

Wilson et al. (2009) compared homogeneously mixed (ThU) O_2 fuel with conventional UO_2 fuel in typical PWRs, in equilibrium fuel cycles. They concluded that it was possible to achieve a substantial economy of uranium resources, in spite of the fact that the fleet was unable to breed its own fuel. A high fleet breeding ratio was accomplished while circumvented costly reactor redesigns or design changes. The proposed three-component systems were shown to become economically competitive in the wake of high uranium prices (i.e. >300 \$/kg). A cursory evaluation indicates that this condition is easily met in 2023 - a thorough techno-economic analysis, re-evaluating and updating all model parameters, may prove valuable.

Saglam et al. (2004) established that prevailing (2004) economic conditions rendered the use of homogeneous thorium-uranium fuel in LWRs economically unfeasible. This was due to additional fuel cycle cost as a function of the fuel cycle length, in spite of extrapolation of the techno-economic results and a further increase in burn-up. Thorium fuel cycle studies in the early 1960s, based on ^{233}U recycling and relatively low burn-ups rendered smaller cost differences, while current once-through cycles designs at much higher burn-ups, did not render (ThU) O_2 -fuelled cores with significant gain.

Since thorium needs to be accompanied by enriched ^{235}U , the enrichment needs to be increased, but it is limited to 19.99 wt% LEU. The LEU is then diluted with ^{232}Th , which results in an initial fissile content of ~3–8 wt% (see Table 2). Even though the SWU cost is higher for the uranium share, the fraction of the uranium is usually much lower than for conventional 5 wt% enriched fuel. The cost balance as a function of the tails assay suggests a pro rata lower cost of higher enrichment

levels. The cost penalty for higher levels of uranium enrichment is considered negligible if the total fissile content of a new fuel is maintained, based on the assumption that the difference in cost is limited to enrichment only (World Information Service on Energy, 2020).

Drera et al. (2014) reported on a fuel production and irradiation programme aimed at licencing Th-containing fuels for use in currently operating LWRs. They reported slight differences in the fabrication of thorium-bearing pellets, in their efforts to achieve satisfactory fuel density and other characteristics such as fuel microstructure and material integrity. The initial results of the irradiation tests indicated improved core fuel performance and fuel manufacturing trials; indications were that (ThU)₂O₂ and (ThPu)₂O₂ fuels can be manufactured with existing scalable technologies. Improved fuel characteristics and a significant reduction in fuel centreline operating temperatures were reported at BOL, based on initial results.

The conversion of fuel manufacturing plants from UO₂ to (ThU)₂O₂-based manufacturing was found to be feasible (MacDonald et al., 2002; MacDonald and Lee, 2004; Shwageraus et al., 2004). Vaidyanathan, 2020 examined a thorium cycle for PWR utilising a bimetallic thorium-zirconium alloy cladding. Various challenges were identified for the proposed fuel concept with bimetallic cladding, including the following: bimetallic cladding material and manufacturing specifications; cladding and fuel performance qualifying tests; development of a proven scheme for the reprocessing of cladding and oxide material; lack of a MFR scheme to optimise discharge exposure and concomitant material reprocessing requirements; lack of fuel performance data and fuel safety data (including MTC, BW, CRW, DTC, reactivity change associated with going from HFP to CZP, and others). Lastly, the current cost of reproduction (reprocessing fuel in closed fuel cycles), compared to disposal, seems prohibitive.

8. Discussion

In this section, first principles are employed to elucidate the differences in results on thorium use in PWRs reported in the literature. Researchers report sometimes vastly different results for e.g. cycle length and burnup, levels of incineration, safety parameters, conversion, operability etc. As summarised in the paragraphs above, differences in results stem from different fuel and/or cladding composition, geometry

and arrangement, use of burnable poisons and flux levels. These differences in design influence moderation and hence neutron spectrum, burnup behaviour, safety parameters, proliferation resistance, radiotoxicity, operability and operational efficiency as well as fuel manufacturing cost.

In Figs. 3 and 4 the remit has been limited to calculations of microscopic cross sections of the fertile and fissile nuclides respectively, in comparing conventional fuel with addition of thorium and conventional fuel without the addition of thorium. ENDFB-VIII data (Brown et al., 2018) (using the generic Janis PWR neutron spectrum (Soppera et al., 2014), with five groups per decade on an energy log scale) was used for calculations. The assumptions include comparisons for similar designs, equal total fissile content (at BOC) and utilising a flat neutron spectrum. These plots render useful insights for considering the impact of spectral hardening on thermal fission factor, thermal utilisation factor, resonance escape probability and fast fission factor (while ignoring fast and thermal non-leakage probabilities based on the assumption that leakage for both fuels would be the same). The qualitative considerations assist in understanding the impact on conversion, fuel utilisation, deep incineration potential, reduction in radiotoxicity, without elaborate modelling anew. The impact of these effects depends on the macroscopic cross sections and fuel geometry.

Fig. 3 compares the ratio of absorption in ²³²Th to ²³⁸U as well as the ratio of captures of ²³²Th to ²³⁸U.

Fig. 3 illustrates:

- the strong influence of ²³²Th on the breeding/conversion (IAEA, 2002) in comparison to ²³⁸U for the ratios above 1 over the entire neutron spectrum, except in the range 2eV–20eV and 25eV–40eV;
 - o the presence of ²³²Th hardens the neutron spectrum due to enhanced captures of freshly fissioned fast neutrons down to 40 eV;
 - o the potential for better conversion of ²³²Th to ²³³U than the conversion of ²³⁸U to ²³⁹Pu, in the presence of a hardened neutron spectrum;
 - o the advantage of acting as burnable absorber to reduce excess reactivity at the beginning of fuel life;

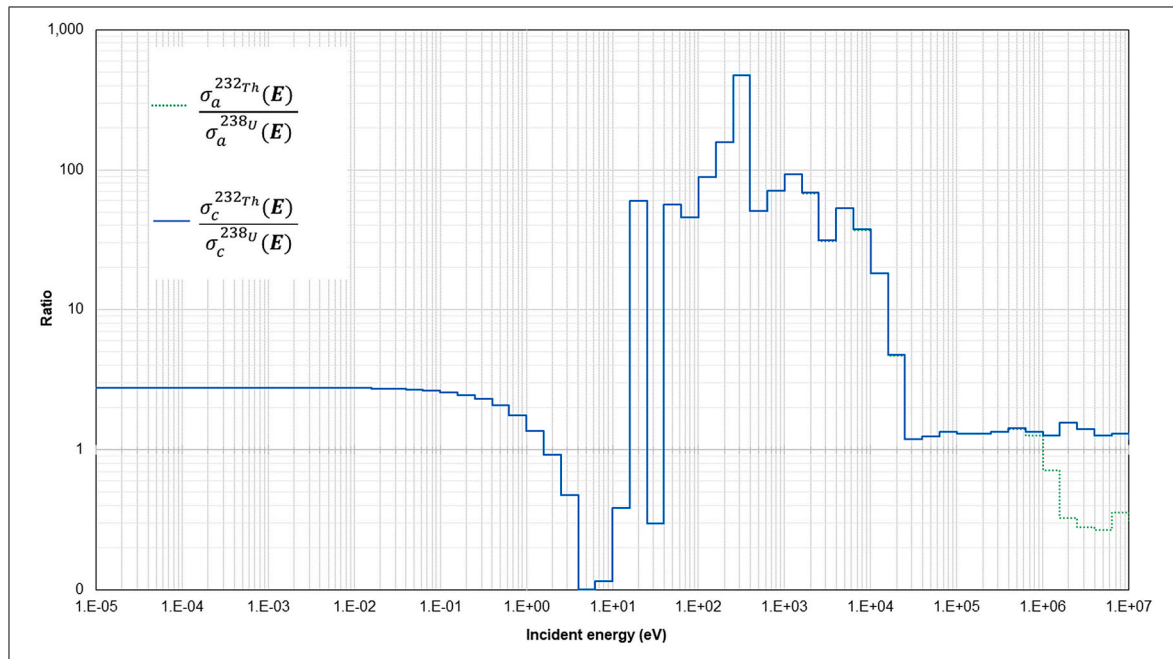


Fig. 3. Ratio of microscopic absorption and capture cross section in ²³²Th to microscopic capture cross section in ²³⁸U as a function of energy.

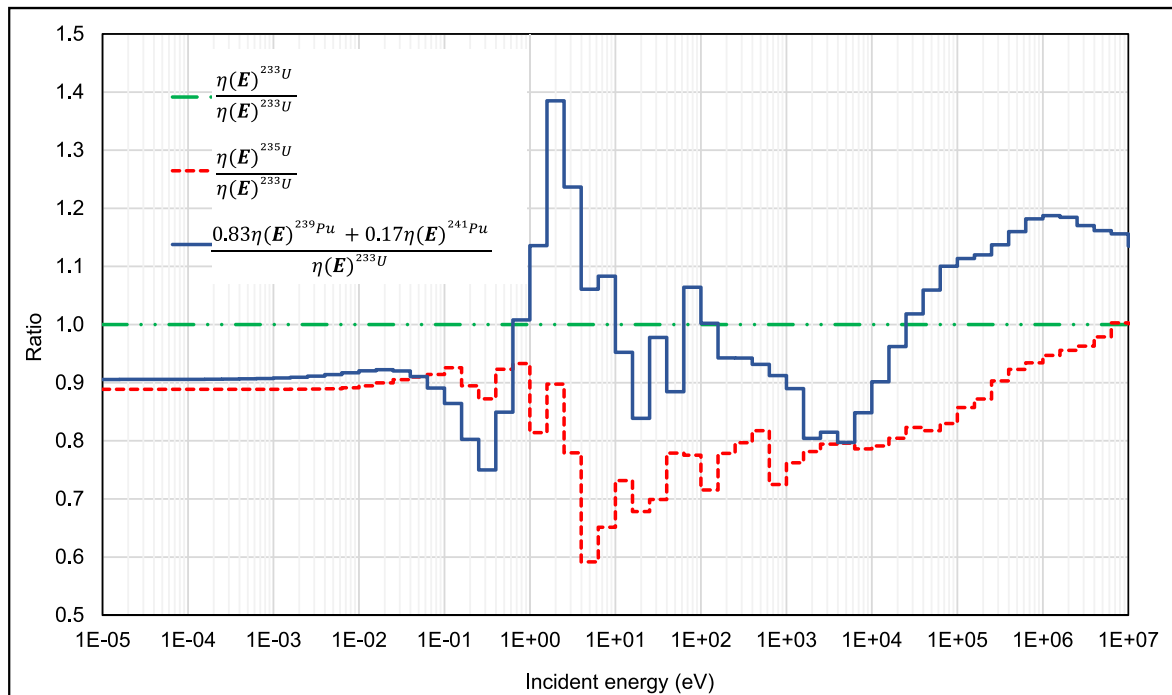


Fig. 4. Comparison of the thermal fission factor of ^{235}U to the thermal fission factor of ^{233}U .

- the higher fast fission contribution of ^{238}U , (see the difference in absorption cross section between ^{232}Th and ^{238}U in the energy range above ~ 700 keV.
- the more negative DTC for thorium containing fuel due to the dominance of capture cross sections in the neutron spectrum above ~ 40 eV;
- the dominance of the ^{238}U capture cross section in the $\sim 1\text{eV}$ – 20 eV energy range, which weakens the negative DTC feedback in over-power transients (Perry and Weinberg, 1972);
- The presence of dominant capture cross section resonance peaks at different resonance energies for ^{232}Th and ^{238}U explains why some studies achieved better breeding/conversion than others, and that is why future research should focus on altering the neutron spectrum to move towards 40 eV and higher epithermal energies.
- Micro heterogeneous fuels achieve better conversion/breeding due to a different neutron spectrum in the fissile and fertile regions. These varying neutron spectrums enhance burning of the fissile fuel and breeding in fertile fuel. Further investigation is recommended to evaluate the spectral difference at BOC and change during burnup of micro heterogeneous fuels.

In Fig. 4 ratios of the thermal fission factor, (η)

$$\eta(E)^x = \frac{\nu(E)^x \sigma(E)_f^x}{\sigma(E)_a^x}$$

calculated for ^{235}U and RGPu (taken as 0.83 at.% ^{239}Pu and 0.17 at.% ^{241}Pu (IAEA, 2012; Trellue, 2006), are utilised and displayed in comparison to η for ^{233}U . The following conclusions can be drawn:

- ^{233}U has a higher η than ^{235}U over the entire applicable energy range;
- The energy (~ 10 – 60 eV, ~ 100 eV to ~ 25 keV) in the epithermal intervals where ^{233}U has a higher η than RGPu are evident in the graph;
- The energy in the epithermal and fast energy range (~ 1 – 10 eV, 60 – 100 eV, >25 keV) where RGPu has a higher (η) than ^{233}U are

indicated. This indicates that the best performing fissile driver at epithermal energies is RGPu mixed with ^{232}Th .

- The higher η of RGPu in a hardened neutron spectrum, points to the reduction in Pu levels in thorium-containing spent fuel in comparison to conventional fuel.

9. Conclusion

The focus of this paper was to present an overview of the potential of Th-containing fuels in LWRs, in terms of neutronic in-core behaviour, fuel performance and thermal hydraulics, waste and proliferation resistance, feasibility and safety, economics and manufacturing. In Section 8 we attempted an explanation for the results reported for the use of thorium in LWRs. In general, the majority of results reported indicate that thorium:

- performs better in a hardened neutron spectrum; and as such:
- achieves better conversion ratios, which leads to (i.a.) improved burnup – especially in micro-heterogeneous designs due to more favourable spectra on thorium regions at BOL.
- achieves an overall better economic performance.

Thorium containing fuel still performs within the safety margins set for conventional fuel. Multiple researchers found that introduction of thorium in LWRs has a negative impact on safety parameters (notably a reduced delayed neutron fraction, reduced CRW and a reduced negative MTC), although in general the safety characteristics are still acceptable.

In general, thorium renders improvements in power and flux profiles, except in axially heterogeneous fuel designs where power peaking can occur at BOL.

The use of thorium in nuclear fuel may lead to decreased radio-toxicity, improved proliferation resistance and holds promise for deep transuranic incineration. Multiple authors report a significant reduction in plutonium and minor actinides (compared to conventional fuel) after burnup adding to proliferation resistance of Th-containing fuel. Proliferation resistance evaluated against fleet considerations for open and closed fuel cycles leads to different outcomes. Enhancing proliferation is

possible by denaturing thorium sections with ^{238}U . However, the possibility of separating ^{233}Pa chemically from used nuclear fuel, and allowing it to decay into pure ^{233}U , has implications for nuclear proliferation.

Thorium fuel production seems feasible in current fuel manufacturing plants. Some authors do not find economic benefit in switching to Th-containing fuel from in open fuel cycles, except when considering different reactor types in ideal fleet arrangements with closed fuel cycles.

Over the past number of years research on thorium has progressed from scoping studies to more refined investigations:

- The level of neutronic analysis has progressed from pin to full core.
- Safety parameters were reported at various levels of burnup and equilibrium cycles (Ganda et al., 2012; Kotlyar et al., 2017; Lau et al., 2013; Lau et al., 2014; Permana, 2020).
- Thermohydraulic parameters were also evaluated by investigating the maximum fuel temperature, DNBR, axial offset, radial and axial hot channel factors etc (Gorton et al., 2019; Lapanporo and Su'ud, 2022; Raites et al., 2009).
- Multiphysics analysis where the fuel performance is also evaluated (Bell, 2017; Lapanporo and Su'ud, 2022; Liu et al., 2020; Qiu et al., 2021; Raites et al., 2009).

In order for Th-containing fuels in LWRs to become commercially ready it is suggested that future work be focused on evaluating 3D full core equilibrium cycles coupled with thermohydraulic and fuel performance physics to evaluate steady state and accident scenarios performance (Lindley et al., 2014a). Nonetheless, it is encouraging to see that research on Th-containing fuel are persistent and thorium is even considered for accident tolerant fuel research.

CRedit authorship contribution statement

Maria Hendrina Du Toit: Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization. **Frederik Van Niekerk:** Writing – review & editing, Writing – original draft, Visualization, Investigation. **Shervineh Amirkhosravi:** Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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