National Nuclear Laboratory

Comparison of thorium and uranium fuel cycles

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EXECUTIVE SUMMARY

The UK National Nuclear Laboratory has been contracted by the Department for Energy and Climate Change (DECC) to review and assess the relevance to the UK of the advanced reactor systems currently being developed internationally. Part of the task specification relates to comparison of the thorium and uranium fuel cycles. Worldwide, there has for a long time been a sustained interest in the thorium fuel cycle and presently there are several major research initiatives which are either focused specifically on the thorium fuel cycle or on systems which use thorium as the fertile seed instead of U-238. Currently in the UK, the thorium fuel cycle is not an option that is being pursued commercially and it is important for DECC to understand why this is the case and whether there is a valid argument for adopting a different position in the future.

NNL has recently published a position paper on thorium [1] which attempts to take a balanced view of the relative advantages and disadvantages of the thorium fuel cycle. Thorium has theoretical advantages regarding sustainability, reducing radiotoxicity and reducing proliferation risk. NNL's position paper finds that while there is some justification for these benefits, they are often over stated.

The value of using thorium fuel for plutonium disposition would need to be assessed against high level issues concerning the importance of maintaining high standards of safety, security and protection against proliferation, as well as meeting other essential strategic goals related to maintaining flexibility in the fuel cycle, optimising waste arisings and economic competitiveness. It is important that the UK should be very clear as to what the overall objectives should be and the timescales for achieving these objectives.

Overall, the conclusion is reached that the thorium fuel cycle at best has only limited relevance to the UK as a possible alternative plutonium disposition strategy and as a possible strategic option in the very long term for any follow-up reactor construction programme after LWR new build. Nevertheless, it is important to recognise that world-wide there remains interest in thorium fuel cycles and as this is not likely to diminish in the near future. It may therefore be judicious for the UK to maintain a low level of engagement in thorium fuel cycle R&D by involvement in international collaborative research activities. This will enable the UK to keep up with developments, comment from a position of knowledge and to some extent influence the direction of research. Participation will also ensure that the UK is more ready to respond if changes in technology or market forces bring the thorium fuel cycle more to the fore.

It should be noted that this paper is <u>not</u> intended to provide an exhaustive review and assessment of potential advanced reactor technologies in order for DECC or other UK interested parties to immediately down select reactor options. The study and the approach developed was deliberately limited in its assessment of reactor options primarily due to time and in particular budget constraints. As such, only a limited cross section of reactor technologies were assessed and no design variants were assessed either e.g. prismatic or pebble VHTR options.

The UK NNL would like to also recognise and thank all of the external reviewers for their time taken to review the study and for their comments on the paper. As with any such review process, not all of the comments were able to be included in the final version of the report either due to opposing views not simply between the authors and the reviewers, but also between the reviewers themselves. Nevertheless, every comment was considered and included where appropriate.

VERIFICATION STATEMENT

This document has been verified and is fit for purpose. An auditable record has been made of the verification process. The scope of the verification was to confirm that : -

- The document meets the requirements as defined in the task specification/scope statement
- The constraints are valid
- The assumptions are reasonable
- The document demonstrates that the project is using the latest company approved data
- The document is internally self consistent

The above is a minimum requirement. Add any additional appropriate criteria

HISTORY SHEET

Issue Number	Date	Comments
Issue 1	21 April 2011	Issue to customer for comment
Issue 2	3 June 2011	Revised to address customer comments
Issue 3	5 Jan 2012	Re-issue taking account of comments received from reviewers
Issue 4	27 Jan 2012	Correction of minor typographical error
Issue 5	5 Mar 2012	Security clearance removed to allow publication

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1. Introduction

The UK National Nuclear Laboratory (NNL) has been contracted by the Department for Energy and Climate Change (DECC) to review and assess the relevance to the UK of the advanced reactor systems currently being developed internationally. Part of the task specification relates to comparison of the thorium and uranium fuel cycles. Worldwide, there has for a long time been a sustained interest in the thorium fuel cycle and presently there are several major research initiatives which are either focused specifically on the thorium fuel cycle or on systems which use thorium as the fertile seed instead of U-238. In the UK, the thorium fuel cycle isn't currently regarded as a mainstream option and it is important for DECC to understand why this is the case and whether there is a valid argument for adopting a different position.

All commercial power reactors in operation today are reliant on the uranium-plutonium (U-Pu) fuel cycle, in which U-235 is the principal fissile nuclide providing the fission neutrons needed to maintain criticality and power output. Most of the commercial reactor fleet uses Low Enriched Uranium (LEU), containing typically < 5 weight percent of U-235, though some reactor types (CANDU being the most prevalent) use natural uranium at 0.71 weight %. In all these reactors the U-238 (which constitutes the bulk of the fuel mass) undergoes fertile neutron captures to produce Pu-239, which is fissile and which increases the useful energy that can be extracted from the fuel. The Pu-239, along with the higher plutonium isotopes produced by neutron captures, is partly consumed as it is produced and some remains in the spent fuel. The remaining plutonium can be recycled in various forms to increase the energy extracted and in a fast reactor breeding cycle the extracted plutonium is sufficient to meet the reactor's fuel requirements without any further inputs of uranium.

The thorium fuel cycle is an alternative to uranium-plutonium. Thorium is widespread in the Earth's crust and is known to occur in economically accessible deposits in many locations. Natural thorium is made up entirely of the isotope Th-232, which is fertile, but not fissile. When irradiated by neutrons, Th-232 is converted to U-233, which is fissile. In principle, if there are sufficient spare neutrons from a uranium fuelled reactor available, useful quantities of U-233 can be produced by irradiating Th-232. The U-233 can then either fission in situ in the fuel, increasing its useful energy output, or be separated and recycled into new fuel. This is the basis of the thorium fuel cycle.

NNL has recently produced a position paper on thorium [1] which attempts to take a balanced view of the relative advantages and disadvantages of the thorium fuel cycle. This report develops the arguments further by considering the possible relevance of the thorium fuel cycle in the context of potential applications in the UK, comparison being with the uranium-plutonium fuel cycle.

Section 2 gives a brief history of the development of the thorium fuel cycle. Section 3 describes the salient features of the uranium-plutonium fuel cycle, which forms a reference point for the rest of the report. Section 4 describes the thorium fuel cycle and explains why it is of interest in the international research community. Section 5 discusses the potential role of thorium-plutonium fuel as an option for plutonium management in the UK. Section 6 discusses the potential role of thorium in the nine advanced reactor systems considered in a report written for the first phase of this study [2]. Finally,

Sections 7 and 8 discuss the key points that need to be considered in determining the best strategies that the UK might adopt if it decides to recycle its plutonium stockpile.

2. Thorium history

The potential benefits of the thorium fuel cycle have led to a number of historic R&D projects world-wide: The first attempt to demonstrate the thorium fuel cycle at large scale was in the Shippingport PWR in the late 1950s [3]. This operated in the 1970s with a high enriched uranium (HEU) driver fuel and thorium fertile targets. This was the Light Water Breeder Reactor (LWBR) programme [4]. The ultimate objective was to reprocess the thorium targets and recycle the U-233 into new driver fuel assemblies which would in turn provide the neutrons for the next generation of thorium targets. However, the LWBR programme was not followed up after the project ended.

Further R&D on thorium fuels was carried out in the USA and Germany as part of the early High Temperature Reactor (HTR) programmes of those countries which started in the early 1960s and continued to the mid-1980s. It was recognised that that HTRs are especially suited to thorium fuels, because HTR fuels are capable of very high burnups, which is an essential requirement if U-233 is to be utilised in-situ in a once-through fuel cycle. Moreover, some of the HTR fuel cycle schemes being considered at that time involved reprocessing and U-233 recycle, which offered the possibility of high conversion ratios and low fuel requirements.

A long standing R&D programme currently led by LightBridge [5] is developing a two-part fuel assembly for PWRs in which a central LEU driver sub-assembly provides the seed neutrons to breed U-233 in an outer thorium sub-assembly. This seed-blanket concept uses a once-through fuel cycle in which the seed sub-assemblies are replaced more frequently than the blanket sub-assembly. This allows the U-233 in the blanket more time to build up and for it to be fissioned more completely. Lightbridge have been working closely with Russian researchers and the seed sub-assembly uses LEU metal fuel elements based on submarine reactor technology.

In the past two decades, there has been a large amount of interest in Accelerator Driven Systems (ADS) using thorium fuels. These use a sub-critical reactor core which maintains a steady fission power with an external source of neutrons generated by a spallation source driven by a beam of high energy protons from an accelerator. This was an old idea that was revived by Nobel laureate Carlo Rubbia in the Energy Amplifier [6] and has recently been taken up in projects such as the Accelerator Driven Thorium Reactor (ADTR) proposed by Jakobs (formerly Aker Solutions) and the Accelerator Driven Subcritical Reactor (ADSR) proposed by a consortium of universities [7] [8]. ADS are capable of burning any type of fuel and choosing thorium potentially provides low radiotoxicity, fuel diversity and proliferation resistance.

More recently, there have been several small companies involved in promoting thorium fuels, mostly with links to Norway (eg Thor Energy), which has large thorium reserves. In this case, the main driver is to establish a market for thorium that Norway could subsequently exploit.

The European Union Framework Programme (FP) has sponsored several projects related to thorium fuel and in 2011 a new proposal for FP-7 called THORIZON was developed by NRG and AREVA, with NNL amongst other partners. Although THORIZON was not supported by the EU, some useful pointers came from it. AREVA's interest centred on the use of thorium fuel in PWRs with reprocessing and recycle of the U-233. They cited

studies showing a benefit of up to 40% in reduced uranium demand if plutonium, reprocessed uranium and U-233 are recycled [9]. AREVA felt this was a worthwhile justification for a modest level of R&D spend on thorium in PWRs. AREVA made the point that without recycle of U-233, the uranium demand benefits in PWRs appear to be too marginal to justify the necessary investment.

Acting largely independent of international developments on thorium, India has maintained a sustained interest in thorium fuels for many decades. To date, this has mainly been focused on India's Heavy Water Reactors (HWR). Future plans will involve the breeding of U-233 in thorium blanket assemblies in India's planned fast reactor fleet. The U-233 will then be separated and manufactured into U-233/Th fuel assemblies to be irradiated in the planned Advanced Heavy Water Reactors (AHWR). These reactors could meet about two-thirds of their long term U-233 requirement from breeding in the thorium matrix, with the balance being provided by the fast reactor breeder blankets.

India's situation is special. The main justification for thorium is that India has large thorium reserves, but no reserves of uranium. India has been isolated from the broader international nuclear R&D community because of not having signed the Non-Proliferation Treaty (NPT). India's nuclear industry does not operate on the same commercial footing as most other countries, so that justification of the thorium fuel cycle does not have to be made on the same basis. Finally, there is a strong element of India wanting to demonstrate its technical prowess and the thorium fuel cycle provides a powerful vehicle for this purpose.

3. Uranium-plutonium fuel cycle

3.1. General principles

The uranium-plutonium fuel cycle is the only one that has been used in commercial reactors, despite there having been an early interest in the thorium/U-233 fuel cycle. In the uranium-plutonium fuel cycle the primary fissioning nuclide is U-235. U-235 is the only naturally occurring fissile nuclide and was necessarily therefore the starting point for both military and civil nuclear programmes. In graphite moderated systems (such as MAGNOX) and heavy water moderated systems (such as CANDU), the 0.71 weight % abundance of uranium is sufficient to achieve criticality. In other systems, such as light water reactors (LWRs), criticality is only achievable with low enriched uranium (LEU). In both natural and LEU systems, U-235 accounts for about 60% of the fission events in the nuclear fuels over their irradiation lifetimes, with the balance coming principally from Pu-239 and lesser contributions from Pu-241 and U-238. Plutonium is generated in uranium fuel by neutron capture events in U-238, which after two beta decays results in Pu-239. This is the fertile capture mechanism whereby the fertile nuclide U-238, which is reluctant to fission, is converted via a neutron capture event into a fissile nuclide which fissions readily.

Fertile conversion is a key element of the uranium-plutonium fuel cycle. The production of Pu-239 in this manner contributes to about 30% of the fission events in the nuclear fuel over its lifetime, increasing the effective energy output over that achievable with U-235 only. This contributes to reducing fuel costs, since the fuel throughput is decreased proportionally and at the same time uranium ore requirements are reduced by the same amount. The U-238 fertile capture mechanism also has a key role in reactor safety because many of the neutron captures in U-238 occur in the resonant energy range from

6 eV upwards. The resonances are very sharply defined peaks in the neutron capture cross-section that are broadened by the thermal motion of the atoms. When the fuel temperature increases, this Doppler broadening of the resonances increases neutron captures because the population of neutrons with kinetic energies matching the resonances is increased. This is a fast acting negative feedback effect that is essential to ensure safe operation of all reactors.

Another benefit of fertile conversion is that not all of the plutonium produced in the fuel is fissioned before the fuel is discharged. The residual plutonium at discharge (typically about 1% of the heavy metal mass) can potentially be recovered in reprocessing and either recycled in a thermal reactor (as is the case today in France) or in a fast reactor. Thermal reactor plutonium recycle as Mixed Oxide (MOX) fuel gives approximately a 15% increase in the energy recovered from the original uranium ore. On the other hand, plutonium recycle in a fast reactor gives the possibility of much higher energy recovery in a breeding cycle, with the possibility of a fully self-sustained fuel cycle with minimal uranium ore input required. In principle, it is possible to attain about a 50 to 100-fold improvement in the energy extracted from uranium ore. This is the justification usually cited for fast reactors, which would allow a country to be strategically independent of the uranium market. However, the practical difficulties of realising this theoretical gain have not yet been overcome in any country. Moreover, such a large gain could only be realised over a large number of recycle steps. Since each cycle of irradiation, cooling and recycle last about 10 years at the minimum, the timescales involved extend to around one hundred years. Whether such timescales are actually relevant and meaningful in practice is questionable and in any practically relevant scenario, the recoverable energy is likely to be much lower. This is a practical limitation that is usually glossed over in the literature and in strategic analyses.

The fertile conversion of U-238 to Pu-239 in uranium fuel is the first step in a chain of neutron capture events that leads to higher isotopes of plutonium and to the production of the minor actinides (principally neptunium, americium and curium). This has important implications for this report in two respects:

Firstly, the accumulation with burnup of higher plutonium isotopes (especially Pu-240) is seen as beneficial for reducing the potential proliferation risk, because in high burnup fuels the proportion of Pu-240 makes the plutonium unattractive for weapons applications. Although all plutonium is formally regarded for safeguards purposes as being weapons usable, there is undeniably a vast difference in attractiveness between plutonium in low burnup fuels and fuels discharged at high burnups from modern LWRs; plutonium with Pu-240 < 6% is classified as “weapons plutonium” . This can be regarded as a beneficial characteristic of high burnup uranium-plutonium fuel cycles. This point is noted here because, as will be seen later, it contrasts strongly with the thorium fuel cycle.

Secondly, though the total minor actinide content of LWR fuel is only of the order of 0.1 weight %, the minor actinides contribute significantly to radiotoxicity, heat production and neutron output in spent fuel or vitrified high level waste (VHLW) from reprocessing. The presence of U-238 in the fresh fuel makes it impossible to avoid significant production of minor actinides. Again, this is a point which is strongly contrasting in the thorium fuel cycle.

3.2. Resource availability

Total identified resources of uranium ore have been estimated by OECD-NEA [10, 11] to be sufficient to meet 100 years of supply at 2008 rates of consumption. While uranium availability poses a strategic risk, this will most likely materialise as an escalation of uranium prices that will have only a limited impact on total generating costs; uranium ore makes up only a small percentage of the overall nuclear generating cost. If world nuclear capacity remains static or grows slowly, uranium price escalation is unlikely to have be a major limitation. Pressure on uranium ore prices is likely to be most severe in a scenario with rapid growth of world nuclear capacity. Estimates of economic uranium reserves are strongly linked to market prices – an increase in market price greatly increases the reserves which are economically viable. Therefore, even in high growth scenarios, uranium availability is not likely to be limiting and utilities are unlikely to view alternatives to uranium as a strategic priority for some considerable time yet. Also, reprocessed uranium and plutonium recycle are available to help mitigate this risk if required.

3.3. Economics

The total generating cost of a nuclear power plant is dominated by the capital cost (typically ~60%), followed by operating and maintenance (~20%) and then the fuel cost (~15%), as illustrated in Reference [12]. The back-end fuel cost and the decommissioning provision cost accounts for the remainder. The fuel cost is comprised of the cost of buying uranium ore on the world market, the cost of converting and enriching the uranium and finally the cost of fuel fabrication. The uranium ore cost is variable, being determined by market prices, but at the present long term contract prices, it equates to about one third of the fuel cost. Therefore, the cost to an utility of uranium ore represents only a small component of overall generating costs (typically ~5%) and overall generating costs are relatively insensitive to escalations in uranium ore prices. Again, reprocessed uranium and plutonium recycle are available to help mitigate this risk if required.

At present, although there are pressures on utilities from uranium market trends, these are insufficient at present to force them to seriously look at alternatives.

3.4. Radiotoxicity

The radiotoxicity of spent uranium fuel is dominated for the first 500 years by fission products. After this time the fission products have mostly decayed and the radiotoxicity becomes dominated principally by transuranic elements, particularly plutonium. This persists until approximately 100,000 years, when the long-lived fission products such as I-129 become the dominant contributors. The radiotoxicity is an important measure of the hazard potential in the geological repository. The period between 500 years and 10,000 years is usually considered to be a key factor in repository performance, since this is when waste packages are likely to lose their integrity and radionuclide transport out of the repository is most significant.

Reducing radiotoxicity is currently not regarded by utilities as a concern in reactor operations. Radiotoxicity has been cited in justification arguments for new build in the UK and are likely to be used by utilities in justifying future fuel cycle and operational strategies. Nevertheless, the practical impact of radiotoxicity calculations has to date

been relatively low and there is no prospect of it becoming important enough to warrant major changes of strategy by an utility. Plutonium recycle as MOX can be shown to give a modest reduction in overall radiotoxicity.

One of the benefits of the thorium fuel cycle is to reduce the inventories of plutonium and minor actinides, which control radiotoxicity between 500 and 100000 years. Minor actinide burning systems also cite reduced plutonium and minor actinide inventories in justification. In practice, the impact of reducing plutonium and minor actinide inventories on the performance of a geological repository is limited. A recent OECD-NEA review [13] has concluded that minor actinides have little influence on peak environmental dose rates from a repository. This arises because the minor actinides tend to be immobile and peak doses are controlled by fission products, which are similar for all fission reactors. The only area where the OECD-NEA review shows a significant benefit from reduced minor actinide inventories is in scenarios involving inadvertent intrusion into a repository.

3.5. Proliferation risk

Spent uranium fuel from LWRs contains just over 1 weight % of plutonium. This is considered to represent the main proliferation risk associated with the uranium fuel cycle. In a once-through fuel cycle, the plutonium remains relatively inaccessible in the spent fuel. In contrast, in a reprocessing fuel cycle, separated plutonium oxide is produced which needs to be subject to stringent physical protection. Measures to increase the inherent proliferation resistance of the reprocessing fuel, such as avoiding the separation of pure plutonium oxide are considered desirable in designing new reactors and associated fuel cycle facilities. However, reducing proliferation risk is not a factor in strategic decision making for utilities and is unlikely to become so in the foreseeable future. Therefore, there currently is no incentive for utilities to seek alternatives to U-Pu fuel.

3.6. Reprocessing

The purpose of reprocessing spent uranium fuel is to separate it into a pure uranium stream for recycle, a pure plutonium stream for recycle and a vitrified high level waste stream which contains all the fission products and transuranics other than plutonium for disposal. The PUREX process is used for this purpose. It involves mechanically shearing the spent fuel and dissolving the fuel pellets in nitric acid. Tri Butyl Phosphate (TBP) in kerosene is used as the extractant to separate out the fission products and to separate the uranium from the plutonium. The PUREX process is well established, with commercial plants operational in France, Japan, Russian Federation and the UK. The recycled uranium can be re-enriched for re-use as Reprocessed Uranium (REP U) fuel. The recycled plutonium can be reused as UO_2/PuO_2 mixed oxide (MOX) fuel.

Only a small proportion of utilities have their fuel reprocessed, the vast majority preferring to opt for a once-through strategy with direct disposal of spent fuel, which utilities regard as a less expensive option. Many utilities which already have reprocessing contracts in place have been seeking to reduce their commitments in favour of direct disposal. Although this attitude may change in the future, it is unlikely to occur in the near future and there is not likely to be any pressure from utilities to invest in new reprocessing plants.

4. Thorium fuel cycle

This section discusses the potential advantages of the thorium fuel cycle and comments on their practical relevance.

4.1. General principles

In the thorium fuel cycle, the starting point is naturally occurring thorium, which consists of just the single isotope Th-232. This is a fertile isotope, analogous to U-238, and on capturing a neutron it is transformed via two beta decays to U-233, which is fissile. There are two strategies for making use of the U-233 produced in this way: The once-through strategy involves the fissioning of as much of the U-233 as possible in situ in the thorium matrix and not to attempt to recover any from spent fuel. The spent fuel eventually undergoes geological disposal. The recycle strategy involves the reprocessing of the thorium fuel to recover the U-233 for fabrication into U-233/Th fuels. Only the latter option is capable of delivering the full benefits of the thorium fuel cycle, but technological uncertainties with thorium fuel reprocessing and fabricating U-233 fuels, identified at the R&D level, have posed obstacles to its implementation to date.

In the thorium fuel cycle Th-232 is analogous to U-238 in the U-Pu fuel cycle, because it is the fertile component. Some of the neutron captures in Th-232 are resonance events, so that the Doppler broadening role of U-238 is very closely replicated. U-233 is analogous to Pu-239 in the uranium fuel cycle, because these are the fissile nuclides produced from fertile neutron captures. Unlike the uranium fuel cycle, in the thorium fuel cycle there is no naturally occurring fissile isotope analogous to U-235 to provide the first neutrons and the thorium fuel cycle relies on the supply of neutrons from another source to produce the fissile material, which in practice means fission neutrons from U-235 or Pu-239. This is a crucial difference between the thorium and uranium fuel cycles that in large part explains why the uranium fuel cycle became established first and why the thorium fuel cycle has failed to make any inroads: the uranium fuel cycle necessarily had to be established first and once the infrastructure was in place the thorium fuel cycle was disadvantaged.

The nuclear industry committed to the U-Pu fuel cycle more than 50 years ago and it is important to bear in mind that many of the considerations that might influence current and future fuel cycles were not present at that time. It is therefore right that thorium should be reconsidered in this light.

4.2. Resource availability

Thorium represents an alternative resource to uranium and has a higher abundance and a different geographic distribution to uranium, as illustrated in Table 1, which shows the distribution of thorium resources according to the World Nuclear Association [14]. It may therefore be a strategic benefit in the event of high uranium prices. It should be noted that the external radiation dose is much higher for thorium than uranium leading up to the purification stages because of the decay to thallium-208. Nevertheless, mining of open pit monazite deposits (presently the main source of thorium) is easier than that of most uranium bearing ores, and management of thorium mine tailings is also simpler than in the case of uranium mainly because of the much shorter half live of “thoron” (= Rn-220 : 55 sec) than of radon (Rn-222 : 8 days, daughter of Ra-226, 1600 years).

Thorium is presently recovered as a by-product of Rare Earth mineral extraction. In the event that the thorium fuel cycle was to be widely adopted, there would be a need for large efforts to develop thorium mine prospecting and development of a thorium purification process at the front end of the fuel cycle. The thorium demand would be very dependent on whether a once-through or a full recycle strategy was adopted. In the case of full recycle the equilibrium thorium demand would be very low (approximately 1 tonne per GWye), but there would be a much higher transient demand during the period when the thorium systems were first being introduced.

Table 1: Reasonably assured thorium resources (< $80/kg) from World Nuclear Association

Country	Tonnes	Percentage
Australia	489,000	19
USA	400,000	15
Turkey	344,000	13
India	319,000	12
Venezuela	300,000	12
Brazil	302,000	12
Norway	132,000	5
Egypt	100,000	4
Russia	75,000	3
Greenland	54,000	2
Canada	44,000	2
South Africa	18,000	1
Other Countries	33,000	1
World total	2,610,000	

It should also be noted, however, on the basis that neutrons from U-235 or plutonium are needed to convert fertile Th-232 to fissile U-233, the thorium fuel cycle would not be completely independent of uranium until a fully self-sustaining thorium cycle is eventually established. In practice, the self-sustained equilibrium requires several years to establish.

The thorium fuel cycle is in principle capable of achieving higher conversion ratios in thermal reactors than uranium fuel, which is advantageous for resource availability. The conversion ratio is the number of fissile atoms generated by fertile captures divided by the number of fissile atoms consumed in the process. A conversion ratio of 1.0 implies that a fuel cycle is capable of operating a self-sustained cycle. Thermal reactors with uranium fuel typically have conversion ratios in the region of 0.6 and although this can be increased, it is not feasible to reach 1.0. Thorium fuel, however, in a thermal reactor, can achieve conversion ratios much closer to 1.0 and this was one of the main

attractions. The basis of these statements comes from the nuclear cross-sections of U-233 in comparison with U-235 and Pu-239. The so-called eta parameter, which is the number of neutrons per fission multiplied by the ratio of the fission and absorption cross-sections, in the thermal neutron energy range, is highest for U-233 [15].

4.3. Economics

While economic benefits are theoretically achievable by using thorium fuels in existing LWRs, in current market conditions the position is marginal and insufficient to justify major investment by utilities:

In a once-through LWR thorium cycle, thorium will displace only a fraction of the uranium fuel, the latter being necessary to provide the neutrons to convert the fertile Th-232 to fissile U-233. Moreover, the uranium fuel remaining will need to have a higher U-235 enrichment to compensate for neutron captures in Th-232, so that any savings in uranium ore and enrichment costs are likely to be marginal. On the other hand, the thorium fuel will require new fuel production facilities, with a substantial investment. Any marginal reductions in uranium ore and enrichment costs are unlikely to justify the necessary investment.

In a reprocessing LWR cycle, in which the U-233 is recycled, the uranium ore and enrichment savings are likely to be improved still further and could even be eliminated altogether in the long term if a breeding cycle could be established. However, to reach this position will require major investment in thorium reprocessing and fuel fabrication plants, with significant technical and investment risk which appears not to be merited by current or reasonably foreseeable market conditions.

It cannot be ruled out that the thorium fuel cycle may become competitive in LWRs in a future market environment of restricted uranium ore availability and thus very high uranium prices. This is not considered very likely for the foreseeable future, given that economically recoverable uranium reserves are thought to be very price dependent and therefore if uranium prices were to increase, then more uranium would be available to the market. It is therefore concluded that adopting the thorium fuel cycle in LWRs would only offer limited benefits.

In the longer term, with strong pressure on uranium prices, Generation IV (Gen IV) systems operating with closed fuel cycles might then become competitive and that these systems would then set the competitive standard for the thorium fuel cycle. This sets the timescale on which thorium might become competitive. This is dictated by the development timescale for Gen IV systems, 20 to 30 years.

4.4. Radiotoxicity

The thorium fuel cycle generates only trace quantities of plutonium and higher actinides, which can reduce the long term radiotoxicity of spent nuclear fuel. Figure 1 shows a typical result for thorium systems for a scenario which was analysed for this study. The green curve shows the radiotoxicity in Sieverts per tonne of initial Heavy Metal (tHM) for a Light Water Reactor (LWR) fuelled with Th-Pu as a function of cooling time after discharge. For comparison, the blue curve shows the radiotoxicity profile for UO_2 fuel irradiated to the same discharge burnup. Between 100 and 100,000 years, the thorium fuel cycle shows a modest reduction. The thorium case, is however, higher after 100,000 years, a result which is typical of many studies, due to the in-growth of daughter nuclides from the thorium decay chain. There is virtually no difference in the cooling time needed to reach the radiotoxicity of uranium ore in the uranium fuel cycle, which is often used as a reference point. The key point to note is that the comparison between the radiotoxicities of the thorium and uranium cycles depends on the decay time being considered.

Figure 1 is intended to illustrate the typical behaviour observed with thorium systems. It should be stressed that the results are system and scenario specific and other thorium scenarios (especially those involving recycle of U-233) can be envisaged which would give larger reductions in radiotoxicity than in this particular example. However, care is required because such results are often quoted for an equilibrium fuel cycle in which U-233 is fully established in a self-sustained system. To get to an equilibrium condition will require the use of fuels containing U-235 or plutonium which will contribute higher radiotoxicities. In realistic scenarios, with the evolution of the scenario modelled explicitly in time, the overall radiotoxicity is usually significantly higher than the equilibrium case.

The overall conclusion is that while trace production of minor actinides in the thorium fuel cycle is without question advantageous for radiotoxicity, there is insufficient potential benefit to utilities to encourage the necessary investment.

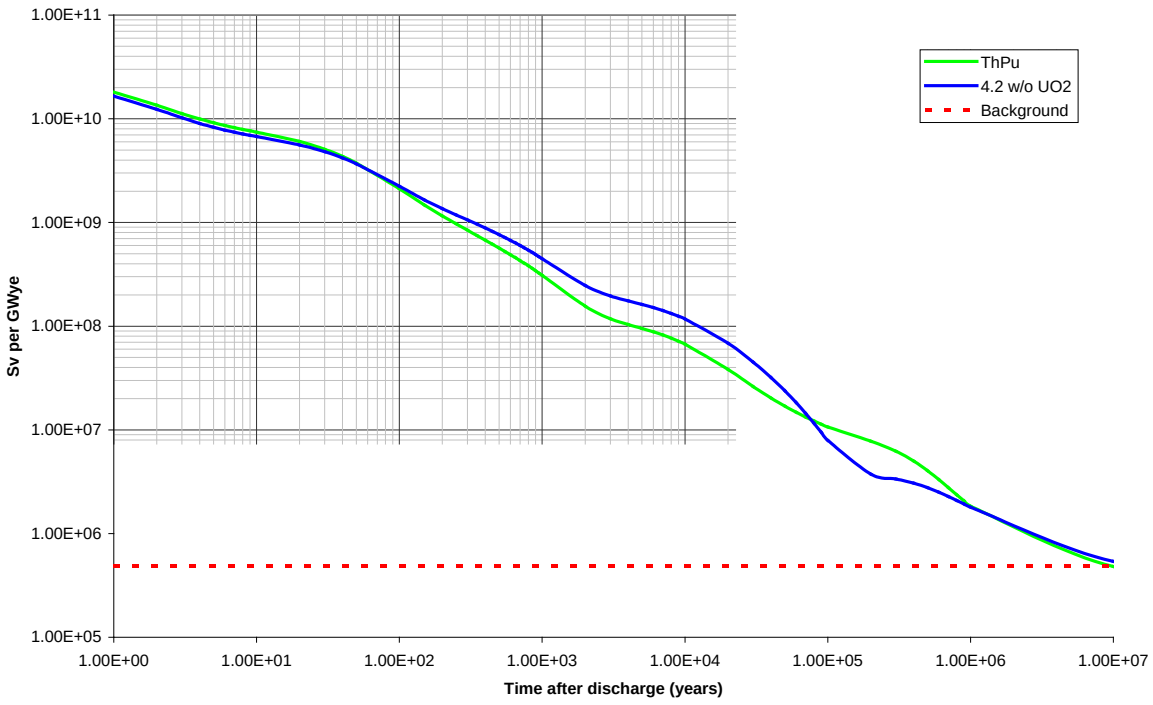

Figure 1: Radiotoxicity of Th-Pu fuel compared with UO_2 fuel irradiated in an LWR as a function of cooling time

4.5. Proliferation risk

The absence of plutonium is in the thorium fuel cycle is claimed to reduce the risk of nuclear weapons proliferation, though Reference [1] questions whether is this is completely valid, given that there were a number of U-233 nuclear tests (the “Teapot tests”) in the US in the 1950s. U-233 is in many respects very well suited for weapons use, because it has a low critical mass, a low spontaneous neutron source and low heat output. It has been stated [eg Wikipedia entry on U-233] that because U-233 has a higher spontaneous neutron source than Pu-239, then this makes it more of a technical challenge. However, this is erroneous, because even in weapons grade plutonium the main neutron source is from Pu-240. A further consideration is that the U-233 produced in thorium fuel is isotopically very pure, with only trace quantities of U-232 and U-234 produced. Although the U-232 presents problems with radiological protection during fuel fabrication, the fissile quality does not degrade with irradiation. Therefore, if it is accepted that U-233 is weapons useable, this remains the case at all burnups and there is no degradation in weapons attractiveness with burnup, unlike the U-Pu cycle.

The presence of trace amounts of U-232 is beneficial in that it provides a significant gamma dose field that would complicate weapons fabrication and this has been claimed to make U-233 proliferation resistant. However, there are mitigating strategies can be conceived and the U-232 dose rate cannot be regarded as a completely effective barrier to proliferation. As such, U-233 should be considered weapons usable in the same way as HEU and plutonium. This is also the position taken by the IAEA, which under the Convention on the Physical Protection of Nuclear Materials [16] categorises U-233 in the same way as plutonium. Under the IAEA classification, 2 kg or more of U-233 or plutonium are designated as Category I Nuclear Material and as such are subject to appropriate controls. By way of comparison, the mass of U-235 for Category I material is 5 kg. Attempts to lower the fissile content of uranium by adding U-238 are considered to offer only weak protection, as the U-233 could be separated relatively easily in a centrifuge cascade in the same way that U-235 is separated from U-238 in the standard uranium fuel cycle.

The overall conclusion is that while there may be some justification for the thorium fuel cycle posing a reduced proliferation risk, the justification is not very strong and, as noted in Section 3.5, this is not a major factor for utilities. Regardless of the details, those safeguards and security measures in place for the U-Pu cycle will have to remain in place for the thorium fuel cycle and there is no overall benefit.

4.6. Reprocessing

The purpose of reprocessing of thorium fuels is to separate the U-233 from the bulk Th-232 and the fission products. The U-233 and the Th-232 are then purified to leave only trace quantities of other radioactive materials suitable for recycle. The THOREX process has been developed for this purpose and is similar to the PUREX process used for separating uranium and plutonium. The THOREX process starts by shearing fuel assemblies and uses a mix of nitric and hydrofluoric acid to dissolve the nuclear fuel pellets. Tri Butyl Phosphate (TBP) in kerosene is used as the extractant to separate out the fission products, to separate the uranium from the thorium and to purify them for

recycle. The process is analogous to the PUREX process for reprocessing uranium/plutonium fuel, but there are a number of difficulties that are best illustrated by comparing THOREX and PUREX:

1. PUREX uses nitric acid for dissolution, which is sufficient to dissolve uranium/plutonium fuel. THOREX requires hydrofluoric acid in addition to nitric, because thorium is not completely dissolved in nitric acid on its own. Hydrofluoric acid is much more reactive than nitric acid towards structural metals and requires special alloys for reaction vessels, pipework, valves, pumps and sensors. Corrosion of the reprocessing plant components will need careful control to ensure the operational lifetime is not compromised.
2. The PUREX process takes advantage of the chemistry of uranium and plutonium, which are easily separated from one another. In the THOREX process, thorium is characterised by relatively poor extraction and this will complicate the design of the reprocessing plant, with possibly a cost penalty.
3. Waste streams from a THOREX plant will be different from those from a PUREX plant, because of the different reagents used and work will be required to establish if they can be managed using existing methods. The THOREX process, for example, is expected to generate 50-70 % more glass than PUREX [9].
4. The THOREX process has not been demonstrated beyond laboratory scale, which represents a technical risk when scaling up to commercial throughputs. Considerable R&D spend will be required to demonstrate the process at commercial scale and with a minimum timescale of 15-20 years before consideration of commercial scale facility could be considered.
5. The U-233 product will contain trace quantities of U-232 which has a very energetic gamma emitter as part of its decay chain. A short while after production of the U-233, the surface gamma dose will build-up to very significant levels and if there is a requirement to store the material, a shielded and remote access storage facility will be needed.

Based on the NNL's historic experience of reprocessing plant R&D and design, developing the THOREX process to commercial readiness will require a minimum of 15 to 20 years.

Other reprocessing methods, such as fluoride volatility are potentially viable alternatives for thorium which will avoid many of the difficulties with THOREX. However, these have not been developed beyond laboratory scale testing.

4.7. Recycle

Recycling U-233 presents some difficult challenges in fuel fabrication because of the daughter products from U-232. U-232 builds up to part per million (ppm) levels in the U-233, compared with parts per billion concentrations in reprocessed uranium fuels. U-232 has a half-life of 68.9 years and its decay chain includes daughters with very energetic gamma emissions, especially Tl-208. When the U-233 is chemically separated from the thorium fuel, the daughter products from U-232 are partitioned with the VHLW and the gamma activity of the U-232 is initially very low. However, the U-232 decay daughters re-establish themselves quite quickly, reaching equilibrium after about 2 years, at which point the U-233 has a very high gamma field. The activity of U-232 becomes significant at parts per billion (ppb) levels, so that the ppm concentrations in U-233 are very

serious, demanding substantial shielding and remote fabrication methods. This is a significant technological barrier to full recycle of U-233 and poses a technical risk.

MSR is unique in that it avoids these problems entirely, with no fuel fabrication required.

4.8. Technological readiness

NNL has assessed the Technology Readiness Levels (TRLs) of the thorium fuel cycle. For all of the system options more work is needed at the fundamental level to establish the basic knowledge and understanding. Thorium reprocessing and waste management are poorly understood. The thorium fuel cycle cannot be considered to be mature in any area. Much of the fundamental knowledge requirements and experimental measurements at laboratory scale have a high degree of commonality for the different systems. The relative immaturity of the thorium fuel cycle is reflected in its inclusion in the European Framework Programme.

5. Plutonium-thorium fuel

Plutonium-thorium fuel is a technical option that potentially could be of interest in the UK. This would consist of a mix of plutonium and thorium oxides (PuO_2-ThO) analogous to conventional PuO_2-UO_2 mixed oxide (MOX) fuel. Although there is only laboratory scale experience of manufacturing and irradiation Pu/Th fuel, its physical properties are very close to PuO_2-UO_2 MOX fuel and its in-reactor behaviour would be expected to be comparable.

In the UK, the application would be as an option for the disposition of separated plutonium instead of PuO_2-UO_2 MOX. There are some potential advantages in this approach:

Firstly, ThO matrix has been cited as potentially being more stable than a UO_2 matrix in geological disposal, with reduced leaching of plutonium. If this can be confirmed, this would fit with a strategy of irradiation of the PuO_2-ThO fuel followed by spent fuel storage and eventual disposal.

Secondly, the use of ThO as the matrix implies that there is no production of new Pu-239, as is the case in conventional MOX fuel. Production of new Pu-239 in conventional MOX to some extent offsets the destruction by fission of the Pu-239 that was present in the fresh fuel. While there is still net destruction of plutonium in conventional MOX, the discharge inventory remains quite high at typically about two-thirds the initial inventory. In PuO_2-ThO fuel the lack of a Pu-239 fertile production source causes the discharge plutonium inventory to be lower (Pu-239 is reduced to about one-third its initial inventory and total plutonium to about half[1]). The fissile quality of the plutonium at discharge is therefore exceptionally low, well below the level at which it would realistically be attractive for weapons use. The radiotoxicity of PuO_2-ThO fuel is also lower than that of the equivalent MOX fuel, though the difference is fairly marginal.

These potential advantages need to be balanced against the disadvantages, which are dominated by the relative immaturity of PuO_2-ThO fuel technology. R&D work would be needed to better determine the fuel thermo-physical properties and establish fuel fabrication methods, carry out irradiation testing (starting out with small scale irradiation

[1] This is based on an analysis of a PuO_2-ThO assembly in a PWR with 12 weight % initial plutonium loading irradiated to 50 GWd/t.

trials in a research reactor and progressing eventually to commercial scale tests in a power reactor). In addition, R&D would be needed to demonstrate the impact on core nuclear design behaviour and to better understand the behaviour of PuO_2-ThO fuel during irradiation, in store and in the repository environment. This R&D would still be required even though PuO_2-ThO fuel is only a relatively small step removed from conventional MOX fuel and would involve a significant R&D spend. The timescales required are quite protracted, as any R&D programme involving irradiation testing is necessarily a long process. Realistically, it is difficult to envisage such an R&D programme being completed in less than 10-15 years even with significant investment. This defines the minimum feasible timescale for such a strategy, but if it was accepted that there is no immediate urgency for plutonium disposition in less than, say 15-20 years, such a programme might be regarded as feasible.

6. Thorium in advanced reactors

This section considers how thorium fuels fit with the nine advanced reactor systems considered in the earlier report produced in this study [2]. These systems are:

1. Sodium Fast Reactor (SFR).
2. Gas Fast Reactor (GFR)
3. Lead Fast Reactor (LFR)
4. Very High Temperature Reactor (VHTR)
5. Super Critical Water Reactor (SCWR)
6. Molten Salt Reactor (MSR)
7. Accelerator Driven Sub-critical Reactor (ADSR)
8. Hyperion Power Module (HPM)
9. Small modular Light Water Reactor (LWR)

The first three systems are all lumped together, while the remaining systems are considered independently.

6.1. SFR, GFR & LFR

These are the three fast reactor systems being developed as part of the Generation IV international collaboration. All three systems could in principle operate with the thorium in place of the conventional U-Pu cycle, although there is currently no work specific to thorium in the Generation IV programme.

6.1.1. Uranium-plutonium fuel cycle

The base assumption in GIF is that all three systems will be U-Pu fuelled. The fuel will be plutonium in a natural or depleted uranium diluent and the plutonium will be recycled in a fully sustainable fuel cycle independent of uranium ore requirements. In principle, a fully self-sustaining U-Pu cycle could extract up to a factor of 100 times more useful energy from each kg of uranium ore than the once-through LWR cycle i.e. using/converting all of the uranium (U235 and U238) compared with only 0.71% U235 in a once-through fuel cycle. What is usually overlooked in this fuel cycle is the fact that actual realisation of the factor 100 improvement in fuel utilisation implies multiple

recycle, with the U-238 passing through the phases of fuel fabrication, in-reactor irradiation, spent fuel cooling and reprocessing/recycle many times. Since each passage through all these phases last for a minimum of 6-7 years, the timescales involved are very protracted.

The U-Pu fuel cycle is capable of achieving conversion ratios well over 1.0, which is an essential requirement for a breeding cycle to be established. It is particularly important for the breeding ratio to exceed 1.0 by a comfortable margin in a scenario in which the number of fast reactors is increasing rapidly, because this margin determines how quickly new reactors can be phased in. The initial deployment of fast reactors on a self-sustaining fuel cycle will be limited by the availability of stocks of fissile material generated by breeding. In the case of the U-Pu fuel cycle the initial deployment will be limited by the availability of plutonium.

The U-Pu fuel cycle is well understood, much of it being based on existing thermal reactor recycle technology. However, there are exceptions, the principal one being the strong drive to adopt alternatives to PUREX reprocessing to avoid separating pure plutonium. Other notable exceptions are that the characteristics of fast reactor fuel are different to those of thermal reactor fuel and therefore the specifications of the recycle plant will need to be modified to reflect the differences. Fast reactor recycle has been demonstrated only at sub-commercial scale and further development will be needed for full commercial readiness. Therefore the U-Pu fuel cycle for the GIF fast reactors can be regarded as being well understood, but in need of further development for commercial readiness.

6.1.2. Thorium fuel cycle

GIF is not planning to investigate the thorium fuel cycle for the Generation IV fast reactors, although thorium does represent a possible alternative.

A thorium fuel cycle in a fast reactor is compatible with a self-sustained breeding fuel cycle, potentially extracting up to 100 times more energy from each kg of Th-232 compared with 1 kg of uranium ore in the once-through thermal reactor cycle i.e. based on comparisons with a once-through LWR cycle, using only the U235. However, the same comment applies that complete energy conversion is only achievable on very long timescales.

Although the thorium fuel cycle is capable of achieving a conversion ratio greater than 1.0 in a fast reactor fuel cycle, the breeding ratio for the thorium fuel cycle in a fast neutron system is smaller than that of the U-Pu cycle. Depending on the specific scenario for deployment of fast reactors, this is potentially a disadvantage for the thorium fuel cycle that might slow the rate at which new reactors can be deployed. In the case of the thorium fuel cycle the limiting factor is the availability of U-233. A smaller breeding ratio for the thorium fuel cycle will limit the initial deployment of fast reactors and the time needed for the fast reactor fleet to expand will be longer. The doubling time for initial deployment is very sensitive to the breeding ratio and relatively small changes can have a large impact, so this is potentially a limiting factor in scenarios where rapid deployment of fast reactors is required. This loss of responsiveness in the deployment of fast reactors and the extra complexity of reprocessing thorium fuel and recycling U-233 are factors which are likely to have discouraged the Generation IV project from pursuing the thorium option for SFR, GFR and LFR. For fast reactors, the thorium fuel cycle offers no advantage in terms of sustainability because the U-Pu cycle is already fully self-

sustainable. For these reasons, there is reduced incentive for thorium in fast reactors, although there would be a modest benefit in terms of reduced radiotoxicity.

Another consideration is whether GIF would take the view that it is better to avoid the production of pure U-233, perhaps by diluting the U-233 with U-238 during reprocessing. Such a strategy would be analogous to avoiding the production of pure plutonium in the U-Pu cycle, but the presence of U-238 would lead to the production of plutonium and other transuranics that would to some extent negate the benefits of the thorium cycle.

The thorium fuel cycle is much less technologically mature than the U-Pu fuel cycle. As noted in Sections 4.6 and 4.7, the THOREX process has not been demonstrated beyond laboratory scale and fabrication of U-233 fuels will have to account for the strong gamma dose fields.

6.2. VHTR

The Very High Temperature Reactor (VHTR) in Generation IV is envisaged as operating with a once-through fuel cycle.

The fuel is in the form of 1 micro-metre diameter microspheres, containing the fuel kernel encapsulated in a TRISO fuel microsphere. The TRISO particle consists of a pyrolytic graphite layer, a silicon carbide or zirconium carbide layer (SiC/ZrC) and a second pyrolytic graphite layer. The fuel microsphere is embedded in a graphite matrix. Recycling VHTR fuel involves separating the microspheres from the bulk graphite and then mechanically cracking the hard SiC/ZrC shell. These are difficult steps that would complicate the recycle of the fuel.

VHTR is in principle capable of using a wide range of fuel kernels, including thorium and minor actinide fuels, but the base assumption in GIF is that it will use uranium.

6.2.1. Uranium-plutonium fuel cycle

The technology base for TRISO fuel manufacture and fuel performance was established from the 1960s to the mid-1980s in the various HTR prototypes that operated then, some of which used uranium fuel kernels. It is likely that further development work will be needed to meet the requirements of the VHTR programme, so the technology cannot be considered fully mature.

VHTR is potentially well suited for plutonium disposition, because the high burnup of the fuel kernels allows a larger proportion of the initially loaded plutonium to be destroyed. Moreover, the isotopic quality of VHTR plutonium fuel at discharge is very low. Deep Burn VHTR fuel is specifically designed to maximise the burnup and minimise the isotopic quality of plutonium fuel to such an extent that it is rendered almost unusable for weapons purposes.

6.2.2. Thorium fuel cycle

Some of the HTR prototypes operated from the 1960s to the mid-1980s used thorium fuel kernels and therefore the Technology Readiness Level of thorium can be regarded as comparable to that of uranium fuel.

There are several reasons why VHTR is especially well suited to thorium fuels:

1. The thorium fuel cycle is capable of achieving higher conversion ratios in a thermal reactor than the U-Pu fuel cycle and since VHTR has a thermal neutron spectrum, it is well suited to thorium. The result is a system with higher fertile conversion and therefore less dependence on external fissile materials.
2. It is important that the fuel discharge burnup should be as high as possible to ensure that the U-233 is fissioned efficiently in a once-through fuel cycle. VHTR fuels will have the required high burnup capability, by using higher enrichments.
3. Thorium oxide is thought to be potentially a more stable matrix than UO_2 for geological disposal of spent fuel and this would be an advantage for a once-through fuel cycle.

These features were the reason why many of the early HTR projects (DRAGON, Peach Bottom, Jülich HTR and Fort St Vrain) all used thorium fuel kernels. These would have been used to breed U-233 that would subsequently undergo fission in the core. The conversion of Th-232 to U-233 requires a source of neutrons, which would have been provided by the U-235 or Pu-239 fissions. This demands that the fresh fuel kernels should contain a mix of U-Th or Pu-Th.

A potential limitation of thorium fuels in HTRs is the need to have relatively high initial enrichments of U-235 in the uranium driver fuel needed to drive the initial conversion of Th-232 to U-233. Some fuel designs developed to date use U-235 enriched to 20.0 weight percent, which is the upper limit for LEU, leaving no margin for design flexibility.

The Technology Readiness Level of uranium and thorium fuel cycles for VHTR fuels can be regarded as being comparable.

6.3. SCWR

The Super Critical Water Reactor (SCWR) is one of the least well developed of the Generation IV concepts, for which one of the main research requirements is to develop fuel and primary circuit materials that can withstand the extremely challenging core conditions of the super-critical water moderator/coolant. The SCWR design is at a very early conceptual stage and no specific consideration appears to have been made towards thorium fuels. However, there is no doubt that thorium fuels could be used in SCWR, but the precise role of SCWR is insufficiently developed to comment further.

6.4. MSR

The Molten Salt Reactor (MSR) being developed by Generation IV is, like earlier molten salt cores, specifically designed for the thorium fuel cycle. For this reason, the discussion here is limited to the thorium fuel cycle.

There are several aspects of the MSR design that are particularly suited to the thorium fuel cycle:

1. MSR has a thermal neutron spectrum in which the thorium cycle can achieve a higher conversion ratio than the uranium/plutonium cycle.
2. MSR avoids some of the loss of conversion efficiency that occurs due to neutron capture events in Pa-233. The conversion of Th-232 to U-233 proceeds via two intermediates Th-233 and Pa-233 which undergo beta decay. Pa-233 has a relatively long half-life of 27 days and a significant fraction of it is removed by

neutron captures which reduces U-233 production. The nuclear fuel in MSR is unique in that it circulates through the entire primary circuit and spends only a fraction of its time in the active core. This reduces the time-averaged neutron flux that the Pa-233 sees and significantly reduces the proportion of Pa-233 atoms that are lost to neutron captures.

3. MSR continually reprocesses the nuclear fuel as it re-circulates in the primary circuit, removing fission products as they are generated. The U-233 produced by fertile captures on Th-232 is recycled simply by being left in the primary circuit. MSR therefore completely avoids the difficulties in conventional reactors with fabricating U-233 fuels (which have high gamma activities from U-232 daughters).
4. Since the nuclear fuel is a molten salt, there are no fuel mechanical performance issues to consider. There is no distinction in this respect between different fuels and therefore no barrier to the adoption of thorium as there is in conventional reactors.

The Technology Readiness Level of the MSR fuel cycle should be regarded as low, because it has never been demonstrated as a whole and experience to date has been limited to small scale laboratory experiments. To date, there has been a very low level of commitment to MSR within GIF. There is interest in MSR in the European Union Sustainable Nuclear Energy Technology Platform (SNETP) and Reference [17] provides an up to date assessment of the R&D challenges that MSR poses.

6.5. ADSR

The Accelerator Driven Sub-critical Reactor (ADSR) [7] is a sub-critical neutron multiplying system in which the external neutron source needed to support steady state operation is provided by a high power proton beam impinging on a spallation source. Most sub-critical concepts, including ADSR, ADTR and the Energy Amplifier are designed around the thorium fuel cycle. For this reason, the discussion here is limited to the thorium fuel cycle.

ADSR shows a great degree of flexibility in several respects: its mission can be energy generation, waste management or a combination of both; the neutron spectrum can be fast, thermal or a hybrid and it can handle fuels with a wide range of isotopic compositions and finally the fuel cycle can be open or closed.

There have been suggestions that U-233 could be generated in an ADS loaded only with thorium, using the spallation neutrons from the accelerator to breed U-233. This would in principle allow the thorium fuel cycle to reach equilibrium without the use of U-235 or plutonium to provide the initial neutrons. However, this is an impractical proposition, because the time taken for the U-233 to build up to the point where useful fission energy produced is excessively long. This arises from the combination of a relatively low capture cross-section for Th-232 combined with the relatively low neutron flux from the spallation source operating in what is initially a non-multiplying medium.

Amongst the advantages cited for ADSR, along with other sub-critical systems, is that it is safer than conventional reactors on the grounds that it is sub-critical and therefore less vulnerable to reactivity insertion accidents and that it is more internationalisable because of its high proliferation resistance. ADSR aims to be more economic than LWRs once uranium ore prices begin to rise in response to demand exceeding supply.

All these advantages are undemonstrated and they can all be disputed. For example, the main threat to the safety of conventional reactors is from decay heat production, not reactivity insertion events and ADSR will be no different in this respect.

ADSR is currently at a low technology readiness level and a commercially ready design will require considerable R&D investment over an extended period of time in many technology areas. There is overlap with LFR R&D, since many elements of the core design are shared with LFR.

6.6. HPM

The Hyperion Power Module (HPM) is an autonomous small power reactor with a capacity of 25 MWe. It is a liquid metal reactor that uses uranium nitride fuel and lead-bismuth coolant. It is designed for passive cooling, passive safety and has a long core life. Hyperion make no mention of a thorium fuelled option. As a very small power unit, it has only very limited relevance to the UK.

HPM is not specifically intended for plutonium recycle, but it is likely to be flexible enough to accommodate it if required, with additional investment needed to fabricate plutonium fuel.

6.7. Small modular water reactors

Small modular water reactor designs are based on existing Light Water Reactor (LWR) technology, but scaled down to benefit from increased applicability of passive safety. Small modular LWRs might use conventional UO_2 fuels or UO_2-PuO_2 MOX fuels or thorium-based fuels.

6.7.1. Uranium-plutonium fuel cycle

The U-Pu fuel cycle in small modular LWRs is identical to that currently deployed in current LWRs and can therefore be considered to be fully technologically mature.

Small modular LWRs could be well suited for plutonium disposition in the UK, with their capacities potentially matching better the requirements for siting at Sellafield, co-located with a MOX fabrication facility. Some small modular LWR cores are designed with long life cores for which MOX fuel is well suited.

6.7.2. Thorium fuel cycle

As with conventional LWRs, thorium fuels are a potential option that would have the major benefit of reducing dependence on uranium ore. There are two approaches that might be used, one based on a once-through cycle and one based on recycle of the U-233:

The Lightbridge fuel assembly discussed in Section 2 [5] is one example of a once-through thorium fuel cycle option that could be used without modification in small modular LWRs. The Lightbridge fuel design should be regarded as having a low Technology Readiness Level at present, because it has innovative design features that have only been demonstrated at small scale. Other options can be envisaged in which current LWR assembly mechanical designs are used without modification, with either a heterogeneous or homogeneous distribution of thorium in the fuel rods. This latter option

could be regarded as having a higher Technology Readiness Level, though there may still remain issues related to thorium fuel manufacture and fuel performance that remain to be demonstrated. The benefits of a once-through thorium fuel cycle are a modest reduction in uranium ore requirements and a modest reduction in radiotoxicity.

Full recycle of U-233 is another potential option for small modular LWRs. This option is already being considered by AREVA [9] for large LWRs and would give more substantial reductions in uranium ore requirements and radiotoxicity that once-through approaches. However, as noted earlier, recycle of U-233 requires the THOREX process and remote fuel fabrication methods, both of which have not been developed, which puts this option at a low Technology Readiness Level.

7. Plutonium recycle strategies

By the time the UK's MAGNOX and THORP reprocessing plants cease operation, it is projected that the UK will have more than 100 tonnes of separated plutonium in store. One option for the eventual disposition of this plutonium would be to recycle it in future reactors. This section explains some of the issues that need to be considered if the UK was to adopt such a strategy and it is hoped that this will guide any future assessment of advanced reactor systems for the UK. In general, there are three plutonium recycle strategies available:

1. Multiple recycle via MOX fuel in thermal reactors such as LWRs; the intention being to maximise depletion of the fissile material, with the minor actinides treated as waste.
2. Single recycle through existing reactors (which includes the disposition of existing UK plutonium), such as LWRs, followed by reprocessing and burning in a fast reactor; this strategy incinerates some of the minor actinides too.
3. Optimised number of recycles in existing reactors such as LWRs, and as such reduce the number of fast burner reactors required; this strategy takes advantage of existing facilities.

Option 1 is very much a theoretical option as there are technical considerations that limit the number of recycles to a maximum of two. Therefore, that leaves Options 2 and 3 for consideration for any potential full recycle in a closed, sustainable sense. This is in line with other options being considered internationally, including in France and in Generation IV for example. Nevertheless, each of these recycling options carries its own associated risk (technical, economic etc) and limitations. Furthermore, the future options can also be seen to fit into three temporal phases in the management of the plutonium:

1. Gradual introduction of the recycling of MOX fuel up to an industrial scale in existing reactors e.g. LWRs. During this time, the stockpile of Pu tends to increase. This is the world-wide position as of today.
2. Ongoing but irregular expansion of MOX recycling in which more countries consider MOX fuel, develop the technology and additional reactors are licensed for MOX. This is up to around 2030.
3. Introduction of advanced reactor systems (thermal and fast) alongside technologies specifically designed for MOX fuel.

The reactor technology and the fuel type chosen by the UK will specifically determine the assumed plutonium loadings in terms of number of tonnes of fuel that can be taken to be

loaded each year e.g. current plants are likely to be able to accommodate approximately 30% MOX core fraction versus 50% or even 100% for future LWRs. The new reactor technologies discussed earlier will have a range of plutonium loadings and proportion of plutonium destroyed, but other than LWRs, none have yet been proven to be able to accommodate plutonium or indeed thorium fuels.

Regardless of the chosen option for the management of the plutonium on these timescales (single or multiple recycle, use of fast or only thermal reactors etc), according to the OECD-Nuclear Energy Agency (NEA) , there are five high-level issues that need to be considered in assessing the technical options:

1. Plutonium management strategies should be consistent in maintaining high standards of safety.
2. Plutonium management strategies should preferably maintain flexibility in the fuel cycle, such that future options are not foreclosed.
3. Plutonium management strategies should be consistent with maintaining satisfactory standards of security and safeguards against proliferation.
4. The quantities and forms of radioactive wastes arising from each technical option are very important considerations.
5. A clear requirement is that the overall fuel cycle should remain economically competitive, though the economics should not be assessed in isolation, but rather as part of a Life Cycle Analysis (LCA) that accounts for all externalities.

Any future UK proposed fuel cycle and Plutonium management options should at least be cognisant and make reference to these key issues and strategies. In particular recognising that the economics are not the only consideration in evaluating plutonium management options e.g. environmental impact, radiotoxicity, proliferation resistance etc. As such, it is important to consider the limitations of any plutonium or thorium scenario (as outlined below) as well as the need to complete a Life Cycle Analysis (LCA) of the issues, other than simply economics.

Furthermore, before the UK can truly determine the most appropriate technology for either long term sustainability and moreover, plutonium management it is vital that the UK understands whether the mission goal is *reduction* or *destruction* of the plutonium stocks as quickly as possible, or *construction* of an integrated fuel cycle and use of the plutonium as a potential valuable resource in the future, e.g., in fast reactors. Associated with this is the determination of the timescales that the UK wishes to address the chosen driver from these three goals. The timescales will in turn dictate which technology is at the UK's disposal at that time e.g. if the UK wishes to reduce its separated plutonium stockpile in the next 20 years, the only possible options available will be MOX (or a related derivative) in light water reactors. A decision by the UK is therefore required on this before the most appropriate technical choice for a reactor re-use option can be made.

The discussion has focused on plutonium recycle as conventional PuO_2/ThO_2 MOX, following current UK Government policy. However, PuO_2/ThO MOX could be considered an alternative option for the future. The thorium MOX option would be beneficial in that there would be almost no in-growth of fresh plutonium and minor actinides. The thorium MOX option, however, would require additional development time to demonstrate satisfactory fuel performance and, for those options involving recycle, commercialising THOREX reprocessing.

8. Discussion

Thorium fuel cycle R&D has a long history dating back to the very beginning of the nuclear industry. Though there are potential advantages, with the exception of India, it has failed to become established in commercial reactors for the reasons that have been explained in this report. Even in India, utilisation of thorium fuels still remains at relatively small scale. In recent years the thorium fuel cycle has been promoted by many research groups and technical companies such as Lightbridge and Thor Energy.

While the thorium fuel cycle has some benefits compared with the uranium-plutonium fuel cycle, these have yet to be demonstrated or substantiated, particularly in a commercial or regulatory environment. The U-Pu fuel cycle has the advantage of being fully mature and of having used in three generations of reactor designs. In contrast, the thorium fuel cycle is disadvantaged because all the supporting infrastructure would have to be established from scratch.

This is very relevant to the UK, especially at the present time in view of plans to start a new build programme in the UK based on LWRs. It could be argued that the main priority for the UK is to ensure the momentum that the new build programme currently has built up is maintained, in order that the new build plants will be available in good time to meet the projected shortfalls of low carbon electrical capacity. This only permits existing reactor designs with the uranium-plutonium fuel cycle. Innovative thorium fuelled reactors will not be a viable alternative for at least 20 to 30 years and definitely cannot meet the new build timescales. A limited role for thorium fuels in new build LWRs might be possible at a later date, with perhaps a partial transition to thorium-U233 fuels later in their lifetimes and any major shift towards the thorium fuel cycle would only be realistic in a follow-on programme of reactor construction.

Thorium fuelled reactors have already been advocated as being inherently safer than LWRs [18], but the basis of these claims is not sufficiently substantiated and will not be for many years, if at all. Suggesting that the UK should consider thorium reactors as a safer alternative to LWRs is not a viable option at this time as the UK energy shortfall and demand is on much shorter timescales than thorium fuelled reactors could respond to. Furthermore, since the energy market is driven by private investment and with none of the utility companies investing or currently developing either thorium fuels or thorium fuelled reactor concepts, it is clear that there is little appetite or belief in the safety or performance claims.

The only area where thorium fuel might be of interest to the UK is possibility of using thorium-plutonium fuels in new build LWRs as a means of dispositioning the UK's plutonium stocks. As discussed, this might offer technical advantages over uranium-plutonium (MOX) fuels, though this remains to be demonstrated. The value of using thorium fuel for plutonium disposition would need to be assessed against the high level issues identified in Section 6 concerning the importance of maintaining high standards of safety, security and protection against proliferation, as well as meeting other essential strategic goals related to maintaining flexibility in the fuel cycle, optimising waste arisings and economic competitiveness. It is important that the UK should be very clear as to what the overall objectives should be and the timescales for achieving these objectives.

Overall, the conclusion is reached that the thorium fuel cycle at best has only limited relevance to the UK as an alternative plutonium disposition strategy and as a possible strategic option in the very long term for any follow-up reactor construction programme

after LWR new build. Suggestions that thorium fuelled reactors may be able to achieve superior safety performance to new build LWRs will take many years to substantiate and are not likely to be helpful to meeting the UK's strategic priorities. Nevertheless, it is important to recognise that world-wide there remains interest in thorium fuel cycles and this is not likely to diminish in the near future. It is may therefore be judicious for the UK to maintain a low level of engagement in thorium fuel cycle R&D by involvement in international collaborative research activities. This will enable the UK to keep up with developments, comment from a position of knowledge and to some extent influence the direction of research. Participation will also ensure that the UK is more ready to respond if changes in technology or market forces bring the thorium fuel cycle more to the fore.

DISTRIBUTION

Name	Location
DECC	Department of Energy and Climate Change, 3 Whitehall Place, London, SW1A 2HD, UK
NNL Corporate Memory	Strategic Assessments, Risley

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