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Book Section

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ABSTRACT

As part of the RCUK-India civil nuclear research collaboration, British and Indian researchers have assessed the merits and disadvantages of, and potential for, open-cycle thorium–uranium-fuelled (Th–U-fuelled) nuclear energy systems. The research centred on fuel cycle modelling and life-cycle assessment of three Th–U-fuelled nuclear energy systems and compared these to a reference uranium-fuelled nuclear energy system, all operating with open nuclear fuel cycles. The results indicate that thorium-based fuels offer little benefit over conventional uranium-fuelled approaches for open-cycle nuclear energy production. This paper provides an overview on the project and stresses over-arching conclusions.

KEYWORDS

THORIUM, NUCLEAR FUEL CYCLE, LIFE-CYCLE ANALYSIS, TECHNOLOGY ASSESSMENT

1. INTRODUCTION

As part of the RCUK-India civil nuclear research collaboration, British and Indian researchers have assessed the merits and disadvantages of, and potential for, open-cycle thorium–uranium-fuelled (Th–U-fuelled) nuclear energy systems. An overview of the systems chosen and the rationale for choosing these systems is presented in Ref. [1]. The work centred on assessing various performance indicators spanning material flows, waste composition, economics, emissions, and proliferation resistance. These performance indicators were determined by using the UK National Nuclear Laboratory's fuel cycle modelling code ORION [2,3] and also the life-cycle analysis code GaBi [4]. In addition, background issues surrounding the proliferation resistance of Th–U-based fuels were presented at the UK PONI 2012 Conference [5]. The purpose of the paper is to provide a summary of the project. To serve this end the paper refers to some example results from component studies [3,4], and stresses the over-arching project conclusions.

2. SCOPE OF THE RESEARCH

Most considerations of thorium-fuelled nuclear energy focus on closed nuclear fuel cycles. That is cycles in which spent reactor fuel is reprocessed to yield fissile material for further useful electricity generation. The intention motivating the research was to understand whether thorium might have a useful role to play in open nuclear fuel cycles in which spent nuclear fuel is sent for disposal as radioactive waste without reprocessing. The motivation of the research has been described at greater length elsewhere [1].

It would not have been practical to seek to assess all conceivable technologies that could utilise thorium in open nuclear fuel cycles. Hence, three Th–U-fuelled reactor systems using uranium enriched to ~20% ^{235}U were assessed and compared to a reference technology. These were: AREVA's European Pressurised Reactor (EPR); India's Advanced Heavy Water Reactor (AHWR); and General Atomics' Gas-Turbine Modular Helium Reactor (GT-MHR). The reference technology was a uranium-fuelled EPR. These three Th–U-fuelled reactor systems are considered to be "near term" technologies, in so far as one (the EPR) is under construction, another is ready for deployment (AHWR) and the third (GT-MHR) appears to be based entirely on proven technology—albeit with some engineering challenges remaining.

Accelerator Driven Subcritical Reactors (ADSRs) were excluded from this study on the grounds that significant reliability challenges lie in the path of commercial deployment of this technology for power production [6]. Another technology with potentially strong synergies with thorium fuel cycles is the concept of the Molten Salt Reactor (MSR). MSR concepts were also considered out of scope, as (i) significant engineering challenges lie ahead for this technology, and (ii) the recirculation of liquid fuel/coolant shapes and constrains the fuel cycle towards approaches that have more in common with conventional closed fuel cycles than conventional open cycles.

This work considers a strong definition of the "open" nuclear fuel cycle, i.e. no separated fissile materials (such as separated plutonium) are available from previous reprocessing. As such, the reactor systems are initiated and operated using enriched uranium. This restriction implies that potential technologies to address the disposal options for the UK's surplus separated civil plutonium are out of scope. An example of one of the out-of-scope technologies is the CANMOX approach (from CANDU Energy) whereby UK separated plutonium might be used to manufacture a Th-Pu mixed-oxide (MOX) fuel suitable for use in the company's EC-6 reactor [7].

Although this study focusses on technologies that have a high technological readiness level, certain advances (most notably in fuel cladding materials) would be required. Advanced fuel cladding materials (i.e. silicon carbide and TRISO) are assumed for the Th–U-fuelled EPR and Th–U-fuelled GT-MHR respectively. It is well established, see for instance Ref. [8], that the increased burnup afforded by advanced cladding materials enables greater ^{233}U breeding and thus improves the performance of thorium cycles. Changes in the neutron spectrum, in particular hardening of the spectrum by reducing moderation, can also be exploited in proposed future reactor systems to alter the breeding or burning characteristics of thorium-based fuels [9]. Further developments in either of these areas of technology could change the conclusions reached here about the potential of open thorium fuel cycles.

3. METHODOLOGY

To assess the three open cycle Th–U-fuelled reactor systems, various analyses were performed. The bulk of the analysis derived from the UK National Nuclear Laboratory's ORION fuel cycle modelling code [2]. 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, when applicable, reprocessing facilities. To model the isotopic inventories within a reactor, ORION requires shielded cross-sections which are dependent on burn-up. These are produced by post-processing the results from deterministic or Monte-Carlo-based neutronic assessments of the reactor core. In addition, radiotoxicity and decay heat calculations can be performed from the generated radionuclide inventories. Further details on the ORION fuel cycle modelling code and the reference data and reactor physics codes used to generate the burn-up-dependent shielded cross-sections for the reactor technologies are contained in Ref. [3]. In addition, the results from the ORION fuel cycle modelling code provided the necessary inputs for the economic modelling: both levelised nuclear fuel cycle costs and levelised cost of electricity (LCOE) values (using SimLab) and proliferation resistance assessment (using the National Nuclear Laboratory's proliferation resistance tool) which are also detailed in Ref. [3]. A brief summary of these results is presented in Section 4.

Life-cycle environmental emissions associated with thorium production and use in open Th–U-based nuclear fuel cycles were also investigated [4]. A comparative life-cycle analysis (LCA) was performed for the three Th–U based systems using GaBi4 and the EcoInvent database [4]. The LCA considered the construction, operation, and decommissioning of each of the reactor systems including all of the associated facilities of an open fuel cycle. This included the development of LCA models to describe the extraction of thorium from monazitic beach sands and for the production of heavy water. Life-cycle impacts per kWh (or per kg for thorium dioxide production) were obtained and are summarized in Section 4. Further details on this methodology, the underlying data used in this analysis, and all life-cycle impact analysis results are detailed in Ref. [4].

4. RESULTS

The full results have been published previously in Refs. [3,4] and are summarized in Table 1.

Table 1: Performance indicator values per kWh electricity generated [3,4]. Green (italic) denotes better performance (whereas red (underlined) denotes poorer performance) than the benchmark uranium-fuelled EPR.

Reactor	U_3O_8 (mg)	Enrich. (μSWU)	U fuel (mg)	SNF (nm^3)	Radiotox. (Sv)*	Heat (μW)*	FC Cost (¢)	LCOE (¢)	CO_2(eq) (g)	PR score
EPR UO_2	18.4	14.1	1.76	3.77	0.39	2.11	0.77	12.1	6.60	7.06
EPR UO_2/ThO_2	25.4	24.3	*0.68*	*3.03*	*0.35*	2.21	0.90	12.2	6.86	*7.22*
AHWR UO_2/ThO_2	22.0	21.2	*0.51*	4.55	*0.33*	2.47	0.99	13.7	13.2	*8.68*
GT-MHR UO_2/ThO_2	52.6	50.8	*1.21*	32.3	*0.28*	*1.52*	2.37	15.7	10.7	6.40

* Values for radiotoxicity and decay heat are taken 50 years after the fuel has been discharged.

To summarise, the three Th–U-fuelled nuclear energy systems involved a larger amount of separative work capacity than the equivalent benchmark U-fuelled system, with higher levelised fuel cycle (FC) costs and with a greater LCOE. While a decrease of approximately 6% is seen in the amount of uranium ore per kWh needed by the Th–U-fuelled AHWR when compared to the U-fuelled EPR reference, the two other Th–U-fuelled systems needed more uranium ore per kWh than the U-fuelled EPR reference. Insignificant advantages and disadvantages were seen for both the quantity and the properties of the spent nuclear fuel (SNF) produced by the various nuclear energy systems investigated. Two of the Th–U-fuelled systems revealed some improvement regarding the proliferation resistance (PR) of the SNF produced. While open-cycle uranium-fuelled pressurized water reactors (PWRs), such as the EPR, can be considered to be highly resistant to proliferation, some improvement could be achieved by using a thorium-uranium MOX fuel in an EPR [3]. Similarly good scores are also achieved by a Th–U-fuelled AHWR [3].

In Figure 1, indicative results from the most challenging aspect of this research, a comparison of the fuel cycle costs per kWh of electricity generated considering all seven stages of the open nuclear fuel cycle, are presented. These 7 stages are:

1. Producing milled ore (U_3O_8 or ThO_2)
2. Converting U_3O_8 to UF_6
3. Uranium enrichment
4. Nuclear fuel fabrication
5. Fuel transport
6. Interim SNF storage
7. Final SNF waste disposal

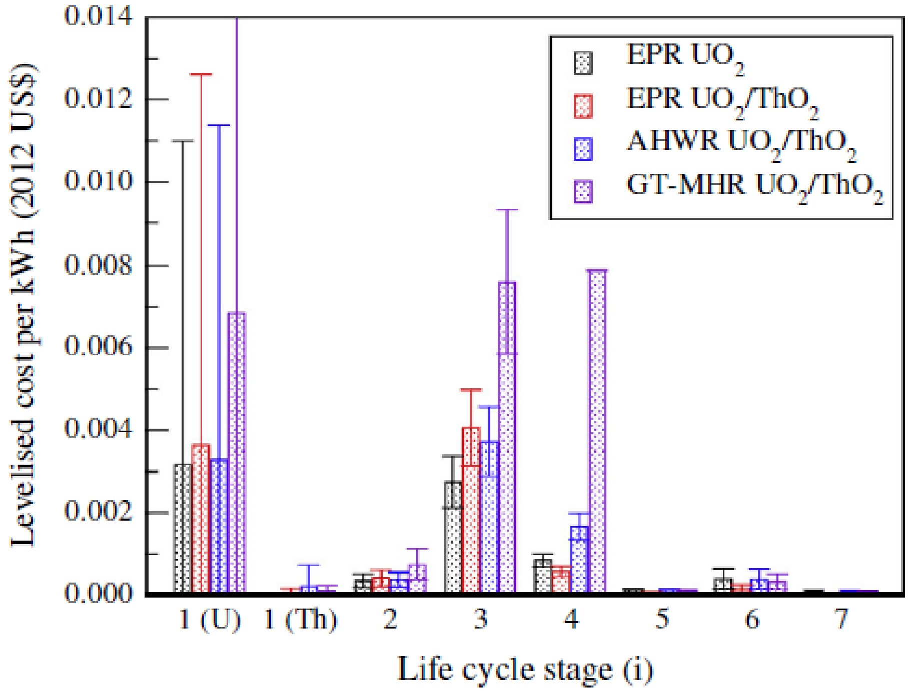

Fig. 1. Levelised nuclear fuel cycle costs per kWh generated [3]. The life cycle stages (i) are described in the text. If the figure is monochrome: each set of four bars follows the sequence in the key.

Bringing together the aspects illustrated in Figure 1, and having deployed a Monte Carlo analysis, the mean LCOE (and uncertainty to one standard deviation) was found to be 121±16 US$/MWh for the reference U-fuelled EPR, 122±17 US$/MWh for the Th–U-fuelled EPR, 137±18 US$/MWh for the Th–U-fuelled AHWR, and 157±14 US$/MWh for the Th–U-fuelled GT-MHR. Noting the error bars and the difficulties inherent in such an analysis, it is apparent that thorium does not represent an economically attractive fuelling option for these systems operating with an open nuclear fuel cycle.

The results of the life-cycle impact analysis highlight that the reference U-fuelled EPR has the lowest greenhouse gas (GHG), ozone depletion and eutrophication emissions per kWh generated, this is largely a consequence of the second-lowest requirement for uranium ore per kWh generated. The GHG result is shown in Figure 2. The results demonstrate that the the greatest overall contributor to environmentally harmful emissions is the requirement for mined or recovered uranium (and thorium) ore, albeit with the possible exception of nuclear energy systems requiring heavy water (please see Ref. [4] for a detailed description and breakdown of the various emissions). Thorium obtained from monazitic beach sands is associated with lower overall damaging emissions than uranium (either conventionally mined or recovered from in-situ leaching) when considered in a like-for-like comparison of mining and recovery methods. If thorium were to become a viable nuclear fuel we would expect monazitic beach sands (and equivalent placer deposits) to be utilized first and preferentially, despite such resources only forming 30% of the overall known thorium ore deposits. Generally, and unsurprisingly, for the four nuclear energy technologies considered, the range of CO_2(eq) emissions per kWh generated (6.60–13.2 gCO_2(eq)/kWh) appears to be low when compared to the emissions generated by the dominant fossil-fuel combusting electricity-generation technologies.

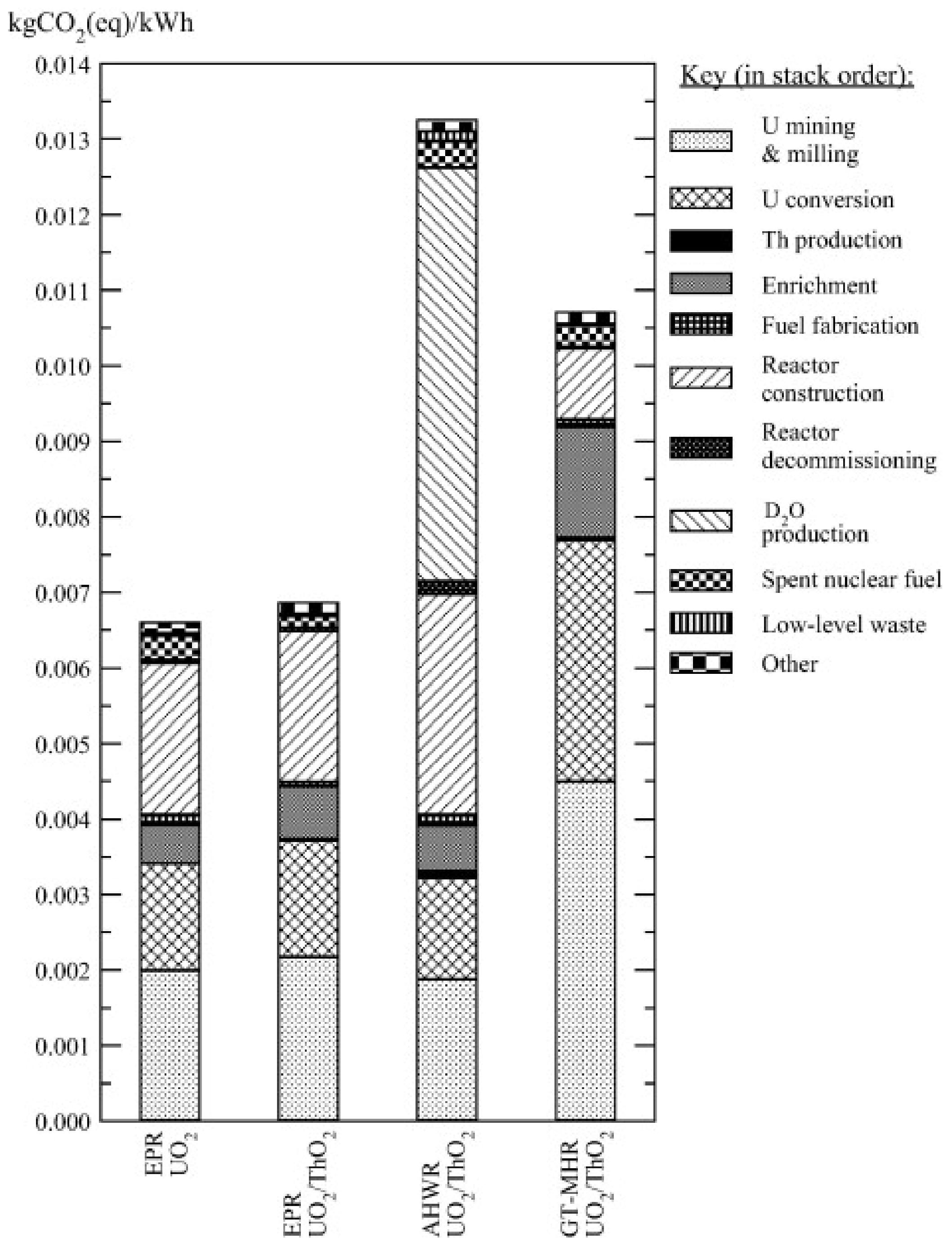

Fig. 2: Greenhouse gas impact per kWh of electricity generated for each of the four systems studied. For details please see Ref. [4].

5. CONCLUSIONS

The analysis shown here indicates that thorium fuel offers little benefit over conventional uranium-fuelled approaches for open-cycle nuclear energy production limited to the low-enriched uranium standard of 20% ^{235}U. Hence, short- to medium-term interest in thorium should be restricted to those countries with an interest in spent nuclear fuel reprocessing or with a need to reduce inventories of fissile material (such as separated plutonium).

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NOMENCLATURE

ADSR	Accelerator-Driven Subcritical Reactor
AHWR	Advanced Heavy Water Reactor (DAE India funded)
CANDU	A widely adopted type of Pressurised Heavy Water Reactor developed in Canada
EPR	European Pressurised Reactor (AREVA)
FC	Fuel Cycle
GHG	Greenhouse Gas
GT-MHR	Gas-Turbine Modular Helium Reactor (General Atomics)
LCA	Life-Cycle Analysis
LCOE	Levelised Cost Of Electricity
MOX	Mixed-Oxide (nuclear fuel)
MSR	Molten Salt Reactor (various concepts)
PR	Proliferation Resistance
PWR	Pressurised Water Reactor
SNF	Spent Nuclear Fuel

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