



Introducing advanced thorium-based fuel cycles in SA: an evolutionary approach

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DECLARATION

I, Marina Du Toit, hereby declare that I am the sole author of the dissertation entitled:

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ABSTRACT

Past experience in several thorium fuelled research- and power reactors provides the basis and history of thorium. The material properties, fertile- and fissile isotope properties as well as the decay chain of thorium are discussed for purposes of evaluating thorium as a source of fuel.

The different thorium-based fuel designs for PWR cores are discussed and resulting difficulties and solutions are outlined. The different options for each strategy are compared in terms of advantages and disadvantages. A process of elimination selects the best option for each strategy, which results in a combination of mitigation and optimisation strategies to be implemented at the starting point of the roadmap.

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

The prices of uranium and thorium are discussed. This chapter focuses on the economic advantages of thorium-based fuel cycles, especially the fuel cycle cost and the refuelling outage costs. Thorium-based fuels can extend the refuelling cycles, which in turn reduce the fuel requirements and the spent fuel for disposal, as well as the reactor downtime for refuelling.

The results show that both $(\text{Th/U})\text{O}_2$ and $(\text{Th/Pu})\text{O}_2$ present economic benefits over traditional uranium fuel cycles. The total savings were calculated by adding the fuel cycle savings and the refuelling outage saving. $(\text{Th/U})\text{O}_2$ -fuel proved to be the most economical and Eskom could save up to 49 billion rand in 60 years.

Based on the research and results obtained, a systematic strategic thorium-based fuel implementation roadmap is developed. Economic-, strategic- and historical aspects direct the roadmap. The advantages of thorium-based fuels are summarised and form the initiative to implement thorium-based fuels in SA.

A timeline (which forms the basis of the roadmap) is developed. 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. 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.

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NOMENCLATURE

Abbreviation	Description
ADS	Accelerator Driven System
AVR	Arbeitsgemeinschafts Versuchsreaktor
BOC	Beginning of Cycle
BP	Burnable Poison
BWR	Boiling Water Reactor
DC	Doppler Coefficient
DNBR	Departure for Nucleate Boiling Ratio
FPs	Fission Products
FR	Fast Reactor
GT-MHR	Gas Turbine-Modular Helium Reactor
H/HM	Hydrogen to heavy metal ratio
HEU	High Enriched Uranium
HTGR	High Temperature Gas cooled Reactor
HWR	Heavy Water moderated Reactor
IFBA	Integral Fuel Burnable Absorber
IMF	Inert Matrix Fuel
IRP	Integrated Resource Plan
IXAF	Internally and externally cooled annular fuel
LEU	Low Enriched Uranium
LFTR	Liquid Fluoride Thorium Reactor
LMFBR	Liquid Metal Fast Breeder Reactor
LWBR	Light Water Breeder Reactor
LWR	Light Water Reactor
MA's	Minor Actinides
MIMAS	Micronized Master Blend
MSBR	Molten Salt Breeder Reactor
O&M	Operation and Maintenance
ODSS	Oxide Dispersion Strengthened Steels
PBMR	Pebble Bed Module Reactor
PCMI	Pellet Cladding Mechanical Interaction
PHWR	Pressurized Heavy Water Reactor
PRATT	Proliferation Resistant Advanced Transuranic Transmuting
PUREX	Plutonium Uranium Extraction

PWR	Pressurized Water Reactor
RCN	Research Council of Norway
RGPu	Reactor Grade Plutonium
RI	Resonance Integral
RIA	Reactivity Initiated Accident
SA	South Africa
SDM	Shutdown Margin
SNF	Spent Nuclear Fuel
STL	Steenkampskraal thorium limited
Th-MOX	Th/Pu Mixed Oxide
THTR	Thorium High Temperature Reactor
U-MOX	U/Pu Mixed Oxide
UOX	Uranium Oxide
WABA	Wet Annular Burnable Absorber

Symbol	Description	Unit
Am	Americium	-
Be	Beryllium	-
Bi	Bismuth	-
Ca	Calcium	-
Cm	Curium	-
Hg	Mercury	-
I	Iodine	-
K	Potassium	-
Mg	Magnesium	-
Na	Sodium	-
NaOH	Sodium hydroxide	-
Np	Neptunium	-
Pa	Protactinium	-
Pb	Lead	-
Pu	Plutonium	-
Sb	Antimony	-
T_{1/2}	Half-life	years
Th	Thorium	-
Tl	Thallium	-
U	Uranium	-
UF₄	Uranium tetrafluoride	-
UF₆	Uranium hexafluoride	-
Xe	Xenon	-
α	Capture to fission ratio	
β_{eff}	Effective beta factor = precursor atoms / (prompt neutrons + precursor atoms) [for U-235 $\beta = 0.0064$]	pcm
$\eta_{\text{epi ave}}$	Eta average over epithermal energies in PWR	-
η_{f}	Eta in fast energy range	-
η_{th}	Eta in thermal energy range	-
$\eta_{\text{th ave}}$	Eta average over thermal energies in PWR	-
σ_{a}	Microscopic absorption cross-section	barn
Σ_{a}	Macroscopic absorption cross-section	cm ⁻¹
σ_{c}	Microscopic capture cross-section	barn
σ_{f}	Microscopic fission cross-section	barn
σ_{s}	Microscopic scattering cross-section	barn
Σ_{s}	Macroscopic scattering cross-section	cm ⁻¹

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