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Fuel cycle modelling of open cycle thorium-fuelled nuclear energy systems

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ABSTRACT

In this study, we have sought to determine the advantages, disadvantages, and viability of open cycle thorium–uranium-fuelled (Th–U-fuelled) nuclear energy systems. This has been done by assessing three such systems, each of which requires uranium enriched to ~20% ^{235}U, in comparison to a reference uranium-fuelled (U-fuelled) system over various performance indicators, spanning material flows, waste composition, economics, and proliferation resistance. The values of these indicators were determined using the UK National Nuclear Laboratory's fuel cycle modelling code ORION. This code required the results of lattice-physics calculations to model the neutronics of each nuclear energy system, and these were obtained using various nuclear reactor physics codes and burn-up routines. In summary, all three Th–U-fuelled nuclear energy systems required more separative work capacity than the equivalent benchmark U-fuelled system, with larger levelised fuel cycle costs and larger levelised cost of electricity. Although a reduction of ~6% in the required uranium ore per kWh was seen for one of the Th–U-fuelled systems compared to the reference U-fuelled system, the other two Th–U-fuelled systems required more uranium ore per kWh than the reference. Negligible advantages and disadvantages were observed for the amount and the properties of the spent nuclear fuel (SNF) generated by the systems considered. Two of the Th–U-fuelled systems showed some benefit in terms of proliferation resistance of the SNF generated. Overall, it appears that there is little merit in incorporating thorium into nuclear energy systems operating with open nuclear fuel cycles.

1. Introduction

At the time of writing, the majority of the world's electricity generating nuclear energy systems are fuelled with low-enriched uranium (LEU) and operate on open nuclear fuel cycles, where the U-based fuel is used only once with a view to being directly disposed of after a cooling period, i.e. the spent nuclear fuel (SNF) is neither reprocessed nor reused. Uranium reserves are typically graded in terms of their economic viability (United Nations, 2007). According to the most recent OECD report (OECD-NEA Report, 2012) there are 3.08×10^6 tonnes of uranium recoverable for less than US$80/kgU, 5.33×10^6 tonnes of uranium recoverable for less than US$130/kgU, and 7.10×10^6 tonnes of uranium recoverable for less than US$260/kgU. Present estimates for global uranium reserves, including unconventional resources such as coal ash and phosphates (but excluding seawater), range from 1.92×10^7 tonnes (Tulsidas, 2011) to 3.93×10^7 tonnes (Romanello et al., 2012). At 2012 consumption rates of 67,990 tonnes of uranium per year (World Nuclear Association, 2013), this global supply would last 78.3 years for ore recoverable for under US$130/kgU and 578 years for assumed global uranium reserves of 3.93×10^7 tonnes. The work of Romanello et al. (2012) suggests that a burgeoning demand for electricity across the world will yield a significant increase in nuclear energy capacity, and correspondingly a significant increase in uranium consumption. Their predic-

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tions (assuming only open nuclear fuel cycles) suggest that the reserve of ore recoverable for under US$130/kgU would be exhausted by ~2060 and a total reserve of 3.93×10^7 tonnes would be exhausted by ~2160.

One way in which this finite resource could be extended is by incorporating thorium as a nuclear fuel. Present estimates suggest that global thorium reserves total 6.4–7.5 million tonnes; however, due to its long half-life, it is expected that thorium is 3–4 times more abundant in the Earth's crust than uranium. Thorium is traditionally associated with closed nuclear fuel cycles, where fissile isotopes (such as ^{233}U formed from ^{232}Th, and ^{239}Pu and potentially other minor actinides primarily formed from ^{238}U) are recovered from the SNF and reused. Advocates claim that Th-based fuels offer advantages over U-based fuels. Foremost, since ^{232}Th has a larger thermal neutron capture cross-section than ^{238}U, ^{233}U can be bred more efficiently from ^{232}Th within thermal spectra than ^{239}Pu can be bred from ^{238}U. Given that ^{233}U is formed, it is often mentioned that less plutonium and fewer minor actinides are formed and these elements form the bulk of long-lived radiotoxicity, spontaneous neutron emission and decay heat (over 1000–100,000 years) of SNF, see e.g. Kamei and Hakami (2011). In terms of economics, thorium is currently characterised as a waste by-product, typically from rare-earth element processing, and it is suggested that the introduction of thorium has the potential to suppress the volatility of uranium prices. Thorium has been commonly ascribed as having enhanced proliferation resistance due to the facts that: (1) less LEU fuel is contained within the reactor, yielding smaller amounts of plutonium; (2) the ^{233}U that is bred within the fuel is denatured with unreacted ^{238}U; and (3) the short-lived isotope ^{232}U is also formed, the daughter products of which (particularly ^{208}Tl) add an additional radiological barrier.

For countries that want to adopt new nuclear energy systems, open nuclear fuel cycles are typically considered due to their lower infrastructure requirements and the significantly greater costs of reprocessing and refabrication than those of direct disposal. Therefore, the question arises as to whether thorium can be utilised in an open nuclear fuel cycle and incorporated in existing or novel nuclear energy technologies. It should be noted that this work treats the open nuclear fuel cycle in its strongest sense, i.e. plutonium disposition fuel cycles are considered to be out of scope, due to the need for prior SNF reprocessing. From a recent review paper (Ashley et al., 2013), a number of technology families have been highlighted that could prospectively use open Th–U-based fuel cycles. These include: (1) existing light water reactors (LWRs), (2) novel heavy-water-moderated, light-water-cooled reactors, and (3) novel high-temperature gas-cooled reactors.

This paper seeks to compare three candidate technologies operating with open Th–U-based nuclear fuel cycles to a 'reference' U-fuelled nuclear energy system over various performance indicators. The Th–U-fuelled technologies include AREVA's European Pressurised Reactor (EPR), the Indian Advanced Heavy Water Reactor (AHWR), and General Atomics' Gas-Turbine Modular Helium Reactor (GT-MHR). The reference U-fuelled system chosen was an EPR. Section 2 provides an overview of the fuel cycle modelling software, ORION, that was used in this work to derive mass flows and separative work units, isotopics associated with the SNF, and uranium and plutonium vectors for assessing the proliferation resistance of the SNF. Section 3 outlines the reactor systems further, the simulation techniques used and the parameters adopted in the neutronic analyses. Section 4 covers the mass flows of uranium, thorium, and separative work units for each of the four nuclear fuel cycles that are reported. Section 5 covers the isotopics of the SNF and the corresponding volumes, radiotoxicities, spontaneous neutron emission rates, and decay heats, and the potential issues surrounding deep geological disposal. Section 6 outlines an economic analysis of the fuel cycles and the corresponding nuclear energy systems to yield levelised nuclear fuel cycle costs and levelised costs of electricity. Section 7 covers the proliferation resistance methodology that was developed at the UK National Nuclear Laboratory (NNL) and is applied to each of the four nuclear fuel cycles. Finally, Section 8 provides a discussion of the results of Sections 4–7 and indicates the areas where open Th–U-based nuclear fuel cycles will need to be more competitive if they are to compete with open U-based cycles.

2. Fuel cycle simulation with ORION

ORION is a fuel cycle modelling code developed at NNL. The code performs inventory analysis to determine the throughput of material throughout a number of facilities in the nuclear fuel cycle, including storage buffers (that can represent the mine, mill and deep geological repositories), fuel fabrication facilities, reactors, and reprocessing facilities. For modelling the isotopic inventories within a reactor, ORION requires burn-up-dependent, shielded cross-sections produced by post-processing the results from deterministic or Monte-Carlo-based neutronic analyses of the reactor core. ORION has the capability to calculate the radiotoxicity, toxic potential, activity, spontaneous neutron emission rate and decay heat throughout the fuel cycle, as ~2500 isotopes including fission products and actinides are tracked. For radiotoxicity calculations, doses are evaluated using ingestion conversion coefficients provided in International Commission on Radiological Protection (1996). For decay heat and neutron emission rates, data from the JEF-2.2 Nuclear Data Library (OECD-NEA, 2000) are used.

A major strength of ORION is its ability to model complicated multi-reactor, multi-recycle options than can be used in energy pathway analyses, as outlined in Gregg and Grove (2012). This paper will outline its use in novel, open Th–U-based nuclear fuel cycles.

3. Selection of nuclear energy systems fuelled with thorium and LEU

Nuclear energy technologies that can potentially utilise open Th–U-based nuclear fuel cycles are described in Ashley et al. (2013) and references therein. Three different reactor technologies that broadly cover LWRs, heavy-water-moderated, light-water-cooled reactors, and high-temperature gas-cooled reactors have been selected for this study, these are respectively: AREVA's EPR, the Indian AHWR, and General Atomics' GT-MHR. In each case, the maximal enrichment of the uranium component of the fuel is ~20% ^{235}U.[2] As a reference for comparison, these three cases will be compared with a U-fuelled (with ^{235}U = 5%) EPR. In general, detailed simulations for these reactor configurations have previously been performed by a number of groups and these are highlighted in the following sub-sections. The neutronic simulations outlined in this work were performed to generate burn-up-dependent cross-sections required to determine the composition of the SNF and mass flows of feed materials.

3.1. Reference LEU-fuelled nuclear reactor: The EPR

The reference system considered in this study is AREVA's EPR, which is prospectively going to be constructed in the UK at Hinkley Point in Somerset and Sizewell in Suffolk. The parameters used to model this reactor are detailed in Table 1, the majority of these being taken from the submission to the UK Generic Design Assess-

[2] In this paper, all compositions with the exception of those in Table 5 are quoted in wt%.