

Chapter 7: Strategic roadmap

“Research is to see what everybody else has seen, and to think what nobody else has thought.”

~ Albert Szent-Gyorgyi~

Overview

A systematic strategic thorium-based fuel implementation roadmap has been developed, based on the research and results obtained from the previous chapters. Economic, strategic and historical aspects direct the roadmap. The accumulated advantages of thorium-based fuels are summarised from knowledge gained from Chapter 1 to Chapter 5. All these advantages form the initiative to implement thorium-based fuels in SA.

A timeline (which forms the basis of the roadmap) is constructed from different assumptions. Phase 1 starts in 2013 and extends to 2030. Phase 2 starts in 2031 up to 2044 and Phase 3 from 2045 to 2060. Each phase is discussed with regard to construction-, implementation- and research activities. This roadmap will progress and advance to future technologies, corresponding to the evolutionary approach.

7.1 Introduction

Past experience on thorium-fuelled research and power reactors are given to establish the basis and history of thorium as a nuclear fuel. The most important thorium-based fuel options for PWR cores were identified and discussed and resulting difficulties and solutions are given. Different suggestions and modifications to mitigate the negative effects of thorium-based fuels in PWRs are compared in terms of advantages and disadvantages. A critical evaluation then decides on the starting point of the roadmap. A process of elimination selects

best option for each strategy, which results in combination of mitigation and optimisation strategies for thorium-based fuel in PWRs.

The final choice to start the thorium roadmap was selected as homogeneous integral fuel with IFBA coatings and Zirlo/M5 cladding, increased water density, additional water holes and enriched B¹⁰ soluble boron.

Certain countries made significant progress with the thorium-based fuel cycle (India and Norway) and nuclear technology in general (South Korea). Each country is introduced with a summary of their approach and policy. The identified lessons and policies are applied to the current South African context, which results in the different goals aimed at achieving a thorium-based fuel cycle. These goals form an integral part of the roadmap towards implementing thorium-based fuels in SA.

The thorium-based fuel options are economically compared with uranium fuel in the PWR, focusing on the extended refuelling cycles and the reduction of refuelling outage costs. The prices of uranium and thorium are discussed. Thorium-based fuels can extend fuel cycles, which reduce the fuel requirements and the spent fuel, as well as the reactor downtime for refuelling. Results show that both (Th/U)O₂ economic benefits over traditional uranium fuel cycles. Unfortunately (Th/Pu)O₂ showed no economic advantage. (Th/U)O₂-fuel proved to be thorium-based fuel choice an Eskom could save up to 49 billion rand in 60 years.

A thorium-based fuel introduction strategy can now be developed.

7.2 Advantages

The following advantages of thorium-based fuels are summarised based on the knowledge gained from Chapter 1 to Chapter 5. All these accumulated advantages of thorium-based fuels form the initiative to implement thorium-based fuels in SA.

Thorium is said to be between three and four times more abundant than uranium, due to a three times longer half-life than uranium and a crustal concentration about three times more than uranium (Trellue *et al.*, 2011; WNA, 2011).

Thorium-based fuel presents a good breeding ratio and high conversion rates (from Th²³² to U²³³) at thermal energies, due to the larger absorption cross-section of Th²³² (Kang-Mok &

Myugn-Hyung, 2005). The thermal capture cross-section of Th^{233} is about three times larger than that of U^{238} and a breeding cycle, more effective than $\text{U}^{238}/\text{Pu}^{239}$, can be established with $\text{Th}^{232}/\text{U}^{233}$ (WNA, 2011a).

U^{233} has the highest neutron yield amongst all the fissile isotopes at thermal energies (Trellue *et al.*, 2011). This high η value of U^{233} results in much smaller swings of fissile content and reactivity than fuel cycles using U^{235} . Over the core lifetime, power peaking is less compared to uranium cores, which makes thorium-fuelled reactors more controllable (Greeneche *et al.*, 2007).

The value of η stays the most uniform at epithermal energies, among all fissile isotopes, which reduces transient effects due to changes in moderation. $\text{Th}^{232}/\text{U}^{233}$ fuel is less affected by spectrum hardening, which reduces its void and temperature coefficients (Kazimi *et al.*, 1999). The nuclear parameters of U^{233} have a significant weaker dependence on power and temperature, which eases reactor safety and operation, when changing from cold to hot conditions (Greeneche *et al.*, 2007). U^{233} has a high fission cross-section and low capture cross-section, which limits unwanted transmutation (Puill, 2002).

ThO_2 is more stable and robust than UO_2 from a metallurgical- (Caner & Dugan, 2000) and chemical point of view. The specific power and the burnup for reactors utilizing ThO_2 can be raised, due to the higher melting point (Trellue *et al.*, 2011). These characteristics allow enhanced safety- and operational limits and high thermal efficiencies (IAEA, 2012).

Higher burnups will extend fuel cycles and improve plant capacity factors, thus reducing the fuel requirements and spent fuel quantities to handle, move, and deposit. Extended refuelling cycles also reduce the reactor downtime for refuelling.

Reactors using thorium-based fuel present more stable reactivity (k_{eff}) during long irradiations than in a UO_2 , due to the constant thorium conversion to U^{233} (Herring *et al.*, 2001). High burnup thorium-based fuels will improve the weapons material proliferation-resistance in three aspects. Less separable weapons material will be generated, due to the fact that the major fertile material will be thorium and not U^{238} . Extended refuelling periods will make diversion less probable and the isotopic content of the plutonium will be much less attractive to use in weapons (Herring *et al.*, 2001).

The probable radiotoxicity of spent fuel is lower than UO_2 or MOX cores due to lower production of minor actinides (Puill, 1998; Galperin *et al.*, 2002; Schram & Klaasen, 2007). Thorium-based fuels are non-proliferative, due to the lower Pu^{239} production. The long-lived actinides produced from thorium-based fuels are much less than uranium or plutonium fuels, which also reduces environmental risks (Unak, 2000).

$(\text{Th/U})\text{O}_2$ and $(\text{Th/Pu})\text{O}_2$ combinations have notably higher thermal conductivity and lower fission gas release rates. Increased thermal conductivity results in a lower fuel pellet temperature, less swelling, less PCMI (Pellet Cladding Mechanical Interaction) and larger margin for fuel melting (Bjork, 2012).

$(\text{Th/Pu})\text{O}_2$ -fuel can achieve a plutonium destruction rate more than two times that of MOX. The material attractiveness of plutonium in the spent $(\text{Th/Pu})\text{O}_2$ -fuel is reduced as the burnups are increased (Trellue *et al.*, 2011). The radial core power peak is likely to be more pronounced for UO_2 cores than in $(\text{Th/Pu})\text{O}_2$ and MOX cores. $(\text{Th/Pu})\text{O}_2$ cores have a more negative DC, due to the very strong neutron absorption resonance of Pu^{240} at 1eV (Fridman & Kliem, 2011).

Results from Chapter 5 showed that thorium-based fuels (more specifically $(\text{Th/U})\text{O}_2$ -fuel) are economically competitive with UO_2 -fuel. Thorium-based nuclear fuels can reduce the fuel cycle costs by about 6,2%. The implementation $(\text{Th/U})\text{O}_2$ -fuel could save Eskom up to 49 billion rand in 60 years.

7.3 Assumptions

1. Six reactors are planned at a build rate of one unit every 18 months, starting in 2023 (SA, 2011). It is assumed that there will be a one-year delay and the first reactor will start operation in 2024.
2. The reactor construction duration is assumed to be 4 years (Koomey & Hultman, 2007).
3. It is estimated to take 10-15 years to introduce new fuels into modern reactors. It is assumed that the thorium-based fuel cycle could be established in current reactors within the next 15 years, which is comparable to the period required to implement MOX (Hesketh & Worrall, 2010).

4. It is assumed that SA will start to build its own fuel producing and reprocessing facility in 19 years' time, two years after the last reactor starts construction. This will correspond to the suggestion from Eskom to develop together with of the reactor program.
5. The spent UO₂-fuel is cooled for 5 years before reprocessing (Rose *et al.*, 2011).
6. The reprocessing duration after the cooling period is assumed to be 2 years (Shelly *et al.*, 2000).
7. The construction of the reprocess facility would take up to 10 years (Schneider *et al.*, 2009).
8. It is assumed that the lifetime of Koeberg will be extended from 40 years to 60 years, which permits 32 years of operation before decommissioning.
9. A recent Norwegian study stated that Accelerator Driven Systems (ADS) are not likely to become commercial in the next 30 years (Anon., 2008). ADS need 40+ years minimum to be designed, built and reach commercial maturity (Hesketh & Worrall, 2010). It is assumed that ADS will operate 45 years from now.
10. The annual discharge of recyclable plutonium from a standard PWR is about 250kg (Galperin *et al.*, 1997).

All of these assumptions result in the timelines shown in Figure 7.1 and Figure 7.2, depending on the scenarios chosen in Phase 2. These timelines form the basis of the roadmap and will be discussed in more detail in section 7.4.

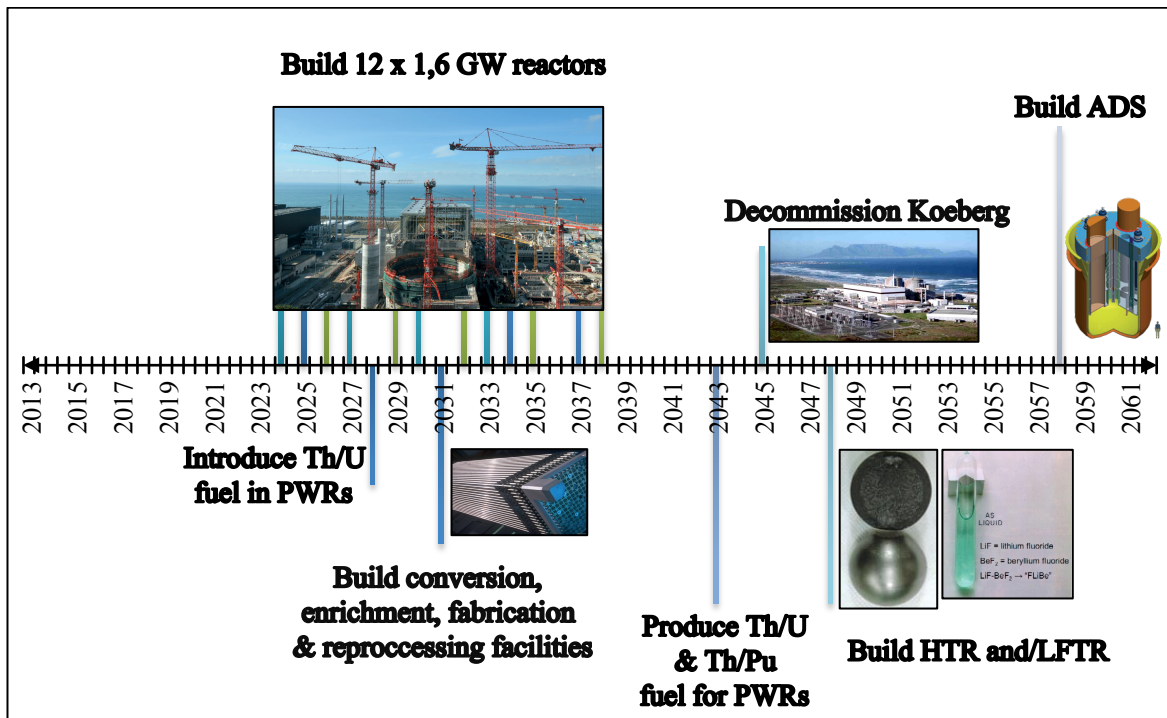


Figure 7.1 Thorium introduction roadmap for scenario A

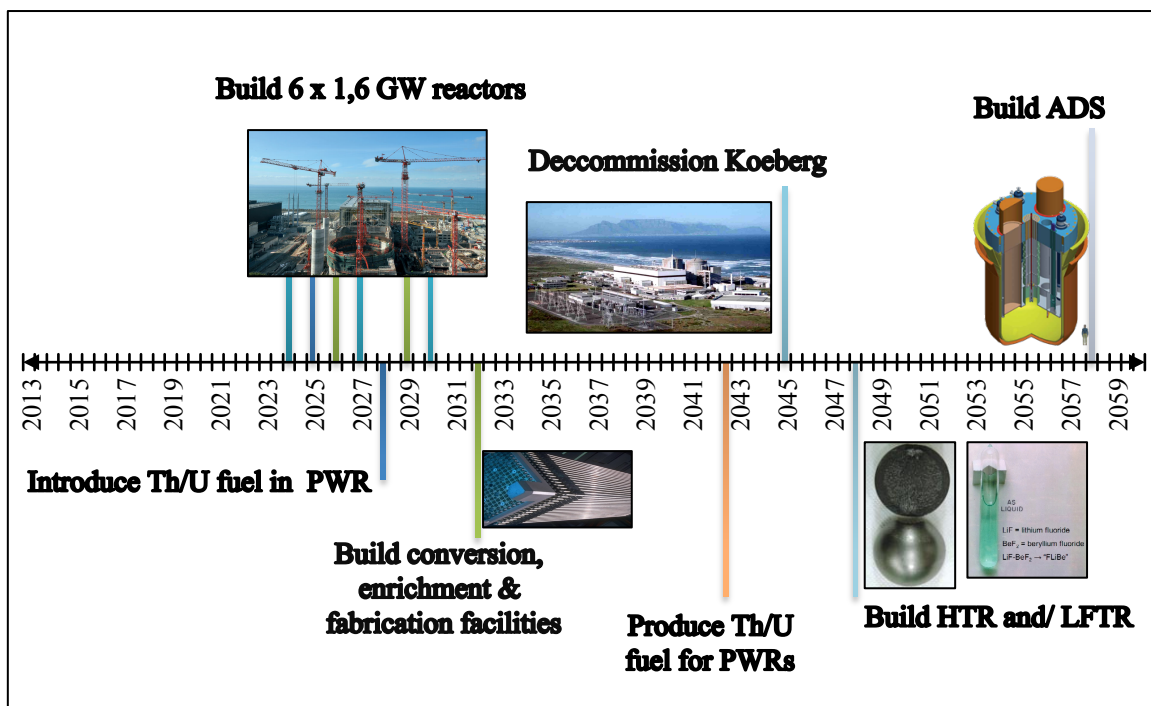


Figure 7.2 Thorium introduction roadmap for scenario B

7.4 Roadmap

The roadmap consists of three different phases. Phase 1 starts in 2013 and extends to 2030. Phase 2 starts in 2031 up to 2044 and Phase 3 from 2045 to 2060. Please note that there are two scenarios for Phase 2. Each phase is discussed with regard to construction-, implementation- and research activities. This roadmap will progress and advance to future technologies, corresponding to the evolutionary approach.

7.4.1 Phase 1 (2013-2030)

Phase 1 describes the starting point of the roadmap to implement thorium-based fuels in PWRs as well as the construction of the six planned reactors.

7.4.1.1 Construction

The first reactor will be commissioned in 2024, followed by three new reactors in 2025, 2026 and 2027. The remaining two reactors will be commissioned in 2029 and 2030. During this time South Africa should obtain as much as possible experience and skills from the vendor/vendors building the reactors. Local contractors and manufacturers should be involved in the nuclear expansion program and start to work independently on the last two reactors.

7.4.1.2 Implementation

In 2028, thorium-based fuels should be introduced in the four completed reactors. The choice for the thorium-based fuel for Phase 1 is, once through (Th/U)O₂-fuel with IFBA coatings and Zirlo/M5 (or similar) cladding, increased water density, additional water holes and enriched B¹⁰ soluble boron, as decided in section 3.4.

The reasons for choosing (Th/U)O₂-fuel are because (Th/U)O₂-fuel investigations prevail over (Th/Pu)O₂-fuels (Schram & Klaasen, 2007). Also, uranium mining has already been established in SA, and SA has no reprocessing facility to recycle Pu to use in (Th/Pu)O₂-fuels. (Th/U)O₂-fuel also proves to be more economical than (Th/Pu)O₂ as discussed in

section 5.3, unless the unit cost for reprocessing and fabrication could be reduced. The proposed fuel cycle is shown in Figure 7.3.

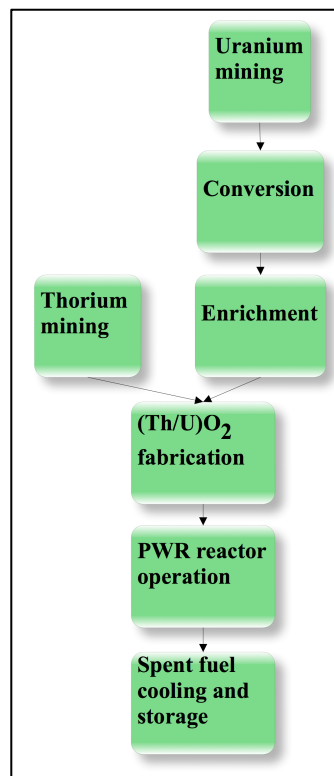


Figure 7.3 Fuel cycle for Phase 1 of the roadmap

7.4.1.3 Research requirements

During Phase 1, investigations should focus on reducing the reprocessing cost to employ (Th/Pu)O₂-fuels in PWRs in the future. The research project developing and planning the construction of a fuel fabrication and reprocessing facility should be well underway.

It should be noted that the implementation of the entire front end and reprocessing step was projected to amount to approximately R 52,3 billion (Balack, 2010). The applications for funding and support to implement the entire front end and reprocessing step should already be in progress.

The behaviour of (Th/U)O₂-fuel in the new PWR should be investigated, analysed and optimised. The strategies that were eliminated or temporarily rejected in section 3.3, due to the need for further research and development, are considered again.

- Annular fuel pellets
- Tight pitch lattices
- Increased fuel radius
- Additional control rods
- Oxide dispersion strengthened steels and SiC as advanced cladding materials
- The PRATT fuel design.

The option to develop thorium-based fuels, not only for SA, but also internationally, should be researched and pursued.

As shown in Figure 7.2, it is proposed to implement HTRs, LFRs and ADS in the future. Research should commence on these systems (HTRs, LFRs and ADS). (Refer to section 2.1.6 for brief introductions to these systems.) It should be noted that HTRs and LFRs both have continuous online refuelling, which completely eliminates the refuelling outage costs to the utility.

The manufacturing of U²³³-based fuels (in the future) must be done completely remotely in a gamma-shielded environment, which is a very expensive technique. The heavy gamma shielding should be investigated and simplified. Research should focus on streamlining U²³³-based fuel fabrication process, reducing the reprocessing cost of such fuels and simplifying the process (Lung & Gremm 1998).

7.4.2 Phase 2 (2031-2044)

Two different scenarios are defined for phase 2, the first one assuming that government decides to continue the nuclear built programme after 2030. The second scenario assumes that the nuclear building programme stops in 2030, which doesn't support the choice to build a reprocessing plant.

7.4.2.1 Phase 2A

Phase 2A focuses on the construction of the conversion, enrichment and fuel fabrication plants (front end) to produce (Th/U)O₂. The main reasons for building local front end facilities lie in security of fuel supply and the beneficiation of locally mined uranium and thorium. Phase 2A also focuses on building the reprocessing facility and producing (Th/Pu)O₂-fuel. It should be noted that reprocessing is a sensitive step in the fuel cycle and depend on local demand. The cost of the conversion, enrichment, fabrication and reprocessing facilities is estimated at R52,3 billion (Balack, 2010). See Figure 7.1 for the scenario roadmap.

Construction

Construction on the nuclear fuel facility (including conversion, enrichment, fabrication and reprocessing plants) will start in 2031 and construction is assumed to continue for 10 years. In 2041 the fuel facility should be online and ready to recycle Pu and produce (Th/Pu)O₂. It is assumed that the same built schedule will be repeated as in phase 1 starting the commissioning of the first reactor in 2032. The construction of these six reactors will be easier due to the experience gained from the first six reactors.

Implementation

(Th/Pu)O₂-fuel could be introduced in reactors by middle 2043, assuming a reprocessing period of two years and another 6 months for fuel fabrication. The reasons for choosing (Th/Pu)O₂ are to utilize spent fuel that accumulated at Koeberg and new plants as well as the drive to burn existing waste stockpiles. According to simplified calculations, the accumulated plutonium from Koeberg can supply approximately 15 (Th/Pu)O₂ core loadings or 30 years in one 1GWe reactor.

(Th/Pu)O₂-fuel improves proliferation resistance, reduces waste with no new Pu and relieves some of the uranium requirements. The reactor-grade plutonium is recycled from current Koeberg spent fuel and mixed with thorium. The proposed fuel cycle is shown in Figure 7.4.

It should be noted that South Africa agreed that they would not reprocess their spent fuel to utilize the Pu. Commercial possibilities to reprocess spent fuel overseas should be

investigated and arranged. SA can also buy reprocessed Pu for the (Th/Pu)O₂-fuel option, but diversion risks can cause difficulties.

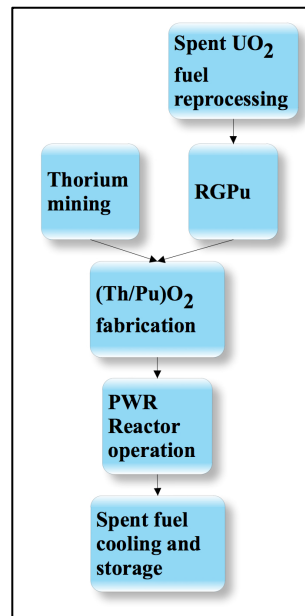


Figure 7.4 Fuel cycle for Phase 2A of the roadmap

Research requirements

The behaviour of (Th/Pu)O₂-fuel in the new PWR should be investigated, analysed and optimised. The strategies that were eliminated or temporarily rejected in section 3.3, due to the need for further research and development are considered again.

- Annular fuel pellets
- Tight pitch lattices
- Increased fuel radius
- Additional control rods
- Oxide dispersion strengthened steels and SiC as advanced cladding materials
- The PRATT fuel design.

The option to develop thorium-based fuels, not only for SA, but also in the future for the whole world should be researched. As shown in Figure 7.2, it is proposed to implement

HTRs, LFRs and ADS in the future. Research on these systems (HTRs, LFRs and ADS) should be complete and moving into the design stages. It should be noted that HTRs and LFRs both have continuous online refuelling, which completely eliminates the refuelling outage costs to the utility.

A permanent and sustainable fuel cycle involves utilizing the U^{233} bred from thorium-based cycles. The manufacturing of U^{233} -based fuels must be done completely remotely in a gamma-shielded environment, which is a very expensive technique. The heavy gamma shielding should be investigated and simplified. Research should focus on streamlining the fuel fabrication process, reducing the reprocessing cost of such fuels and simplifying this process (Lung & Gremm 1998).

7.4.2.2 Phase 2B

Phase 2B focuses on the construction of the conversion, enrichment and fuel fabrication plants (front end) to produce $(Th/U)O_2$. The main reasons for building local front end facilities are security of fuel supply and the beneficiation of locally mined uranium and thorium. The reprocessing market in South Africa is limited, due to the small local demand. The reprocessing facility is not suggested for this scenario, due to the small market.

The cost of implementing the conversion plant, enrichment plant and fuel fabrication facility is approximately R1,1 billion, R16 billion and R2,2 billion respectively. The total capital investment of the above facilities is approximately R 30,3 billion (Balack, 2010). See Figure 7.2 for the scenario b roadmap.

Construction

Construction on the nuclear fuel facility (including conversion, enrichment, fabrication facilities) will start in 2032 and construction is assumed to continue for 10 years. In 2042 the fuel facility should be online and ready to produce $(Th/U)O_2$.

Implementation

The implementation activity for Phase 2B is similar to Phase 1, as the fuel is now only produced locally in South Africa. In 2042, the locally produced Th/U fuels would be

introduced into the remaining reactors. The choice for the thorium-based fuel for Phase 2B is, once through (Th/U)O₂-fuel with IFBA coatings and Zirlo/M5 (or similar) cladding, increased water density, additional water holes and enriched B¹⁰ soluble boron, as decided in section 3.4.

The reasons for choosing (Th/U)O₂-fuel lie in the fact that, because (Th/U)O₂-fuel investigations prevail over (Th/Pu)O₂-fuels (Schram & Klaasen, 2007). Also, uranium mining has already been established in SA, and SA has no reprocessing facility to recycle Pu to use in (Th/Pu)O₂-fuels. (Th/U)O₂-fuel also proves to be more economical than (Th/Pu)O₂ as discussed in section 5.3, unless the unit cost for reprocessing and fabrication could be reduced. The proposed fuel cycle is shown in Figure 7.5.

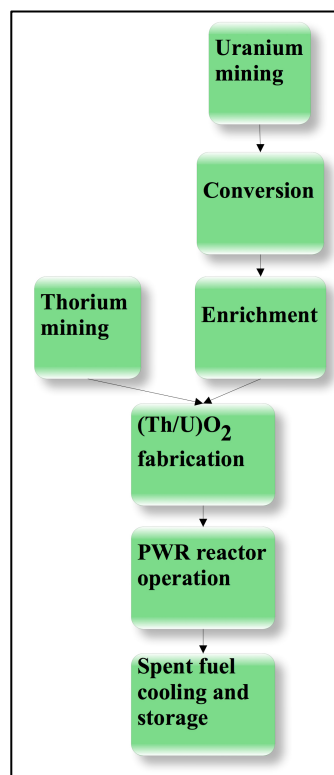


Figure 7.5 Fuel cycle for Phase 2B of the roadmap

Research requirements

Investigations should focus on reducing the reprocessing cost to employ (Th/Pu)O₂-fuels in PWRs in the future. The research project developing and planning the construction reprocessing facility should be well underway. The applications for funding and support to implement the reprocessing step should be in progress.

The behaviour of (Th/U)O₂-fuel in the new PWRs should be investigated, analysed and optimised. The strategies that were eliminated or temporary rejected in section 3.3, due to the need for further research and development are considered again.

- Annular fuel pellets
- Tight pitch lattices
- Increased fuel radius
- Additional control rods
- Oxide dispersion strengthened steels and SiC as advanced cladding materials
- The PRATT fuel design.

The option to develop thorium-based fuels, not only for SA, but also internationally, should be researched and pursued.

As shown in Figure 7.2, it is proposed to implement HTRs, LFRs and ADS in the future. Research should commence on these systems (HTRs, LFRs and ADS). Refer to section 2.1.6 for brief introductions on these systems. It should be noted that HTRs and LFRs both have continuous online refuelling, which completely eliminates the refuelling outage costs to the utility.

The manufacture of U²³³-based fuels (in the future) must be done completely remotely in a gamma-shielded environment, which is a very expensive technique. The heavy gamma shielding should be investigated and simplified. Research should focus on streamlining the U²³³-based fuel fabrication process and reducing the reprocessing cost of such fuels, by simplifying this process, or by a combination of all these factors (Lung & Gremm 1998).

7.4.3 Phase 3 (2045-2060)

Phase 3 consists of implementing (Th/U²³³)O₂ in PWRs and building and planning thorium specific reactor designs such as the LFTR, ADS and the HTR. Please note that some of these reactors can reach commercial maturity before 2045, for instance HTRs. HTRs and LFRs both have continuous online refuelling, which completely eliminates the refuelling outage costs to the utility.

7.4.3.1 Construction

Koeberg would be decommissioned in 2045. HTRs and LFTRs should start construction in 2048. The number and type of reactor would be based on the electricity demand and technological maturity. The ADS should start construction in 2058.

7.4.3.2 Implementation

(Th/Pu)O₂-fuel from Phase 2 (with a higher purity reactor-grade U²³³) is discharged and then cooled for 5 years. (Th/Pu)O₂ spent fuel will be reprocessed to extract the reactor-grade U²³³ and mixed with thorium. The (Th/U²³³)O₂-fuels shall be loaded into the periphery of PWR core to compose so-called “blanket” for low-leakage and long-cycle reload core design, to achieve a Th²³²/U²³³ breeding recycle. The cycle continues with the recycling reactor-grade U²³³ (Si, 2009). The proposed fuel cycle is shown in Figure 7.6.

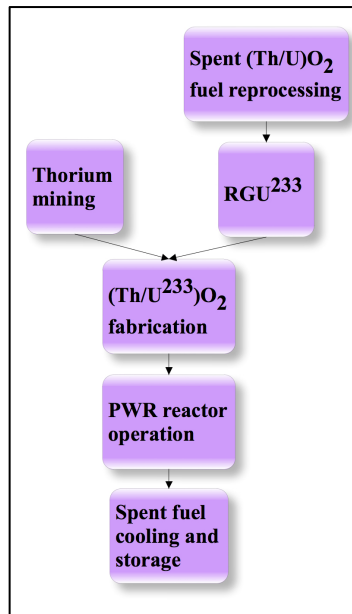


Figure 7.6 Fuel cycle for Phase 3 of the roadmap

7.4.3.3 Research requirements

Research should focus on the optimisation of all the current reactor systems as well as fuel performance. Possibilities to produce fuel for international markets should be explored.

7.5 Conclusion

A three phase pragmatic approach is taken to develop an evolutionary strategic roadmap to introduce and implement thorium-based fuels in the South African nuclear building programme. It has been described in terms of construction, implementation- and research activities. The strategic roadmap is based on historical- (Chapter 2), technical- (Chapter 3), strategic (Chapter 4) and economical (Chapter 5) aspects as well as the advantages of thorium-based fuels.

This should assist in guiding energy policy in South Africa and provides a technical, economic and political justification for pursuing the described roadmap while investing in the identified research opportunities.