The Thorium Fuel Cycle

An independent assessment by the UK National Nuclear Laboratory

August 2010

Position Paper

National Nuclear Laboratory

The Thorium Fuel Cycle

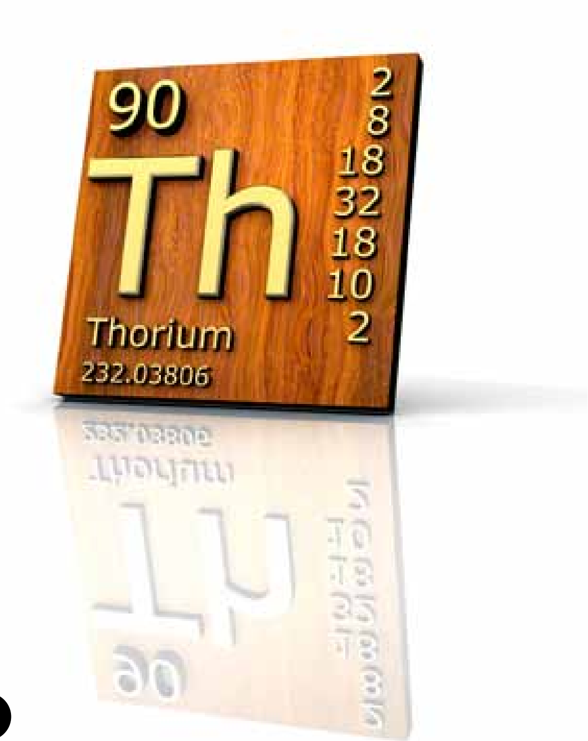
An independent assessment by the UK National Nuclear Laboratory

The thorium fuel cycle presents an alternative option to the usual uranium-plutonium fuel cycle that has long been advocated and researched, but which has yet to be adopted on a commercial scale. In recent years, interest in the thorium fuel cycle has grown notably, with several commercial and research organisations looking to undertake assessments of thorium fuels for a variety of reasons.

This paper provides an independent review of the thorium fuel cycle by the UK National Nuclear Laboratory (NNL), highlighting the strengths and weaknesses of thorium, not just in the UK context, but globally.

NNL has many years experience of the nuclear fuel cycle and associated science and technology, including fuels, reactors and reprocessing. We are therefore in an ideal position to be able to independently assess and advise decision makers on both current and future fuel cycles such as thorium. The statements in this note are backed up by extensive experience of nuclear R&D and the nuclear industry worldwide, including thorium assessments and programmes in which NNL has been involved.

Paul Howarth
Managing Director
National Nuclear Laboratory



National Nuclear Laboratory

Introduction

The past 50 years of the nuclear industry has been dominated heavily by the uranium fuel cycle, virtually without exception other than for several test programmes. The uranium fuel cycle now represents a commercially demonstrated fuel route, deployed worldwide with all of the commercial power stations using uranium as its source of fuel. Therefore, any future alternative to this technically mature, proven, commercial fuel cycle would need to demonstrate clear notable benefits over the existing options in order for it to be adopted e.g., benefits associated with the technology, economics, safety and security, environmental performance, sustainability etc. This paper considers and evaluates the potential benefits that the thorium fuel cycle may offer as an alternative to the existing uranium fuel cycle by way of an independent, informed review based on NNL's many years of experience of current and future fuel cycles and associated technology.

Naturally occurring thorium consists entirely of Th-232, which is a fertile nuclide i.e. it does not undergo fission itself, but on capturing a neutron it is transformed to fissile U-233. In the same way for natural uranium, U-238 is a fertile nuclide which transforms to fissile Pu-239. However, because thorium does not have a naturally occurring fissile isotope (unlike natural uranium which contains U-235) the thorium fuel cycle needs another fissile material, either U-235 or Pu-239 to get started. In its simplest form of implementation, with a once-through fuel cycle, the thorium fuel cycle can be used to augment the useful energy output produced per tonne of uranium ore. However, with reprocessing of thorium fuel and recycle of the U-233, it is theoretically possible to achieve a breeding cycle in a thermal reactor. With the uranium/plutonium fuel cycle a thermal reactor breeder cycle is difficult to achieve.

The thorium fuel cycle is claimed to be advantageous in several respects, one of which is that it generates very low quantities of transuranic materials, including plutonium.This decreases the long term radiotoxicity burden after fission products have decayed. In particular, only very small quantities of plutonium are produced, which is often cited as a benefit in terms of increased proliferation resistance.

As stated above, several organisations and countries have expressed renewed interest in the thorium fuel cycle in recent times. For example, India is more strongly committed to developing the thorium fuel cycle than any other country with a long-established thorium R&D programme which includes plans to utilise thorium in future fast reactors following the breeding of plutonium in its Pressurised Heavy Water Reactors (PHWRs). India is presently further ahead than any other country in the development of the thorium fuel cycle, but even so the R&D has only progressed on a relatively small scale, with only about 1 tonne of thorium fuel having been irradiated in PHWRs to date. India's strong commitment to the thorium fuel cycle can be understood given the large indigenous reserves of thorium, the very ambitious nuclear expansion planned and the acute shortages of access to uranium ore and nuclear fuel that have in some instances adversely affected operations of its current plants. India was until recently prevented from accessing international nuclear technology, including uranium ore and fuel supply and was forced to develop its own technology. In most other countries, it has been difficult for thorium to become established in competition with uranium and especially so given the large amount of R&D that would be needed to provide the underpinning knowledge and experience that would put thorium on a par with uranium. However, because India's circumstances have been so different, thorium development has not been held back in the same way and thorium fits very well with India's goals of wanting to utilise their indigenous reserves and develop indigenous flagship technology.

Similarly, ThorEnergy in Norway has undertaken an extensive research effort and are promoting thorium fuels for use both in current reactors and future reactors, not for Norwegian reactors, but as a worldwide fuel resource. As with India, Norway's interest in thorium is because of the indigenous reserves and it is therefore clear why the level of investment and recent interest has been shown from ThorEnergy. They advocate using thorium fuels in Light Water Reactors (LWRs) and PHWRs as a pragmatic first step, even though these systems can only provide partial benefits compared with full U-233 recycle, such as that

proposed by India. ThorEnergy advocates using plutonium as the initial "seed" material (the fissile material used to generate the neutrons to enable breeding to take place in the fertile thorium) for LWRs, prior to U-233 becoming available at a later stage. The plutonium would be incorporated in Th-Pu MOX fuel. They argue that Th-Pu MOX is fundamentally very similar to U-Pu MOX fuel and therefore that the R&D requirements would be much less onerous than would be necessary for a more radical design change. Nevertheless, ThorEnergy recognise that the large R&D investment will still be required and the timescale to commercial readiness will be long.

There have been many other international thorium fuel studies, including several demonstration programmes in the Shippingport prototype Pressurised Water Reactor (PWR) and High Temperature Reactors (HTRs). However, these were not subsequently progressed to full commercial deployment. The main reason has been that thorium is competing with the uranium/plutonium fuel cycle which is already very mature. To progress to commercial deployment would demand major investments from fuel vendors and utilities. Such investment has yet to be justified by market conditions and there is no immediate prospect of change in the next ten years. Beyond that, however, the conditions may favour thorium if uranium ore prices increase and/or uranium reserves become more scarce.

In the event of thorium fuel cycles being adopted commercially in existing LWRs, the technology can be considered to be well understood, but not fully demonstrated. The historic experience in the Shippingport PWR cannot now be considered adequate to cover modern operating regimes and discharge burnups. Demonstration of thorium/U-233 fuels in commercial LWRs will therefore demand small scale testing in research reactors, followed by large scale tests in commercial reactors. Based on NNL's knowledge and experience of introducing new fuels into modern reactors, it is estimated that this is likely to take 10 to 15 years even with a concerted R&D effort and investment before the thorium fuel cycle could be established in current reactors and much longer for any future reactor systems. Therefore it is not envisaged that thorium fuel in LWRs will be established in the next decade, but could be feasible in the following ten years if the market conditions are conducive.

Assessment

As a result of many years of previous experience of the thorium fuel cycle and associated science and technology including fuels, reactors and reprocessing, NNL has acquired a good working knowledge of the field, both from a research as well as an industrial delivery perspective. Based on that experience and knowledge of the nuclear industry, the following positions statements have been developed in order to guide future involvement and activities within the UK, as well as overseas and to assist the decision makers in industry and governments.

The following statements summarise that NNL position on the thorium fuel cycle.

Reactor type

In the foreseeable future (up to the next 20 years), the only realistic prospect for deploying thorium fuels on a commercial basis would be in existing and new build LWRs (e.g., AP1000 and EPR) or PHWRs (e.g., Candu reactors). Thorium fuel

"It is estimated that it is likely to take 10 to 15 years of concerted R&D effort and investment before the Thorium fuel cycle could be established in current reactors and much longer for any future reactor systems"

concepts which require first the construction of new reactor types (such as High Temperature Reactor (HTR), fast reactors and Accelerator Driven Systems (ADS)) are regarded as viable only in the much longer term (of the order of 40+ years minimum) as this is the length of time before these reactors are expected to be designed, built and reach commercial maturity. While there will be differences in detail between the performance of thorium fuels in LWRs and PHWRs due to the different irradiation times and environment, any benefits are considered roughly comparable. Although thorium fuels in LWRs have to date progressed to a later stage of development than in PHWRs, the LWR experience is now very dated and is less relevant to current and foreseeable future requirements. The lead times for LWR and PHWR implementation are therefore considered comparable. NNL's view is that significant R&D investment will still be required and the timescale to commercial readiness even in existing reactors will be long.

Resource availability

Based on recent OECD-Nuclear Energy Agency (NEA) and International Atomic Energy Agency (IAEA) estimates, there are some 100 years remaining of known uranium reserves at current consumption rates (and assuming the current modest level of recycle of uranium and plutonium). These reserves will provide the raw material for the fleets of LWRs (where the U-235 component is enriched) and PHWRs (using natural uranium) and as importantly, the uranium ore will also provide the fertile U-238 to allow the breeding of plutonium in fast reactors and ensure a closed sustainable plutonium fuel cycle in the longer term, if so required. The need to fully close the uranium-plutonium fuel cycle will be driven primarily by either a shortage in uranium ore (due to a substantial expansion in nuclear energy), or if the uranium prices increase substantially from their current market price. As such, in those countries that either have or can readily access uranium ore and fuels, there is no incentive to move to a thorium cycle either now (as the uranium ore exists at an economic price) or in the future as the closed uranium-plutonium fuel cycle will provide a sustainable option. In those countries such as India where uranium resource was limited, the use of the alternative thorium fuel cycle is understandable.

While the thorium fuel cycle is theoretically capable of being self-sustainable, this is only achievable with full recycle. This would involve the implementation of THOREX reprocessing and a remote fabrication plant for the U-233 fuel due to the high gamma dose from the feed material, both of which present very large technological, commercial and risk barriers, each with a significant cost component.

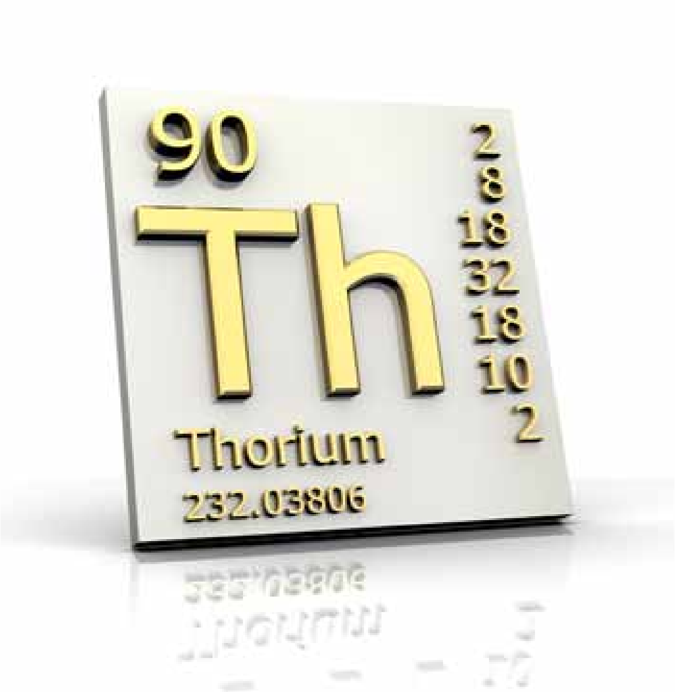
The use of thorium in place of U-238 as a fertile material in a once-through fuel cycle is much less difficult technically, but only yields a very small benefit over the conventional U-Pu fuel cycle. For example it is estimated that the approach of using seed-blanket assemblies (the blanket being the surrounding fertile thorium material) in a once-through thorium cycle in PWRs, will only reduce uranium ore demand by 10%. This is considered too marginal to justify investment in the thorium cycle on its own.

For countries with large indigenous reserves of thorium (such as India), there is a strong incentive to develop the thorium fuel cycle in order to be strategically independent. For a country such as the UK, with neither thorium or uranium reserves, the incentive for thorium is much reduced, as in both cases it would remain dependent on overseas suppliers.

Proliferation resistance

Contrary to that which many proponents of thorium claim, U-233 should be regarded as posing a definite proliferation risk. For a thorium fuel cycle which falls short of a breeding cycle, uranium fuel would always be needed to supplement the fissile material and there will always be significant (though reduced) plutonium production.

NNL believes that U-233 should be regarded as posing a comparable level of proliferation risk to High Enriched Uranium (HEU) and comparable with the U-Pu fuel cycle at best; this view is consistent with the IAEA, who under the Convention on the Physical Protection of Nuclear Materials, categorise U-233 on the same basis as plutonium. 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 in a centrifuge cascade in the same way that U-235 is separated from U-238 in the standard uranium fuel cycle.



The argument that the high U-232 content would be self-protecting are considered to be over-stated. NNL's view is that thorium systems are no more proliferation resistant than U-Pu systems though they may offer limited benefits in some circumstances.

Economics

NNL believes that while economic benefits are theoretically achievable by using thorium fuels, in current market conditions the position is marginal and insufficient to justify major investment.

There is only a very weak technical basis for claims that thorium concepts using seed-blanket PWR cores will be economically advantageous. The only exception is in a postulated 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.

Radiotoxicity

Claims that thorium fuels give a reduction in radiotoxicity are justified. However, caution is required because many such claims cite studies based on a self-sustaining thorium cycle in equilibrium. More realistic studies which take account of the effect of U-235 or Pu-239 seed fuels required to breed the U-233 suggest the benefits are more modest.

NNL's view is therefore that thorium fuel cycles are likely to offer modest reductions in radiotoxicity. It is considered that the realistic benefits are likely to be too marginal to justify investment in the thorium fuel cycle. However, the substantial reduction in radiotoxicity promised by a full thorium recycle does provide a significant incentive in the long term.

Utility view

NNL believes that LWR and PHWR utilities would be unlikely to invest in thorium fuels to the levels required under current market conditions. The potential savings that thorium fuels offer and other claimed benefits are insufficiently demonstrated and too marginal to justify the technical risk that the utility would be exposed to.

Technology Readiness Level

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 established 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.

Generic R&D work is therefore a valuable starting point. R&D work at sub-industrial scale and commercial scale is required for all the systems, but will require substantial lead times to acquire and will necessarily be tied to major investments in developing specific systems.

Accelerator Driven Systems

This reactor concept (an example of which is the Accelerator Driven Thorium Reactor (ADTR)) involves the use of a proton beam to generate neutrons by striking a spallation target. These generated neutrons (about 20 per proton) are then used to irradiate the surrounding fuel. Although ADS is a very active research area in Europe for the transmutation of minor actinides, the justification arguments usually made in support of them are considered weak and technically unsupported. The practical difficulties are often underplayed in the research studies and they are considered a major barrier to commercial implementation.

The view is taken that ADS provides a solution to problems that are not acknowledged by utilities and are therefore irrelevant to power reactor operators in the decades ahead. Even those more mature technologies such as fast reactors and their associated fuel cycles are not considered as relevant for investment by the utilities.

To a large extent, R&D on ADS has been seen as a device for researchers to continue in the nuclear field even though some countries (e.g., Germany) specifically do not allow government funding of fission research. This calls for a cautious approach to assessing the claims made in favour of ADS in terms of the R&D requirements and commercial deployment. This caution is also reflected in the international programmes such as Generation IV or the Global Nuclear Energy Partnership where ADS technology was not even considered. As reflected in the Technology Readiness assessment, it is not only the reactor but also the associated fuel cycle that is immature, a fact often overlooked by advocates of ADS.

UK Plutonium disposition

Th-Pu MOX fuel for existing LWRs or PHWRs, as advocated by ThorEnergy, is of potential interest to the UK as a proposed option for disposition of plutonium.

Th-Pu MOX would present a higher level of technical risk than conventional U-Pu MOX which is now well demonstrated, but the timescales for any UK plutonium disposition programme might allow the necessary R&D to be carried out if the thorium option was to show sufficient benefit (e.g., in the level of plutonium destruction and resulting reduction in heat load etc) and there was the will to invest in the development programmes that would be required.

In the UK context, Th-Pu MOX would be used as a matrix for plutonium disposal that might be advantageous compared with conventional U-Pu MOX, if the long term stability of thorium as a disposal matrix can be confirmed. It may not, however, be the best strategic fit depending on the timescales to re-use the UK's plutonium and/or the potential need of the plutonium for a future fast reactor programme.

Fuel performance

The thermal and mechanical properties of ThO_2 are very similar to those of UO_2 and PuO_2. Generally, the thermal and physical properties of ThO_2 are favourable compared with UO_2 and ThO_2 is completely compatible as a substitute for UO_2.

Though the thermal and mechanical properties of ThO_2 are well known, there has only been limited experience of its use in LWRs. It will be necessary to demonstrate good irradiation performance at the commercial scale and this will likely take a prolonged period of time to achieve.

Starting from fabrication of a commercially-relevant mass of ThO_2 fuel, which might take 1 or 2 years, the subsequent irradiation to full burnup would likely take 4 to 5 years. Subsequent post-irradiation examination might take another 1 to 2 years, so the overall timescale will be of the order of ~10 years. In practice, a gradual ramp-up to commercial scale loading might be necessary, leading to a more realistic timescale of about 15 years for commercial demonstration. This is comparable to the timescale that was required to commercialise MOX in LWRs.

Each prospective fuel vendor will need to be able to demonstrate that its knowledge of ThO_2 fuel behaviour is sufficient to allow accurate modelling with its fuel behaviour code. To an extent, each fuel vendor will need to be able to cite irradiation experience with fuel fabricated with its own process and so the data generated will be proprietary.

Summary

NNL believes that the thorium fuel cycle does not currently have a role to play in the UK context, other than its potential application for plutonium management in the medium to long term and depending on the indigenous thorium reserves, is likely to have only a limited role internationally for some years ahead. The technology is innovative, although technically immature and currently not of interest to the utilities, representing significant financial investment and risk without notable benefits. In many cases, the benefits of the thorium fuel cycle have been over-stated.

Nevertheless, the thorium fuel cycle does offer exciting prospects for R&D needs, with investment and development required across the entire fuel cycle including fuel properties, performance and fabrication, reactor safety and performance and reprocessing technology. In the event that future reactors are chosen as the way forward for thorium utilisation (such as a HTR, fast reactor or ADS), then additional investment will also be required to design, license and construct that new technology. Any investor needs to be cognisant of the immaturity and therefore risk associated with such an undertaking as well as the level of investment needed at each and every process/stage in this entirely new fuel cycle.

"The thorium fuel cycle does not currently have a role to play in the UK context, other than its potential application for plutonium management in the longer term"

2010

Winner

RESEARCH & DEVELOPMENT

Sector Award

Winner 2004-2008, 2010

Highly Commended 2009

www.nnl.co.uk/positionpapers

National Nuclear Laboratory
5th Floor
Chadwick House
Warrington Road
Birchwood Park
Warrington
WA3 6AE

Authors
Kevin Hesketh, Senior Fellow, Nuclear Systems Analysis
Andrew Worrall, Technical Authority, Reactors and Fuels

For further information, please email:
customers@nnl.co.uk

LLOYD'S REGISTER QUALITY ASSURANCE · ISO9001

LLOYD'S REGISTER QUALITY ASSURANCE · ISO 14001

LLOYD'S REGISTER QUALITY ASSURANCE · ISO/IEC27001