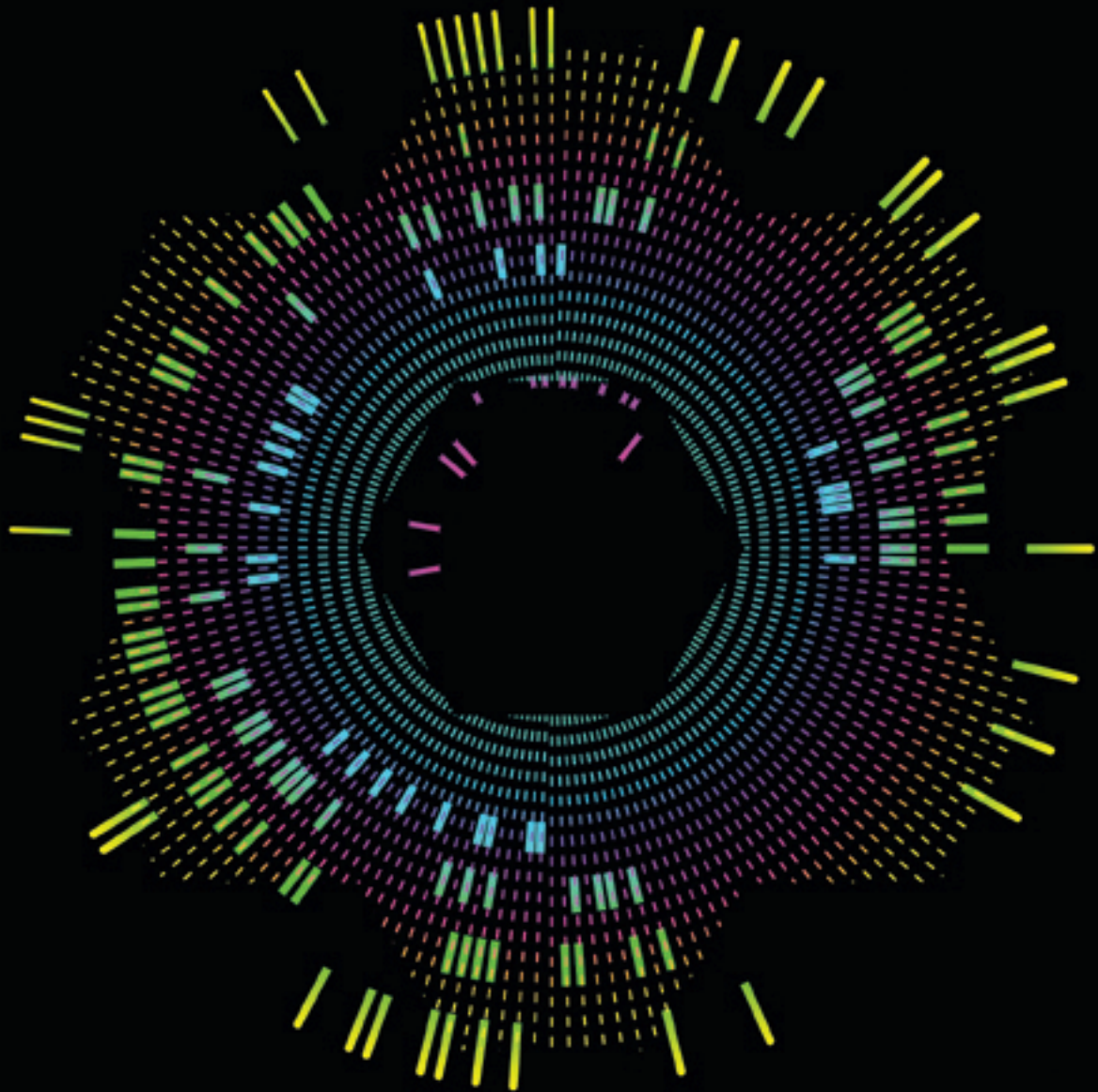
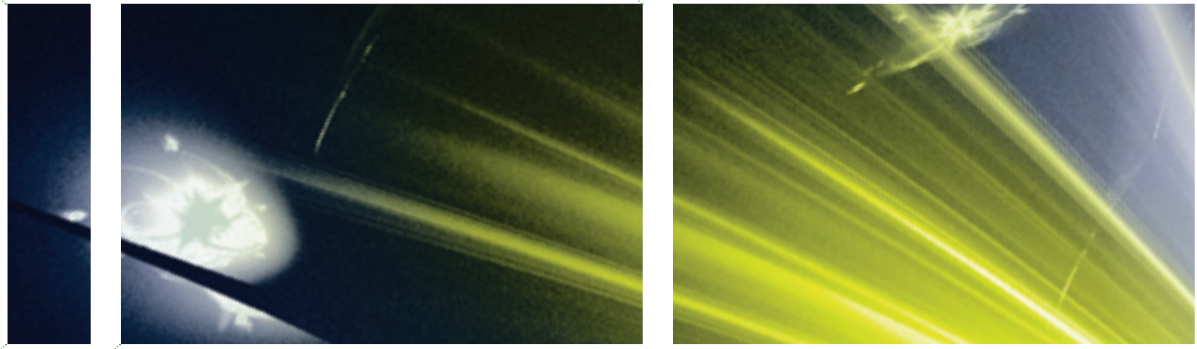


# TOWARDS AN ALTERNATIVE NUCLEAR FUTURE

Capturing thorium-fuelled ADSR  
energy technology for Britain

A report prepared by:  
the thorium energy amplifier association  
2009-2010





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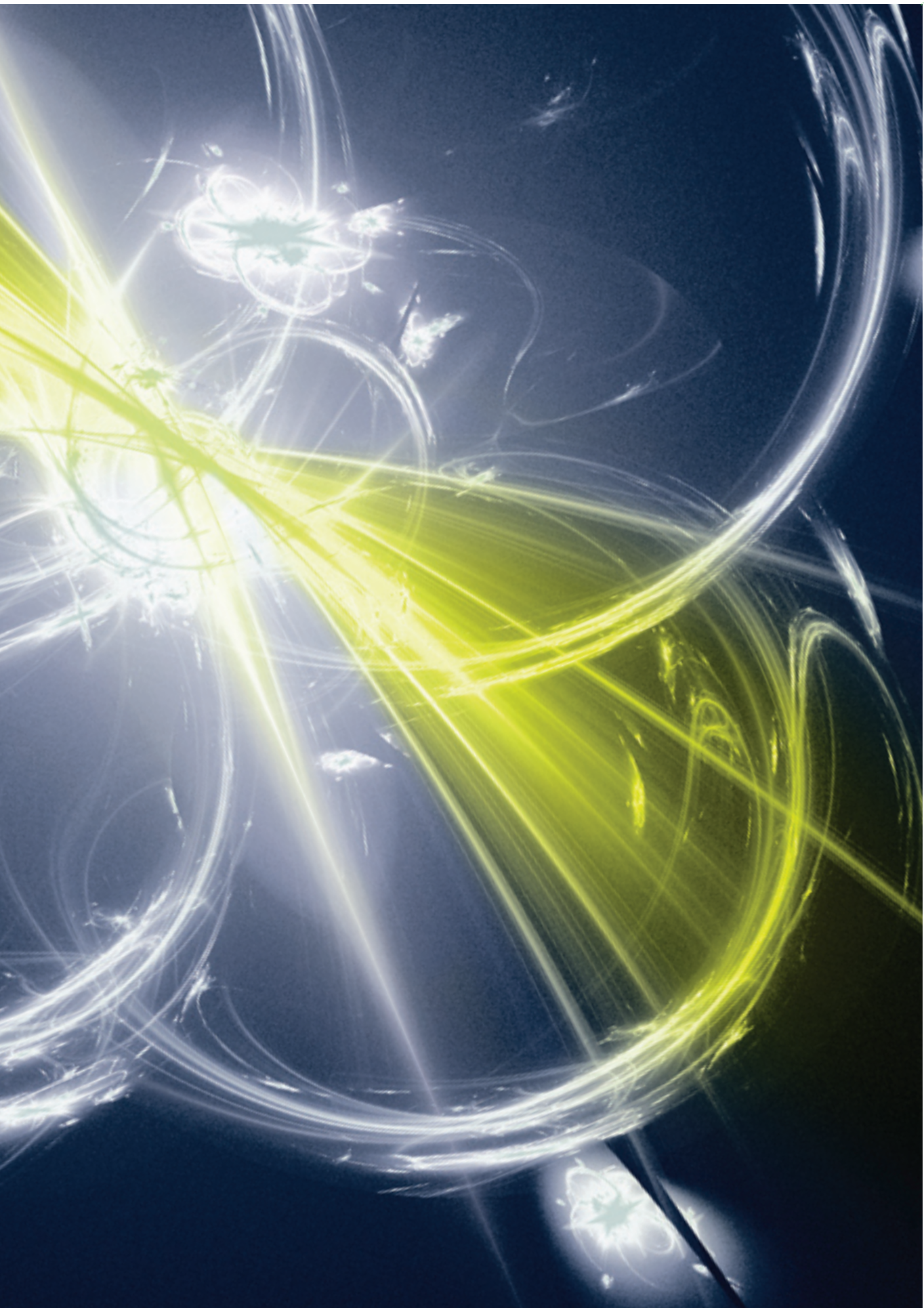
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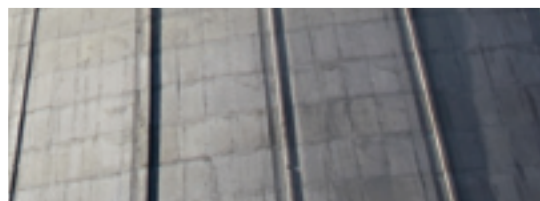
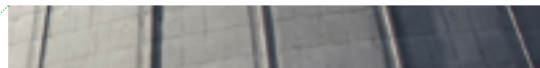
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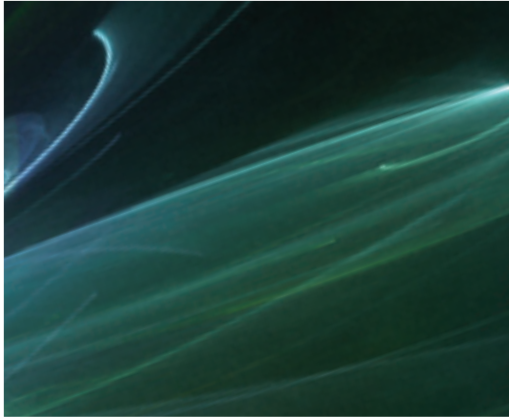


## Statement from IAEA

“IAEA warmly welcomes the proposed accelerator driver development programme embodied in the ThorEA project as a positive contribution to the international effort to secure the eventual global deployment of sustainable thorium-fuelled ADSR power generation systems”

**Alexander Stanculescu**  
Nuclear Power Technology Development Section  
International Atomic Energy Agency (IAEA)  
Vienna

September 2009



## Executive Summary

Recent developments in advanced accelerator technology have provided the UK with a unique opportunity to create, build and sustain a multibillion pound industry based upon alternative, safe, inexhaustible, low waste and proliferation-resistant nuclear power generation. This innovative nuclear industry and its associated technology will:

- allow the UK to compete aggressively in existing nuclear markets;
- open up entirely new international nuclear markets that at present are closed to all current and planned uranium- and plutonium-based nuclear technologies;
- directly impact other high-technology industries, including medicine;
- enable the UK, and other nations, to meet carbon reduction targets without increasing nuclear waste streams.

This vision of a reinvigorated and environmentally acceptable UK nuclear industry can be delivered by adopting and refining the concept of the Accelerator Driven Subcritical Reactor (ADSR), fuelled entirely by thorium, an abundant and robust fuel which produces low levels of waste and virtually no plutonium, and driven by advanced, UK-designed and manufactured particle accelerators.

Immediate investment will enable the UK to benefit from the momentum of its existing accelerator programme to secure a clear world lead in the new nuclear technology. It is entirely realistic to expect that:

- The key ADSR technologies will be developed and functioning demonstrators delivered within five years.
- A privately funded 600MW prototype power station capable of providing electricity to the grid will be constructed and commissioned by 2025.

These objectives can be best achieved through a public private partnership. An initial public investment of £300m over five years will support an intensive research and development programme and, in parallel, develop the industrial capability to deliver practical systems on a commercial basis in advance of the deployment of competitor GEN IV nuclear technology.

It is envisaged that a private company will be created to manage the research and development programme, establish industrial collaborations, secure procurement and capture emerging intellectual property. The research and development programme will lever £1.5-2bn from industry over a further ten years for the design and construction of the world's first thorium-fuelled ADSR power station.

The return on this investment is likely to be a viable and robust UK thorium-fuelled ADSR nuclear industry serving a global need for low carbon, sustainable but safer nuclear electricity, with a projected revenue of at least £10-20 billion per annum beyond 2025.



## Introduction

The capacity to consume energy in both industrialised and non-industrialised nations is growing, and will continue to grow, at an unprecedented rate. At the same time it is also widely accepted that CO<sub>2</sub> resulting from conventional means of energy production is leading directly to global warming and climate change. It is increasingly apparent that any strategy which attempts to avert further man-made damage to the climate whilst also satisfying global demands for energy must include low carbon nuclear power at its core. Moreover, the nuclear option affords what is perhaps the only feasible base line source of electricity that could produce a sufficient surplus for electrical power to challenge oil's supremacy as a fuel for transport.

A recent independent and multidisciplinary Massachusetts Institute of Technology Report entitled *The Future of Nuclear Power* (2003,2009) concluded that *the nuclear option should be retained precisely because it is an important carbon-free source of power*. However, the report also noted that the prospects for nuclear energy as an option are limited by four unresolved problems: *high relative costs; perceived adverse safety, environmental, and health effects; potential security risks stemming from proliferation; and unresolved challenges in long-term management of nuclear wastes*.

It is against this background that we offer the opportunity of building a low carbon nuclear future based in large part upon an innovative nuclear technology that has an inherently higher safety margin than conventional systems; that is low waste; that does not include plutonium as part of its fuel cycle, that is intrinsically proliferation resistant; that, because it utilises thorium as its fuel, is both sustainable and cost effective; and that can effectively burn legacy waste from conventional systems.

This nuclear technology is the **Accelerator Driven Subcritical Reactor**, or **ADSR**.

Although first promoted almost two decades ago, recent advances in particle accelerator technology, notably in the UK, suggest that ADSRs are a realistic, achievable and cost effective near-term technological alternative to existing and planned nuclear fission reactors for power generation. Indeed, with a suitably intensive and coherent research and development programme ADSR power systems could be deployed globally as early as 2025, i.e. ahead of the suggested deployment of GEN IV nuclear systems.

In May 2009 the UK Science Minister, Lord Drayson, visited Daresbury Laboratory and was informed of progress in the research and development of innovative particle accelerators

for thorium-fuelled Accelerator Driven Subcritical Reactor (ADSR) systems for energy generation. Subsequently a request was made to the Science and Technology Facilities Council (STFC) for a report defining the financial investment necessary for the UK to develop, refine and deliver the enabling technologies for the construction of a thorium-fuelled ADSR, whilst additionally appraising the commercial opportunities likely to arise for the UK from such investment.

This report, prepared by the Thorium Energy Amplifier Association (ThorEA) with support from STFC, is the response to this request. The report was delivered to the Minister in October 2009.

The report outlines a research and development programme that will build on existing and acknowledged UK scientific and technological strengths and facilities to deliver all of the underpinning technology necessary to complete the world's first operational 600MW<sub>e</sub> thorium-fuelled ADSR power station in the UK by 2025.

It is argued that immediate investment in such an R&D programme will result in the UK's global leadership in thorium-fuelled ADSR technology, and an invigorated indigenous nuclear industry capable of satisfying a major multi-billion pound export market which, because of the intrinsic proliferation resistance of the technology, could reach nations that uranium- and plutonium-based nuclear power cannot.

Additionally, the R&D programme has the potential generate significant revenue through captured IP not just in the nuclear field but also fields such as medicine which (for example in cancer therapy) increasingly draws upon advanced particle accelerator technology.

**It is concluded that a public investment of £300m over 5 years would deliver the necessary thorium-fuelled ADSR technology and lever sufficient commercial backing (£1.5-2bn) and broad based industrial interest to construct the first ADSR power generation system and develop a new, high-technology nuclear export industry for the UK.**





This report is structured as follows:

Chapter 1 introduces the concept of the thorium-fuelled ADSR, and discusses the advantages to the UK in pursuing the associated technology in the context of exploiting the global nuclear market.

Chapter 2 focuses upon the significance of ADSR technology in a UK context, particularly with respect to carbon reduction and achieving the Government's 'Road to 2010' goals.

Chapter 3 is the core of the report in which the R&D programme necessary to deliver the technologies that will facilitate the widespread deployment of thorium-fuelled ADSRs for electricity generation in the UK and overseas is proposed. A novel approach to the R&D programme ensures that various technological options are incorporated from the start, with the whole programme being robustly appraised at specific key points to ensure a smooth route to a timely and simultaneous delivery of all the final technological goals. A suggested framework for managing and financing such a programme based upon a public-private partnership is also presented. In this context, the interest expressed by potential industrial partners and collaborators is highlighted.

Although the proposed programme is both realistic and achievable, it is also ambitious and not without technical challenges. It is in meeting these challenges that there is enormous potential for the UK to capitalise upon associated innovation and technological leadership, and exploit a plethora of IP and value capture mechanisms. These opportunities are discussed in Chapter 4.

In Chapter 5 it is demonstrated that the costs of the proposed thorium-fuelled ADSR power generation should prove competitive with existing nuclear and non-nuclear technologies and finally in Chapter 6, the report considers the optimal route to securing a lasting scientific and technical legacy based upon this attractive and innovative approach to nuclear energy provision.

The report is accompanied by extensive Appendices, in which detailed background information, technical issues and strategic and economic analyses are presented, and by a set of Frequently Asked Questions extracted from the comments and criticisms of independent expert referees.

# Chapter 1: Thorium-fuelled ADSRs and their potential UK and global impact

## 1.1 The ADSR concept and the advantages of thorium fuel

The term accelerator-driven subcritical reactor system, or ADSR, refers to a device formed by coupling a substantially subcritical nuclear reactor core with a high energy proton accelerator, as illustrated in Figure 1. The core of the reactor is designed such that it is unable to sustain fission processes (i.e. a chain reaction) in the absence of an externally induced neutron flux. The necessary supply of neutrons to the ADSR fuel is provided by high energy protons from the accelerator impacting a heavy metal target embedded

within the core, and “spalling”, or chipping, neutrons from the nuclei of the atoms within the target. This spallation process is particularly efficient, with approximately 25 neutrons being generated by each proton. The resulting spallation neutrons then go on to induce fission in the fuel of the core. A particular and evident advantage of the ADSR is that if the proton accelerator is switched off the nuclear processes also instantly shuts down.

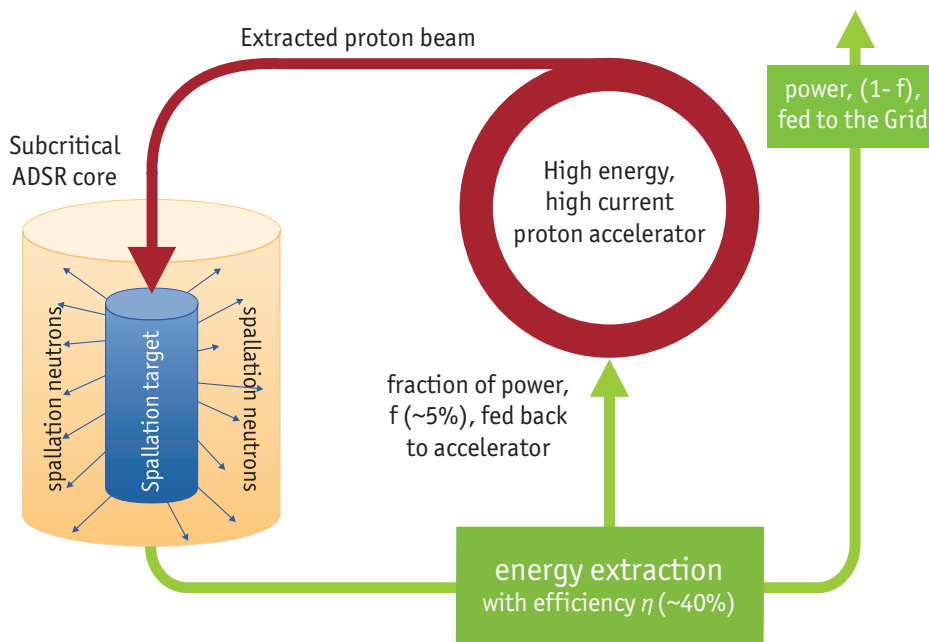


Figure 1. Schematic view of an Accelerator-Driven Sub-critical Reactor

As an example (see Appendix I for details), a 10 MW proton accelerator producing a proton current of 10mA with proton energies of 1GeV, will generate  $1550\text{MW}_{\text{th}}$  in a reactor core with a criticality factor as low as  $k=0.985$ . Assuming typical efficiency factors for thermal to electrical energy conversion, such a system might be expected to produce  $600\text{MW}_e$  of electrical power, comparable to a conventional power station. The 10MW accelerator will require approximately  $20\text{MW}_e$  to sustain its operation. This power can, of course, be taken from the ADSR itself, with the remaining  $580\text{MW}$  of electrical power being fed to the grid.

The enormous multiplication of power afforded by the coupled accelerator-core system has given the ADSR its synonymous label of Energy Amplifier (or EA).

One consequence of the subcritical operation of the ADSR and its effective decoupling of the neutron source (producing spallation neutrons) from the fissile fuel (generating fission

neutrons), is that the range of potential nuclear fuels broadens significantly: minor actinides (MAs), high levels of plutonium and long-lived fission products (LLFPs), which would degrade the neutronic characteristics of conventional critical nuclear cores to unacceptable levels, can be incorporated with standard nuclear fuel and burnt within an ADSR.

Significantly, and perhaps even more importantly, this characteristic enables ADSR technology to exploit fully the enormous and virtually untapped potential of thorium as nuclear fuel (Appendix II).

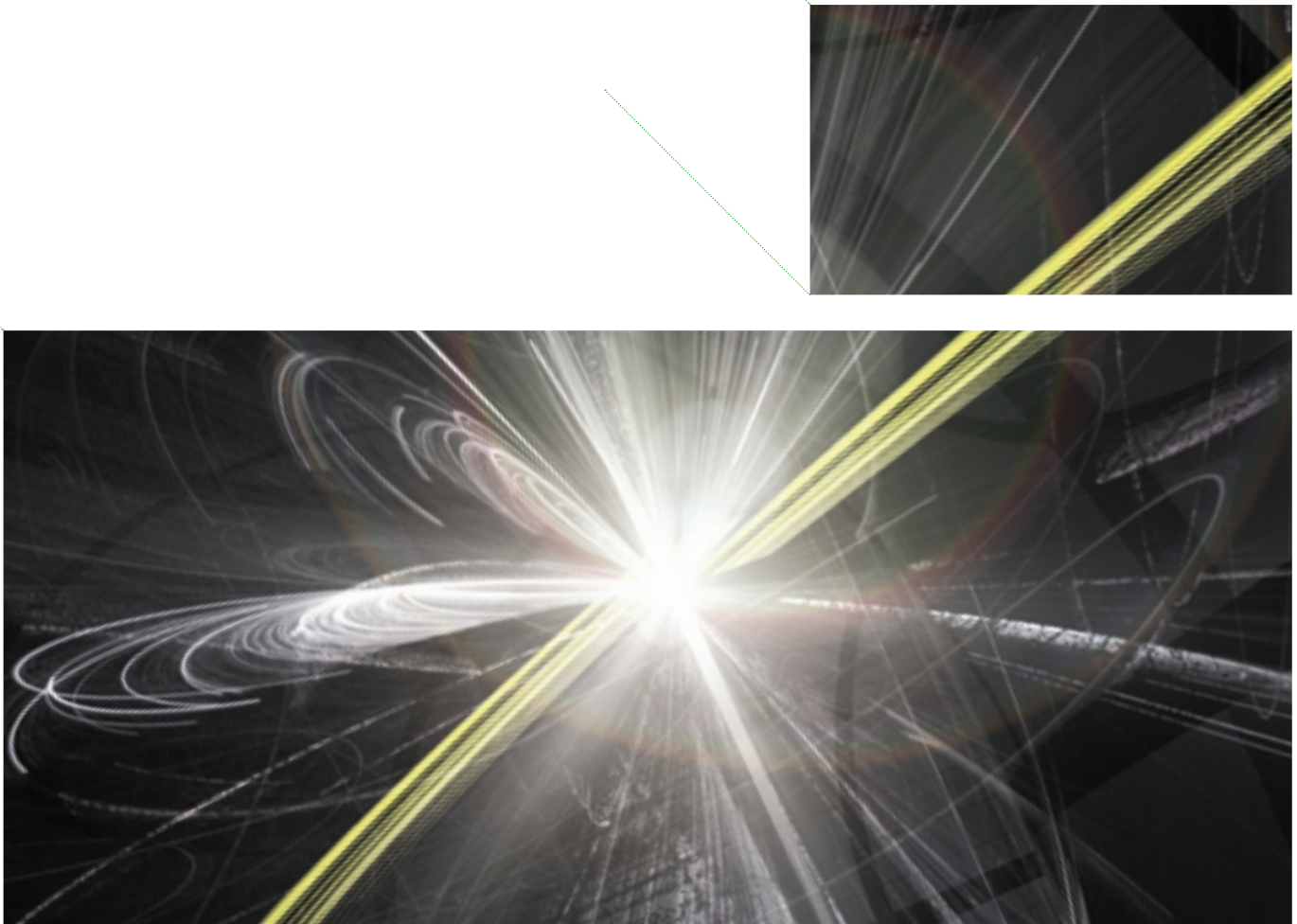
Natural thorium (100% Th-232 isotopic composition) is not fissile and thus cannot, in its natural state, be used as nuclear fuel. However, thorium is fertile and can be converted into a source of fissile material (U-233) through neutron capture. This fertile-fissile conversion, and subsequent fission of U-233, can be effected by the spallation neutrons and induced fission neutrons within the core of an ADSR.

Thorium presents numerous advantages over uranium in terms of availability, proliferation resistance, nuclear waste management and reactor performance. Some specific advantages may be summarised as follows:

- Abundance of thorium in nature (similar abundance to lead and three times more abundant than uranium) and simple extraction process from sedimentary deposits;
- Thorium fuel cycles are intrinsically proliferation-resistant due to radiological barriers, easy denaturation and negligible plutonium production;
- Better nuclear characteristics (better fuel breeding ratio and fission rate), radiation stability of thorium fuels (very chemically stable oxides), and longer fuel cycles than uranium fuels;
- Possibility to eliminate legacy plutonium and other actinides in an efficient and inherently safe manner, given the low equilibrium concentrations of these elements in the thorium fuel cycle. Legacy waste can be incorporated in thorium fuel and burnt, leading to substantial reductions in radiotoxicity;
- Higher energy density than uranium: In principle total annual global energy needs could be provided by 5000 tonnes of thorium.

Thorium has been of interest to the nuclear industry since the 1950's. More recently, in the light of predictions of finite and limited uranium resources, this interest has revived considerably, particularly in thorium-rich nations such as India (Appendix II). Thorium is viewed in many sectors as a reliable alternative to uranium and as a clean, carbon emission-free source of energy, as exemplified by (Rubbia & al., 1995), (IAEA, Thorium fuel cycle – Potential benefits and challenges, IAEA-TECDOC-1450, 2005) and (The Thorium Committee, 2008); and as an efficient method of eliminating radiotoxic waste from conventional nuclear reactors as proposed in (Rubbia(bis) & al, 1995) and (NEA, 1999).

A detailed description of the technical advantages of thorium as nuclear fuel for ADSRs may be found in Appendix II which includes detailed references to global availability of thorium, extraction methods, advantages in terms of neutron economies and fission rates and details of the fuel management strategies. An economic appraisal of the advantages of the thorium fuel cycle and ADSR deployment can be found in Chapter 5.



## 1.2 The advantages of thorium-fuelled ADSR technology in an expanding global nuclear landscape

The energy sector has been a key element underpinning economic growth since the industrial revolution. Today it is becoming a bottleneck for further development as the global need for low carbon options becomes more acute and the demand for secure energy increases in emerging economies. For many industrialised countries the nuclear industry has helped to alleviate this bottleneck, playing a significant role in energy provision and claiming 15% of global electricity

generation with annual sales of the order of £200bn. Subject to issues of sustainability and proliferation resistance, a wider global deployment of nuclear technology is inevitable if the growing demand for electrical energy is to be met.

Yet, despite its size and significance, the nuclear power industry is subject to numerous external parameters working both for and against its further expansion. Some of the major factors shaping the industry, are summarised by Figure 2:

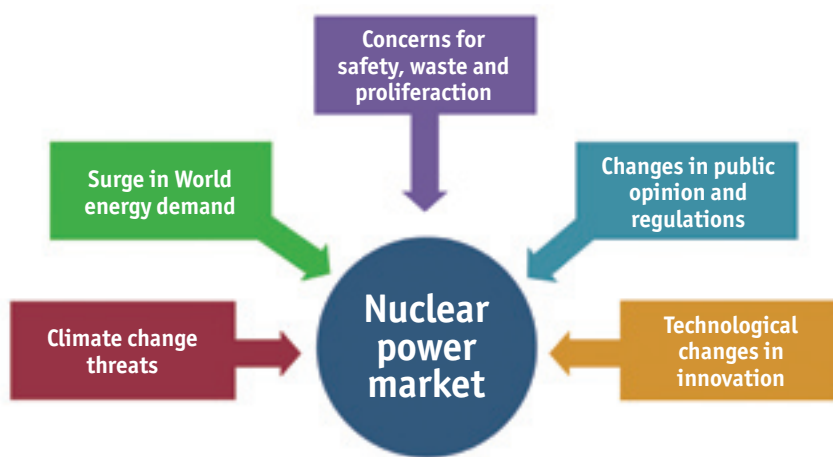


Figure 2. Nuclear power market analysis, including major factors influencing its evolution.

- **Climate change threats:** for the last 20 years awareness on the rising of global temperatures and its correlation with greenhouse gas emission have had an enormous impact on the public perception of, and future prospects for, nuclear power;
- **Surge in world energy demand:** the world's rapid economic growth (an unprecedented 4% average during the last decade) has fuelled an increase in global energy demand which is barely followed by supply, triggering a surge in energy prices and volatility;
- **Concerns for safety, nuclear waste and proliferation:** the 1986 Chernobyl accident did much to set back the clock of nuclear development and expansion; long lived nuclear waste and its effects upon the environment are a growing concern; due to its origins, nuclear power has traditionally been linked to military applications, and although recently commercial nuclear power is succeeding in decoupling itself from such connections in public perception, concerns about proliferation in the context of rogue states and terrorism remain.
- **Technological changes and innovation:** technological developments both in the nuclear industry, such as Generation IV, and renewable energies, are shaping the future of nuclear power; additionally potential niches are opening (e.g. water desalination, hydrogen production) with very few base-load alternatives in sight;

- **Changes in public opinion and regulations:** the previous factors have strongly influenced the public perception of nuclear power; countries such as Germany are re-assessing their phase-out decision, whereas others, such as China and India, will undeniably rely on nuclear power to sustain their rapid growth.

The combination of these factors suggests that the global energy market is ready for the deployment of a new type of nuclear system which is inherently safe, fuelled from a sustainable, low waste source, and which can be exported globally without igniting fears of potential proliferation (Appendix III).

For the UK the development of such a nuclear system, exemplified by thorium-fuelled ADSR technology, would guarantee technological leadership in the global energy sector, with commercial returns far larger than the initial investment.

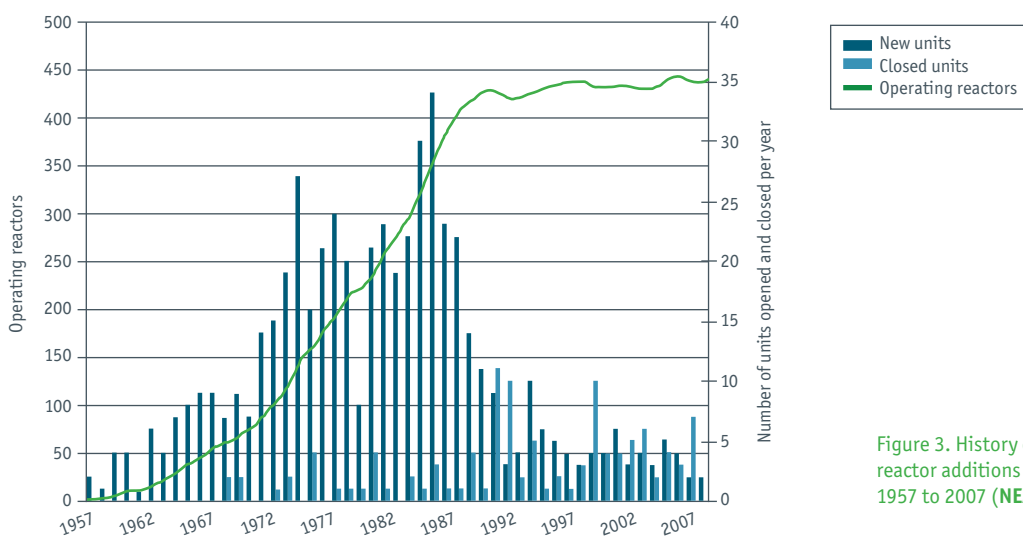
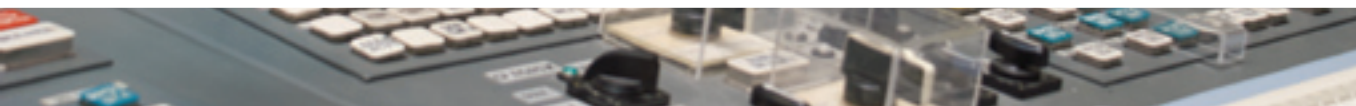


Figure 3. History of worldwide reactor additions and closures, 1957 to 2007 (NEA, 2008)

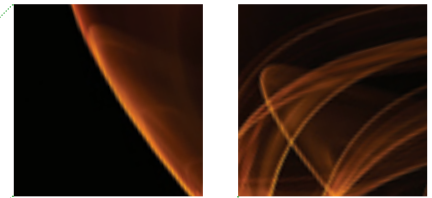
### 1.3 A timely technological transition to thorium-fuelled ADSRs

Figure 3 shows the date at which nuclear reactor units were connected to the grid, together with the integrated number of reactors in operation worldwide, since 1957. The curve representing operating reactors in Figure 3 shows a traditional technology adoption curve, with an upper flat area indicating product saturation.

Clear conclusions can be drawn from these data:

- Most nuclear operating power plants have already passed the midpoint of their 40-yr lifetime;
- There will be a large number of reactors being disconnected from the grid in 10 to 15 years;
- Current nuclear technology has reached maturity, suggesting a market readiness to adopt a new technology.

A technology transition between current conventional light water reactors (LWR) and thorium-fuelled ADSRs could be envisaged by 2025 if initiated now through an experimental programme aimed directly at developing the technology to deliver a commercial unit. Such a transition would represent an evolutionary step towards more sustainable and environmentally acceptable nuclear energy on a time scale that precedes that envisaged for deployment of Generation IV technology. Moreover the transition may become even more favourable because of factors such as the likely increase in uranium prices and the potential multiple applications of thorium-fuelled ADSRs and their constituent technologies (e.g. in hydrogen production or the medical applications of high-energy accelerators etc).



## Chapter 1: Thorium-fuelled ADSRs and their potential UK and global impact *continued*

### 1.4 Why thorium-fuelled ADSRs are an attractive proposition

There is every possibility that industrialised countries will seek to decarbonise almost completely their electricity systems by 2040 (or even earlier) through improved energy efficiency, nuclear energy and growth in renewables. Indeed, such a scenario is already official UK government policy and the UK government hopes that other countries will follow a similar path. Within this scenario there is a clear need to provide more sustainable nuclear energy technology, and ensure affordable nuclear fuel in the long term. Broadly speaking, four sustainable nuclear technology options appear to be available.

- Option 1: PUREX reprocessing of LWR spent fuel for multiple MOX recycling,
- Option 2: Moving to critical fast reactors,
- Option 3: Commercialisation of nuclear fusion energy,
- Option 4: Moving to the thorium fuel cycle.

Option 1 requires a plutonium economy, but might be favoured by moves away from PUREX techniques and towards more proliferation resistant and internationalisable approaches.

Option 2, while attractive, remains subject to significant safety concerns owing to very high core power densities, short time constants and relatively slow reactor control response especially in systems with small Doppler feedbacks (such as are being promoted by the EU).

Option 3, although a long standing goal, remains subject to significant technical uncertainties.

Included within Option 4 are both conventional critical thorium-fuelled thermal nuclear reactors and ADSRs. The ADSR has the benefit that it does not need plutonium or enriched uranium (U-235) to initiate nuclear power generation in a critical thermal reactor. So, for example, in an export market there would be no need to supply fresh Pu-Th fuels to developing countries that are seeking to develop sustainable nuclear energy.

Amongst the sustainable nuclear fission energy options the thorium ADSR has a distinct benefit that favours its internationalisation and widespread deployment. The thorium ADSR can operate with a once-through fuel cycle. Fresh fuel can be prepared in a benign and completely proliferation insensitive forms. No separated or separable plutonium or U-235 is required at any stage. Spent fuel can

be protected by a particularly strong form of the so called 'spent fuel standard'. Thorium-fuelled ADSR spent fuel can be sent for direct disposal without jeopardising sustainability. ADSR technologies are near-term and sustainable. Compared to other long-term future options thorium-fuelled ADSR systems have intrinsically good safety characteristics.

Today raw uranium fuel forms a minor part (roughly 5%) of the lifetime levelised cost of nuclear power. In the event of a major global shift to nuclear power, and much sunk investment in long-lived nuclear power plants, there is a significant risk that global uranium demand in the 2030s could begin to exceed supply. Future prospects for uranium prices could then appear most unattractive when compared to thorium for ADSR systems.

One might imagine a situation where a uranium fuelled PWR has a cost base in which perhaps as much as 50% of levelised costs of electricity are attributable to greatly inflated fuel prices. Crucially it is worth noting that, EU Sustainable Nuclear Energy Technology Platform notwithstanding, only one EU member state is enthusiastic for nuclear fuel reprocessing. If nuclear power undergoes a significant expansion without widespread acceptance of reprocessing then uranium prices will rise very steeply indeed (perhaps by a factor of 10 or more). It is to avoid such economic risks that a move towards thorium-fuelled ADSR should be favoured.

In summary thorium-fuelled ADSRs will be:

- Technologically more accessible than fusion,
- Safer than critical fast reactors,
- More internationalisable and proliferation resistant than reprocessing,
- Cheaper than fuelling LWRs with uranium as demand for fuel begins to exceed supply.

**Thorium-fuelled ADSR technology is sustainable and yet it is consistent with once through fuel cycles. It is wholly consistent with all UK policy goals relating to climate change, nuclear power, reprocessing, and proliferation resistance, and as such deserves careful consideration as a significant component of an emerging nuclear strategy.**



### 1.5 The potential global market for thorium-fuelled ADSR systems

The analysis of the current nuclear market size and its future prospects offers a valuable insight on the market potential for thorium-fuelled ADSRs (see also the five forces analysis in Appendix IV). There are currently 436 nuclear reactors in operation worldwide, generating a total of 372 GWe, i.e. 15% of the electricity consumed globally. In its World Energy Outlook 2006 (IEA, 2007), the IEA forecasts an average 2.6% yearly increase in global electricity demand (4). In the IEA

reference scenario, nuclear electricity production increases an average of 0.7% per year until 2030. The IEA alternative scenario foresees a growth of 2.3% in nuclear energy production. These scenarios are presented in the Figure 4 below, which also includes a potential expansion scenario in which global nuclear electricity share increases from 15% to 22% (current share in OECD countries) from 2007 to 2030, with an average growth of 4% per year.

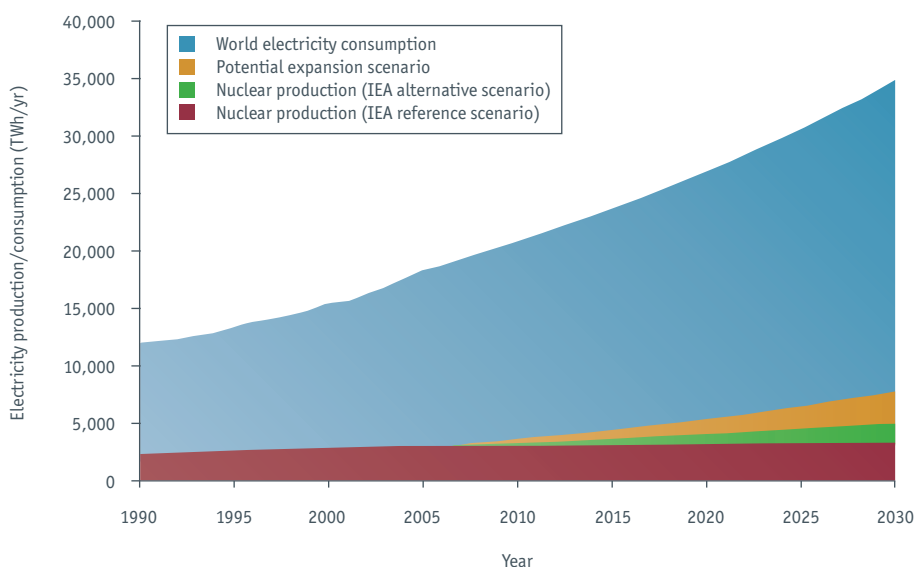
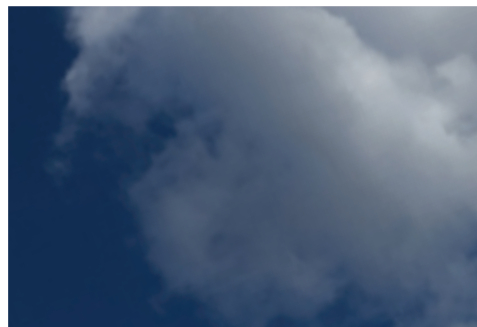


Figure 4. Evolution of the global electricity demand and share of nuclear production for the three different IEA scenarios.

These three growth scenarios would entail an increase in the nuclear energy production of 500, 2,000 and 4,800 TWh, respectively. Such an increase implies the commissioning of 65, 260 and 610 GWe, at 85% availability. The following table,

which summarises these scenarios, clearly indicates the enormous potential market for ADSR systems (~£100b), even if only 30% of the demand is met by ADSRs.

	Yearly growth	Increase in electricity production from nuclear by 2030 (TWh)	New installed nuclear capacity by 2030 (GWe), 85% availability	ADSRs (600 MWe) covering such demand
Reference IEA	0.7%	500	68	114
Alternative IEA	2.3%	2,000	275	458
Potential expansion	4.0%	4,800	645	1,076



## Chapter 1: Thorium-fuelled ADSRs and their potential UK and global impact *continued*

It should be noted that export sales would form a significant component of any commercial proposition. However, in the Potential Expansion scenario, export to non-OECD nations will predominate, yet the export of conventional nuclear power is expected to be limited to those countries with minimal proliferation risks, well established nuclear power infrastructure and tight security.

There is an additional requirement for the technology offered to developing countries to be of the appropriate scale; too small and the contribution to the electricity demand is too little to justify the investment of effort and money; too large and the stability of the existing grid is threatened.

Thorium-fuelled ADSRs, when configured appropriately, overcome these issues. The proliferation resistance and safe sub-critical operation of these systems significantly increases the number of countries to which export is possible. The 600MWe ADSR used as an illustration above is an entirely realistic proposition for export to and deployment in both fully industrialised nations, and those with weaker infrastructure. Moreover, a detailed cost analysis indicates that the lifetime costs of a thorium fuelled ADSR reactor for power generation would be comparable to those of conventional power systems (Appendix VIII).

**During the 1980s a new nuclear power station came on line every 17 days. Over the next three decades demand will be considerably higher. It is precisely this demand into which a thorium-fuelled ADSR industry would tap.**

### 1.6 The consequences of the UK seizing global leadership in thorium-fuelled ADSR technology

Should the UK choose now to develop global leadership in thorium-fuelled ADSR technology, a not unimaginable scenario for the year 2040 could be as follows:

*A rejuvenated nuclear industry is generating 40% of UK electricity. This contribution, combined with renewables and consumption reduction efforts have, much to the surprise of many, enabled CO<sub>2</sub> reduction targets to be hit. This has given the UK considerable credibility at the international climate change negotiating table, where it is pressing for tougher targets.*

*While there are obvious environmental benefits of deeper cuts in CO<sub>2</sub>, Britain has a further incentive: as the world leader in the thorium-fuelled ADSR industry – the safest, most proliferation-resistant, waste-minimising nuclear power technology – further cuts equate to larger markets for IP, technology know-how, and services. From the successful development of reliable off-the-shelf 10MW accelerators and other related technologies in the period 2010-2020 the UK has been able to build a significant ADSR industry. The technical expertise, manufacturing, licensing of IP and support industries are contributing to GDP growth and generating £multi-bn export revenue p.a. for UK plc. Over 30,000 people are directly employed in the industry.*

*The growth in clean indigenous power generation has facilitated the shift to electric vehicles resulting in a dramatic improvement in urban air quality and traffic noise. Spin-offs from the development of various related technologies have enabled further exploitation of IP, both in the UK and overseas. Imports of oil and gas have fallen – the ‘repatriation of the power pound’ as the Daily Mail likes to refer to it.*

*The growth of the UK’s nuclear industry has also contributed to the re-vitalisation of regional economies. The NW has benefited from the research and development efforts of the previous thirty years. The Sellafield site has consolidated its position as a global centre of excellence for re-processing.*

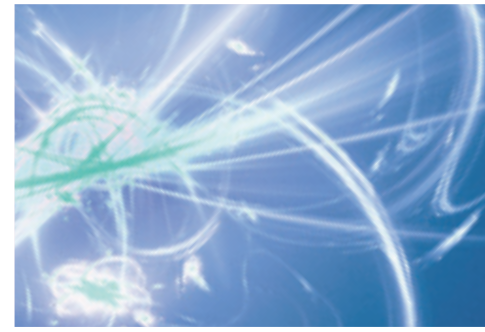
*British industry and consumers are protected from the worst fluctuations in oil and gas prices, and are insulated to some degree from the ever-increasing price of carbon. A further bonus is that UK business benefits from lower energy prices making it more competitive in the global marketplace.*

*Thorium-fuelled ADSRs have become for many ‘the acceptable face of nuclear’.*

**The question is not whether the UK can afford to invest in thorium-fuelled ADSR technology, but whether it can afford not to.**







## Chapter 2: Thorium-fuelled ADSR technology in a UK context

### 2.1 ADSR technology and UK carbon emission commitments

The Government introduced legally-binding targets for CO<sub>2</sub> emissions reductions in the 2008 Climate Change Act. The long-term target is an 80% cut from 1990 levels; an intermediate target of 34% by 2020 has also been set (HM-Government, 2009), with the EU also setting a 2020 target for the UK to generate 15% of its energy for heat, electricity and transport from renewables. (European Commission, 2008). It is widely believed that CO<sub>2</sub> reduction targets will be very difficult to meet (Cambridge-Econometrics, 2009) without significant investment in new nuclear plants.

The combination of binding targets, limited alternatives and a political desire to show leadership (European Union, 2008) should mean that nuclear power generation features prominently in the energy plans of future UK Governments and EU administrations.

The carbon reduction potential of nuclear power is enormous. All power generation technologies face construction emissions, but once nuclear generators are operational the direct carbon emissions are effectively zero. As nuclear is 'base load' power it is an obvious replacement for carbon-intensive coal and gas which have fluctuated in price considerably in recent years.

Nuclear power also has the potential to de-carbonise heating and transport. To achieve this, low carbon power is required on a very large scale. Nuclear power is the only indigenous low-carbon power source available to the UK which has the potential to scale up sufficiently to meet the legally binding emissions reductions targets that have been set.

There are also wider opportunities for global carbon reduction. A key feature of the proposed thorium-fuelled power station design is its suitability for export. There is growing international interest in nuclear power with growth projected to be between 27% and 100% over current capacity by 2030 (IAEA, International Status and Prospects of Nuclear Power, 2009). Potential international customers might also envisage thorium-fuelled ADSR applications beyond just electricity generation, for example in seawater desalination, high temperature chemical processing and industrial or district heat.

### 2.2 Financial Value of Carbon Emission Reduction

If nuclear power is finally considered as the leading CO<sub>2</sub> emissions reduction technology (of which ADSR technology could be a significant component) there is a substantial source of revenues available from trading credits in carbon markets, such as the European Trading Scheme. A first estimate of these profits yields that by migrating from coal-fuelled plants to ADSRs yearly returns could reach £76 million per year per GW<sub>e</sub>, as presented in the Table below. Even if only a fraction of these benefits were granted, it would further enhance the economic appeal of ADSRs.

All three main UK political parties recognise the need to de-carbonise energy sources; only the Liberal Democrats oppose nuclear power. It is pertinent to ask whether thorium-fuelled ADSRs, with their low waste, sub-criticality and proliferation resistance could redress the balance in favour of a nuclear low carbon option amongst the traditional anti-nuclear lobby.

Price per tonne of CO <sub>2</sub>	£12	£/tonne CO <sub>2</sub> -equivalent
Yearly energy produced	7.45	TWh/yr/GW <sub>e</sub> @85%avail
Steam cycle efficiency	33%	
Energy from combustion	81.2	HexaJ/yr/GW <sub>e</sub> @85%avail
CO <sub>2</sub> emissions from coal	1030	kg CO <sub>2</sub> /MWh <sub>e</sub>
CO <sub>2</sub> emissions from nuclear	10	kg CO <sub>2</sub> /MWh <sub>e</sub>
Emission saved per reactor unit	7.6E+06	tonnes of CO <sub>2</sub> /yr/GW <sub>e</sub>
<b>Financial value of emissions reduced</b>	<b>£76,000,000</b>	<b>£/yr/GW<sub>e</sub></b>

### 2.3 Minimizing the economic cost of nuclear waste

There are certain economic factors that favour P&T strategies. The UK has 19 commercial nuclear reactors, with an installed capacity of approximately 12 GW<sub>e</sub>. In (NEA, 1993), this agency estimated the cost of spent fuel to be around 800 US\$ (1993

dollars) per kg, at perpetuity. Bringing this number to 2009 pounds Sterling and multiplying it by UK's yearly spent fuel production, the estimated national expenditure on spent fuel disposal (or secular storage) is of the order of £100 million.

<b>UK: Cost per kg of waste</b>	1,400	US\$ (2009) per kg of HM
<b>Spent fuel burn-up</b>	33	GWd/tonne of HM
<b>Yearly energy (at 85% availability)</b>	310	GWd/yr/reactor per GW <sub>e</sub>
<b>Spent fuel consumption</b>	9	tonnes of HM/yr per GW <sub>e</sub>
<b>Spent fuel cost</b>	£8,230,000	£/yr per GW <sub>e</sub>
<b>UK installed nuclear capacity</b>	11.85	GW <sub>e</sub> from 19 reactors
<b>UK's yearly waste fuel inventory</b>	111	tonnes of HM/yr
<b>UK yearly expenditure on spent fuel management</b>	<b>£97,500,000</b>	<b>£/yr for 11.85 GW<sub>e</sub></b>

With well-developed waste separation and fuel reprocessing facilities, the UK is in a clearly advantageous position to develop appropriate state-of-the art technology. Indeed, BNFL re-fabricates MOX fuel for countries such as Japan, which re-use plutonium from their spent fuel. Through partitioning and transmutation (P&T), Britain has the opportunity to develop a technology capable not only of severely reducing its spent fuel costs but also recycling foreign spent fuel as a safe and stable source of energy. This revenue stream could contribute a financial surplus to the £180 million per year per reactor returns from electricity sales from a fleet of thorium-fuelled ADSRs operating in the UK. Additionally, Britain could receive an equal amount of revenues (i.e. £100 million per year per GW<sub>e</sub> reactor) from eliminating some of the world's nuclear legacy, hence effectively addressing international proliferation risks as well as environmental hazards. Although contentious, this approach is both socially and economically attractive.

### 2.4 Redressing balance of under-investment in energy

The UK has under-invested in energy technology for many years. Figure 5 shows the decline in Government funding of energy R&D. During this period the emphasis has moved towards private sector investment – however, it is empirically clear that private companies are reluctant to invest in long term projects. Even the USA invests significantly more State money in energy research (1.0% vs 0.2%). Not surprisingly, France spends over 4%, considerably more than both the USA and the UK.

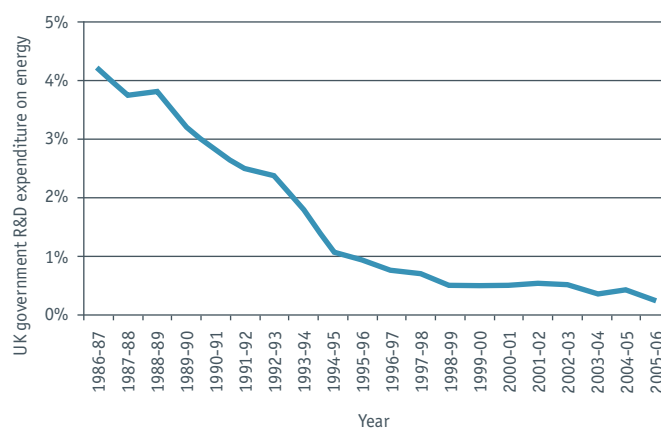


Figure 5. Evolution of UK's R&D yearly expenditure in energy, as a function of the total R&D budget (ONS. SET Statistics, 2008).



Chapter 2: Thorium-fuelled ADSR technology in a UK context *continued*

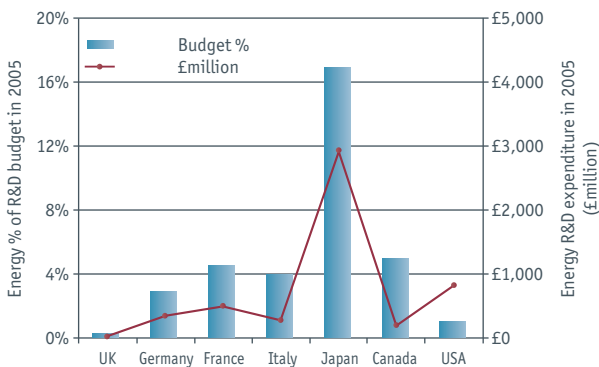


Figure 6. Comparison of R&D expenditure in energy for different OECD countries, in 2005 (ONS, SET Statistics, 2008).

In the absence of evidence that this paucity of private investment is to be reversed it is important that robust mechanisms are established to decarbonise power, prevent shortages (which would be politically very damaging), and build new value-adding industries.

Not only would investment in thorium-fuelled ADSRs reinvigorate an indigenous UK nuclear industry, it would create an ancillary particle accelerator industry capable of producing and exporting off-the-shelf high power particle accelerators for both ADSR drivers and for unrelated industries (e.g. medical therapy, isotope production, ion implantation, etc).

### 2.5 Alignment of the deployment of thorium-fuelled ADSR technology with UK Government policy

In the recently released document ‘The Road to 2010’ the Government sets out its nuclear vision and plans. Not only are three of the central objectives very closely aligned with the proposed thorium-fuelled ADSR programme, the latter will facilitate the achievement of the Government’s objectives. Namely, with reference to the chapter numbers within the ‘Road to 2010’:

- 1.3 ‘The UK Government believes not only that there is a recognised right for all sovereign states to the peaceful use of nuclear power, but that it is necessary to expand access to civil nuclear energy.’
- 1.4 ‘In expanding the use of nuclear power in the twenty first century we must not enhance the risk of further proliferation of nuclear weapons.’
- 1.6 ‘The issue of nuclear disarmament must be addressed. Nuclear weapon states, including the UK, have a duty to work to create the conditions where further reductions in levels of nuclear weapons can take place.’

Indeed ‘The Government will strongly support work to further develop proliferation resistant nuclear technology that will improve international access to the peaceful use of nuclear energy’, and would expect to work closely with the proposed Nuclear Centre of Excellence.

‘The Road to 2010’ was preceded by the 2008 White Paper on Nuclear Power which sets out the actions taken to facilitate investment in civil nuclear power. The outcomes of the thorium-fuelled ADSR development programme would also be fully aligned with this White Paper.

## Chapter 3: An R&D Programme to secure a UK global lead in thorium-fuelled ADSR technology

### 3.1 Towards the first thorium-fuelled ADSR – the 2025 scenario

If the UK is to rise to the challenge of both creating and supplying a world market for thorium-fuelled ADSR power generation systems, it essential that all the underpinning technology is put in place to build and commission a demonstrator ADSR power station by 2025. This is a key date as it places ADSR technology in the market place ahead of the deployment of the proposed Generation IV reactor systems,

thereby allowing a UK ADSR industry to compete in all potential international nuclear markets.

Independent analyses by both ThorEA and Aker Solutions have indicated that the demonstrator should be a medium sized power station capable of supplying the Grid with 600MW of electrical power. One potential configuration of such a system is indicated in Figure 7:

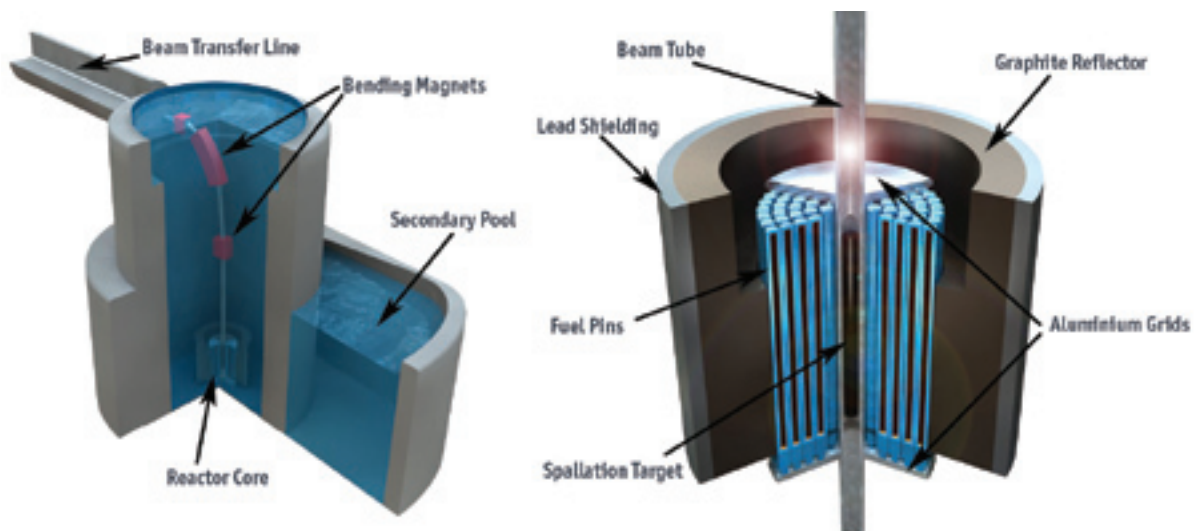


Figure 7. Schematic of a basic ADSR configuration (left) and ADSR core detail (right).

In its most basic form the demonstrator ADSR could consist of a single high power proton beam transported to a spallation target at the centre of the reactor core housing the fuel elements. Preliminary design studies carried out by ThorEA and others indicate that a “fast” rather than “thermal” ADSR system may be preferable, in which case a spallation target of molten lead or lead-bismuth eutectic could be made contiguous with a molten lead or lead-bismuth moderator and coolant system, simplifying both the spallation target and coolant heating and circulation circuits. Additionally, ThorEA has shown that, contingent upon the development of sufficiently compact and low cost proton accelerators, multiple accelerators/proton beams/spallation targets distributed within a single ADSR core could be optimal. Such an innovative configuration would, on the one hand, provide a more uniform spallation neutron flux distribution within the core whilst on the other mitigate against the risk of total loss of power should a single accelerator driver lose its beam current.

It is feasible and realistic that, **if initiated as a matter of urgency**, an extensive and coherent research and development (R&D) programme could secure all underpinning technology necessary to facilitate construction of the world’s first thorium-fuelled ADSR power station in the UK by the target date of 2025. However, in order to achieve this goal, it is clear that a R&D strategy should be implemented that will ensure that several technological options are incorporated and evaluated from the very beginning of the programme. A suitably stringent “gateway” or appraisal process for the whole R&D programme at specific key points will then ensure a smooth route to a timely and simultaneous delivery of *all* final technological objectives.

In this chapter, the scope and structure of the proposed R&D programme, an estimate of the investment required to meet the R&D objectives, and a management structure and financial model that will deliver these objectives and capture emerging intellectual property, are presented and discussed.

### 3.2 Defining and bridging the technological gaps

The ADSR concept is not new, but although the ADSR/Energy Amplifier principle was extensively developed, patented and promoted by Nobel Laureate Carlo Rubbia almost two decades ago, it has since been demonstrated only in brief experiments. No viable ADSR power generating system has yet been proposed or constructed.

One principal limiting technology is that of the proton accelerator driver (Appendix I):

- Cyclotrons can deliver appropriate continuous currents in the mA range, but cannot deliver sufficiently high proton energies.
- Synchrotrons can deliver appropriate proton energies, but only at lower, pulsed currents.
- Linear accelerators can deliver both the required currents and energies but are too large and expensive to be considered as a feasible commercial proposition.

Perhaps more significantly, no existing accelerator technology can meet the stringent reliability demands of a fully functioning ADSR power system. All accelerators are subject to numerous and frequent “trips” or loss of beam for periods extending from milliseconds to seconds, often many times an hour. As the spallation neutrons produced by the proton driver are responsible for the giga-Watt thermal power within the core, repeated loss of beam, even over such short periods, results in rapid thermal cycling and therefore intolerable thermal stress on the ADSR core sub- and super-structure.

It is significant that particle accelerators of a power appropriate for deployment as ADSR drivers (5-10MW) are at the forefront of accelerator technology and are generally developed individually for specific particle or nuclear physics experiments, or as drivers for major scientific facilities such as the planned European Spallation Source (5MW) and the recently commissioned Spallation Neutron Source (1.5MW) in the United States. Moreover, accelerator reliability on the scale demanded by ADSR deployment remains a key performance issue and must be explored through appropriate R&D programmes.

The principal challenge of ADSR technology is thus to develop an appropriately powerful and sufficiently reliable accelerator. Fortunately the UK is able to draw upon its internationally recognised expertise in accelerator design and innovation, and is therefore well placed to meet this challenge.

Indeed the vision of establishing a UK presence in ADSR technology has sprung directly from a Basic Technology programme funded by Research Councils UK (RCUK) known as CONFORM. A major component of CONFORM is the development and prototyping of an entirely innovative, compact, powerful, relatively low cost and potentially reliable accelerator, known as a non-scaling fixed field alternating gradient or ns-FFAG accelerator. CONFORM is being carried out by a consortium of scientists from UK Universities (including the authors of this report), STFC’s Accelerator Science and Technology Group (AsTEC) and the UK centres of excellence for accelerators: The Cockcroft and John Adams Institutes. CONFORM will

commission and demonstrate the world’s first ns-FFAG at Daresbury Laboratory towards the middle of 2010.

**In the first instance it is this novel ns-FFAG accelerator technology, together with the coherent and collective UK expertise necessary to drive forward a highly competitive advanced accelerator development programme, that gives the UK a unique advantage in the field of ADSR development, even in the face of international competition (Appendix IV).**

However, it must be emphasised that the development of a cost-effective, powerful but reliable proton driver is not the only challenge that must be met. Although spallation targets, nuclear core design, molten metal cooling systems, the processing of thorium and its oxides, fuel rod manufacture, thorium fuel cycles and waste management are all reasonably advanced and are well understood in the context of other more conventional applications, each pose new technical challenges when brought together as components of a fully functioning thorium-fuelled ADSR design. Some of these challenges are defined and discussed in Appendix VII.

It will therefore be necessary to augment an extensive and innovative accelerator R&D programme with a parallel programme of refinement and optimisation of each of these complementary ADSR technologies. Fortunately, such a programme is also able to draw upon existing and acknowledged UK strengths, leadership and facilities as provided by, for example the National Nuclear Laboratory, STFC and its laboratories, and recognised academic HEI expertise in nuclear physics and chemistry, and materials science. Additionally, from its outset, the programme would benefit from the participation of key industrial partners. Indeed relevant companies already expressed specific interest in the proposed ADSR R&D programme and its stated objectives.

### 3.3 Delivering the technology:

The ADSR R&D programme has two key objectives:

- The delivery of the necessary accelerator technology,
- The optimisation, refinement and delivery of all other underpinning ADSR technologies.

#### **A phased accelerator development programme: AESIR**

The principal objective of the five year **AESIR** (Accelerator Energy Systems with Inbuilt Reliability) R&D programme is to design, build and demonstrate a robust and reliable prototype accelerator system which will be suitable for mass production and commercialisation as an ADSR proton driver. The AESIR programme must therefore, on the one hand, be coherent and focussed, whilst on the other undertake the task of comprehensively evaluating the suitability of all potential advanced accelerator architectures and components.



In order to meet its objective, AESIR will take a phased approach. The initial phase (years 1-2) will, in parallel

- construct a high reliability, low energy (35MeV) high current proton injector system
- evaluate the optimal design for an intermediate energy (400MeV) proton accelerator driver

Rigorous assessment of the operational performance of the injector and a detailed review of the design of the proton driver will be concluded by the end of year two.

Construction of the intermediate energy proton driver will begin in year 3, and in years 3-5 the R&D programme will focus upon construction and demonstration of a reliable intermediate energy high current accelerator system. The successful demonstration of this accelerator, in year 5, will signal the completion of the R&D phase and commencement of the commercialisation phase in which the proven accelerator design will be refined and upgraded for the final operating frequency of 1GeV.

#### **AESIR Phase I: LOKI**

The initial phase of the programme, named **LOKI (Low Key Injector)**, will construct and commission the first stage of the ADSR proton driver. This will be a 35MeV, high current (~30mA) linear accelerator injector with emphasis on exceedingly high reliability.

High current ion sources (e.g. a 30mA H<sup>-</sup> source) and the low energy transport modules that extract the beam and deliver it to a radiofrequency (RF) quadrupole of the first stage of the linear accelerator are available as reasonably standard commercial items. It is anticipated that more than one ion source may be necessary to enhance reliability margins. Although RF quadrupoles can be obtained commercially, it is preferable to develop, as part of the R&D programme, suitable components to deal with the required high currents and deliver the highest achievable reliability. The linear accelerator, designed to take the proton beam to energies of tens of MeV, will comprise a series of electrodes and an RF power supply. Additional infrastructure, including power supplies, vacuum systems, radiation protection etc will also be essential. If this research is carried out at a site such as Daresbury Laboratory then some savings could be achieved by recycling existing infrastructural components, although refurbishment costs will also be incurred. Such costs would be substantially lower than locating the project at a green field site.

It is considered possible to deliver a reliable low energy ion source and first stage accelerator suitable for ADSR applications, within two years. Total construction costs of LOKI, including manpower and commissioning together with operational costs over the full 5 year AESIR R&D phase will amount to an estimated £40M.

From the start of Phase I a parallel design, modelling and evaluation programme will be initiated with the goal of establishing the most appropriate candidate accelerator design for Phase II of the programme, i.e. the delivery of a high current, intermediate energy (350-400MeV) high reliability accelerator. Initial R&D will focus upon the potential upgrade and exploitation of those ns-FFAG designs currently being explored within the CONFORM programme for medical applications in cancer therapy (i.e. the PAMELA design). However early implementation of a robust optioneering approach will ensure thorough evaluation of all potential competitor technologies (e.g. advanced compact linear accelerators, innovative approaches to rapid cycling synchrotrons etc as described in Appendix I) in the event that the currently preferred choice, the ns-FFAG, cannot be implemented. This optioneering approach is illustrated in Figure 8. This R&D component will add approximately £10M to the cost of Phase I of AESIR (an estimate based upon current expenditure on the RCUK CONFORM project).

On completion of Phase I, i.e. two years from the start of the programme, a rigorous appraisal process will be implemented, with the accelerator R&D programme progressing smoothly into Phase II conditional only upon LOKI achieving full design specifications and a successful feasibility assessment of a completed design study for the intermediate energy, second stage, accelerator.

#### **AESIR Phase II: FREA**

The second phase of the AESIR programme has been named **FREA (FFAG Research for Energy Amplifiers)**. The principal focus of FREA is the construction and commissioning of an accelerator which will provide proton beam energies of up to 400 MeV. using either ns-FFAG or other appropriate technology. Once again, the emphasis of the R&D programme will be upon high reliability delivery of a high current proton beam. Whilst costs for this phase of the programme are similar to those associated with the more extensively studied PAMELA prototype design, and although FREA's magnets will be similar to those of PAMELA, the necessary RF components will be significantly more substantial. For the magnets (which will probably employ superconducting technology), RF and other hardware the estimated cost is £80M. An additional £25M for infrastructure (power, vacuum, shielding etc) and £10M for staff effort, yielding a total cost of £115M. These costs are based upon the ns-FFAG option. Those associated with construction of an alternative driver based upon competitor technologies (see figure 8), cannot be estimated with any accuracy in advance of the robust assessment proposed for the completion of the studies of Phase I of the AESIR programme. However they are likely to be higher than those of the ns-FFAG option.

Phase II of the programme will take 3 years, at the end of which the rigorous project appraisal process will again be applied. A green light at this stage is conditional upon successful delivery of a high reliability, high current beam, and will enable the programme to progress directly to Phase III, the design and construction of a 600MW thorium fuelled power station .



### Phase III: THOR

Successful completion of FREA in Phase II will ensure that the principal components of the required ADSR accelerator technology are in place, and Phase III will therefore focus upon the final design, construction and commissioning of a 600MW thorium-fuelled ADSR power station driven by a fully optimised proton accelerator. From the present perspective it is estimated that the driver(s) should deliver, with high reliability, a total beam current of 10mA at an energy of 1 GeV into an ADSR core with a criticality factor of 0.985. However it is possible that optimal ADSR core design calculations carried out in parallel with Phases I and II, may favour higher

core criticalities and hence lower beam currents, relaxing somewhat the design parameters of the proton accelerator. Successful demonstration of the 400MeV FREA accelerator will ensure that very little additional R&D will be needed to extend the operational energy to the required 1GeV.

It is envisaged that THOR will be funded entirely by the private sector. The accelerator technology demonstrated and optimised in Phases I and II of the AESIR programme will be taken beyond the prototyping stage and into the production stage. The costs of building and commissioning a fully operation ADSR power station is expected to be in the region of £1.5-2bn.

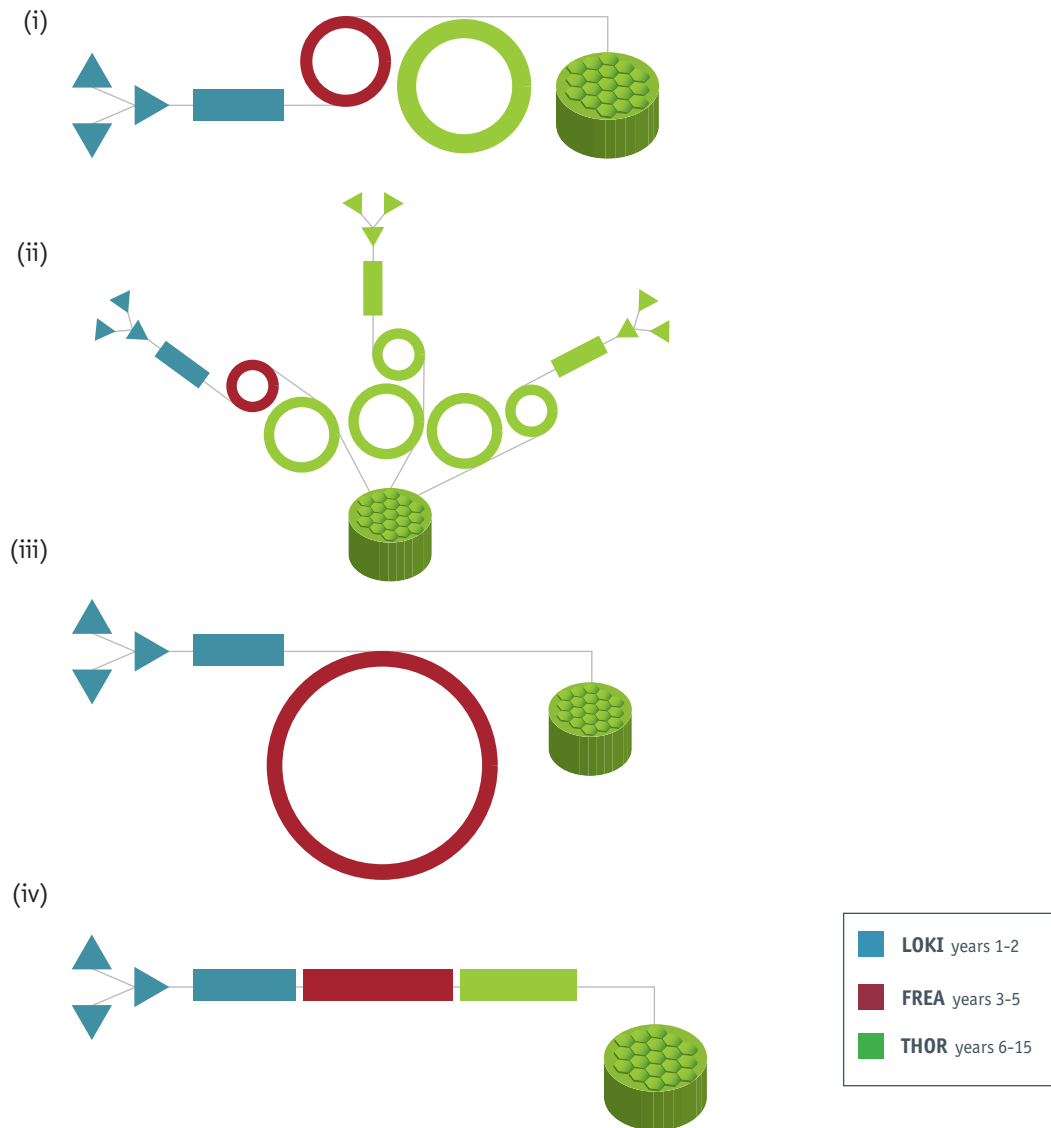


Figure 8. A schematic illustration (not to scale) of the optioneering approach to the AESIR accelerator programme: (i) single ns-FFAG proton driver (ii) multiple ns-FFAG proton drivers (iii) Rapid cycling synchrotron option (iv) Linear accelerator option. Note that LOKI will deliver 35MeV protons and FREA 400MeV protons, THOR represents the privately funded phase of the project in which 1GeV protons are injected into a fully operational thorium fuelled ADSR core.

### 3.4 Additional public investment in ADSR technologies

Appendix VII defines many of the additional technological challenges that must be faced by a UK ADSR R&D programme. As mentioned above, many of these challenges must be quantified and addressed in parallel with the accelerator development and delivery programme, to ensure that **all** necessary technology is delivered together on a time scale appropriate for the construction and commissioning of a thorium-fuelled ADSR power station by 2025.

Several of these technologies have close synergies with the AESIR accelerator programme. For example, the design and development of a functional ADSR core must incorporate an evaluation of the advantages of multiple proton drivers. The outcome of such studies will set the operational parameters (e.g. proton current) demanded of the drivers themselves, and hence feed back into all phases of the AESIR programme. Additionally, issues such as the non-trivial coupling of the proton drivers to a circulating molten metal spallation target require the development of either radiation hard beam windows, or complex confluent fluid flow patterns to present a windowless target to the beam. Materials problems associated with molten metal corrosion of superstructure elements, fuel materials and fuel encapsulants in the presence of high proton-induced radiation fields must also be solved.

A key feature of the ancillary R&D programme is the possibility of performing preliminary ADSR simulation tests using the UK's only civil research reactor, Imperial College's 100KW Consort Reactor at Silwood Park. Consort's design facilitates the addition of a central low power spallation target which could be coupled to a modest power proton accelerator (cyclotron or ns-FFAG), with conventional reactor controls rods defining the effective criticality of the reactor core. Such studies, although performed in thermal rather than fast mode, would represent only the second ever demonstration of the ADSR principle and would provide extremely useful information on neutron flux distributions and control parameters.

In order to manage progress in this and other key activities, it is suggested that the project has an integrated materials R&D funding of £135m over 5 years. Some of these funds will be used to commission and contract research at HEIs and national laboratories (in particular, NNL) and some, will be expended on in-house on R&D appropriately connected to the accelerator delivery programme.

### 3.5 Cost summary

The total cost to the public sector of the AESIR accelerator programme is estimated to be £165m over five years. This estimate is based upon figures provided by members of STFC's ASTEC (Accelerator Science and Technology) Division together with an evaluation of the cost of constructing a similarly powerful (5MW) proton driver accelerator proposed for the European Spallation Source (ESS) for which €465M is allocated (see, e.g., "Responses to the Questionnaire of the ESFRI Working Group on ESS Siting (EWESS)" ESS BILBAO Initiative, April 2008).

It is recognised that the figures for the AESIR project might appear low in comparison with the ESS estimates. This is partly a feature of the accounting system (the ESS figure represents the full cost on a green field site), but is principally because the ESS design is based on a linear accelerator, which is a safe but expensive option. The smaller dimensions of a cyclic accelerator such as a ns-FFAG (i.e. tens rather than hundreds of metres) means that the cost of focussing magnets, RF cavities etc is considerably less. Moreover the AESIR programme intends to deliver a 400MeV accelerator suitable for later enhancement for operation at 1GeV whilst the ESS accelerator is designed to operate at 1GeV.

The cost of the necessary R&D programmes to deliver the ancillary ADSR technology is £135m, bringing the total public sector investment to £300m over five years. This investment is intended to lever £1.5-2bn from the private sector. An approximate spend profile for the public sector investment is presented in Figure 9.

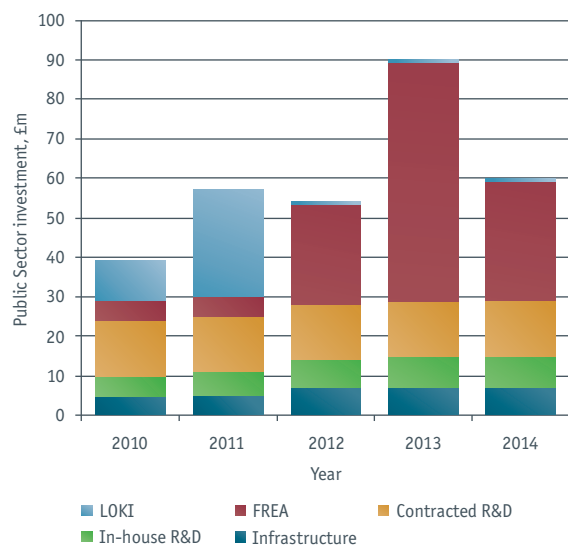


Figure 9. Estimated spend profile associated with the public investment in ADSR technology R&D programme over the period 2010 to 2015.



### 3.6 Private Investment and construction of an ADSR power station

The construction of an operational thorium-fuelled ADSR power station is well beyond the scope of the publicly funded R&D project outlined above. Costs are expected to be at the level of ~£1-2bn. However, should phases I to III of the AESIR project be successful, the resulting knowledge and technology effectively transferred to the UK industrial sector, and the expected links with industry fully exploited throughout, such an enterprise is likely to be not only commercially feasible but also a particularly attractive investment to both industry and government.

It is therefore foreseen that the £300m public sector investment in the project will be supplemented by a steadily increasing private sector investment over the first 4 to 5 years of the project, after which the latter will rapidly dominate, as design parameters for a thorium-fuelled ADSR power station are set and construction commences in years 7-8.

It is evident that a well defined management structure should be set in place to oversee all aspects of the project, and guide the public-private partnership (PPP). This will be discussed in the next section.

### 3.7 The proposed management structure: ThorEACo

It is proposed that a limited company (referred to here by the working title 'ThorEACo') be set up to:

- Provide commercial leadership & management for the project.
- Maintain the focus of the company on the delivery of a practical and commercially-viable Thorium-based ADSR power plant.
- Identify, protect and manage the intellectual property developed by this project.
- Administer the public funding for the project.
- Carry out project management, outsourced contract management and quality systems management.
- Enable commercial investment in the project as applicable.
- Provide a vehicle for capturing value arising from commercial exploitation.



The nature of the company, conceived as a public private partnership (PPP) will evolve as the programme progresses through the three phases that have been previously described. The expected development of this company is:

**Formation:** A limited company will be set up, in a broadly similar manner to the way in which the Diamond Light Source project has been set up. The founding shareholders will reflect the initial contributions, which are likely to be public funding (primarily UK Government) and intellectual property (universities). IP will be licensed or assigned into the company in return for a founding shareholding, but the majority shareholder will be UK government, probably acting through STFC. Other funding sources could be investors at this early stage, but it seems probable that the bulk of the funding requirements for Stage 1 will be public sector. The Board of the company will include shareholder representatives and experienced individuals from the nuclear engineering industry. An appropriate chairman with experience of substantial and complex technology development projects as well as the energy sector will be identified. The company will operate under appropriate industry quality management systems, and will retain specialist expertise in both quality management and intellectual property.

**Phase 1:** The company will manage the project to deliver the accelerator injector, and will identify, capture and protect intellectual property developed in the process. This will apply to both formal IP such as patents and know-how. It is possible that industrial partners may wish to invest in the company during this phase as the basis for a developing relationship in subsequent stages. This may be considered by the company to the extent that it does not prejudice future commercial exploitation prospects. Key technical work will be contracted to existing facilities with project managers from ThorEACo working closely with those facilities.

**Phase 2:** Most of the practical engineering associated with the accelerator will be contracted out by ThorEACo, while retaining ownership of intellectual property. Project management during this phase is likely to be delivered via experienced project managers from the particle physics and/or nuclear engineering sector, either under contract to ThorEACo or seconded in to the company. The opportunities for private-sector contributions to the company will be explored – these may be in the form of financial investment or non-financial contributions.

#### Phase 3:

The construction of a practical power-producing ADSR plant will be carried out by industrial companies. The accelerator technology in particular will be licensed from ThorEACo on a commercial basis, most likely in return for royalties on sales. In this stage it is unlikely that ThorEA will be directly involved in the production of reactor hardware. The extent to which a programme of development is required to deliver future generations of product will be assessed, but it should be clear that the focus of this phase of the project is the development, refinement and delivery of practical technology, rather than upon basic research.



*Chapter 3: An R&D Programme to secure a UK global lead in thorium-fuelled ADSR technology **continued***

Throughout all stages of the project ThorEACo will subcontract, commission and oversee the development and progress of associated ADSR technologies, e.g. those related to thorium fuel cycles, reactor core design and cooling systems, and materials research relevant to spallation targets, sub- and superstructures etc. The company will be responsible for capturing appropriate IP from these activities.

In line with other large-scale programmes the ADSR development project would use the Government Office of Commerce's Gateway review process. In line with the Gateway process – and project management best practice – the ThorEACo would:

- Employ Project Management professionals. Collaboration with industrial partners would help strengthen the teams skills in this important area
- Clearly identify the business case for the alternative outcomes
- Define, from the start, realistic budgets to ensure the objectives can be achieved on time and to budget
- Give due consideration to the procurement strategy

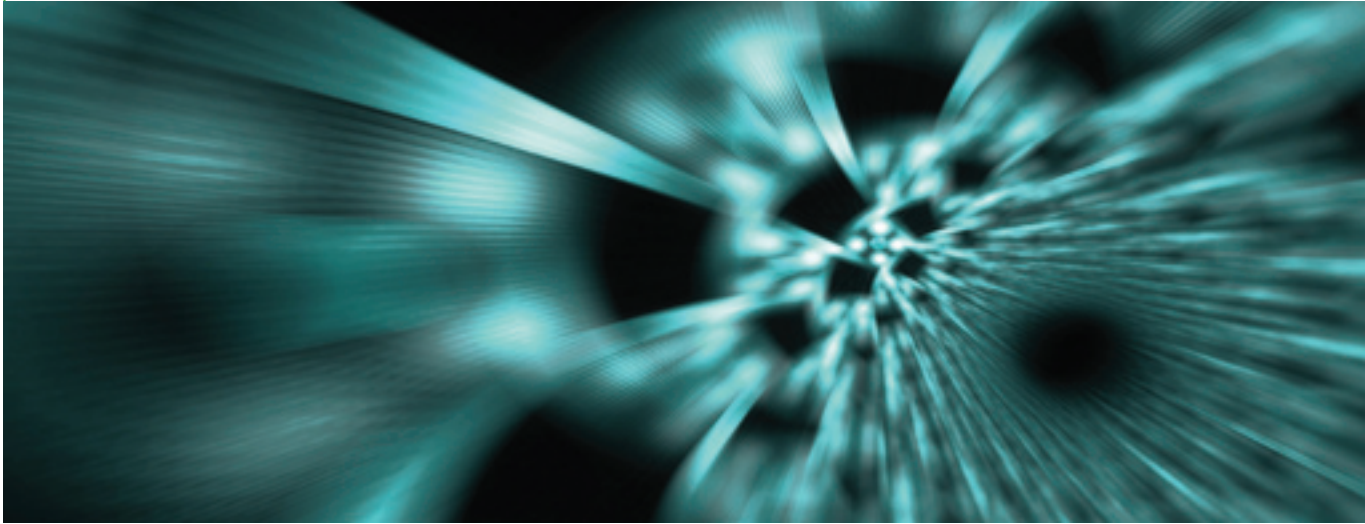
### **3.8 Geographical location of ThorEACo: The case for location at Daresbury Science and Innovation Campus.**

The R&D programme and management structure outlined in this chapter is essentially entirely site-independent. However, given that the principal on-site ThorEACo activity in phases 1 to 3 of the R&D programme is the design, construction and commissioning of an ADSR accelerator driver, there are specific advantages in locating ThorEACo at the Daresbury Science and Innovation Campus (DSIC). These include, for example:

- Close proximity to EMMA and the team which has played the major role in delivering the prototype ns-FFAG from which the thorium-fuelled ADSR project has evolved, and where world-class expertise and training in all aspects of accelerator science and technology resides.
- The potential to re-cycle and exploit buildings, civil and mechanical engineering infrastructures, radiation shielding, and accelerator components and diagnostics all made redundant by the recent closure of the Synchrotron Radiation Facility, thereby saving the proposed R&D programme several tens of millions of pounds.

It should be emphasised, however, that stage 3 of the programme – the construction of a demonstrator thorium-fuelled ADSR power station – will have to be located at an appropriately licensed nuclear facility.





Chapter 3: An R&D Programme to secure a UK global lead in thorium-fuelled ADSR technology *continued*

### 3.9 Evidence of potential industrial engagement in the ADSR programme.

Realisation of the vision of creating an internationally leading thorium-fuelled ADSR industry in the UK is entirely dependent upon commercial engagement with, and investment, in the project. It is useful here, however, to present evidence of two major industrial organisations that have expressed support for the ADSR programme and its objectives:

#### Case Study 1: Statement by Aker Solutions - Working Towards a Thorium-Powered Future

*Aker Solutions is a leading global provider of engineering and construction services, technology products and integrated solutions. Aker Solutions' business serves several industries including oil & gas, refining and chemicals, mining and metals, power generation and nuclear services. Aker Solutions' nuclear services capability spans some 40 years, originating in its Stockton-on-Tees operation in the UK.*

*Aker Solutions has aggregated annual revenues of NOK 54 billion (£5.7bn) [year ended 31 December 2009] and employs approximately 22,000 people in about 30 countries.*

*In recent years investment in nuclear power related projects and development plans have increased considerably. Significant investments have been made:*

- *Mobilised significant resource for nuclear projects in USA/Canada, South Africa, India and China;*
- *Invested £2.2m to date on the development of a potential accelerator-driven thorium-powered reactor (ADTR) as the basis of a power station;*
- *Engaged Carlo Rubbia on contract to support the development work;*
- *Purchased the ADS-related IP of Carlo Rubbia;*
- *Exploratory discussions with potential partners;*

*Having investigated the options, and having taken due consideration of the economic implications, Aker Solutions believes there are commercial opportunities in this field. Notably, Aker Solutions believes that there will be a market for Thorium-powered power generation build in domestic and export markets in time frames which align with those of the Generation IV reactor development programmes, to be operational by 2030.*

*The development of a reliable accelerator (and other enabling technologies) that would result in a Thorium-powered ADSR would be of considerable technical and commercial interest to Aker Solutions. However, as a commercial engineering and construction provider, Aker Solutions' core business does not include the research capability required to develop particle accelerators. Aker Solutions is therefore exploring opportunities with potential organisations/partners to develop the technology. Aker Solutions possesses significant core competencies in large-scale programme management, and this expertise would be of considerable value to a consortium of organisations working together to develop a reliable, high-powered accelerator.*

## Case Study 2: Letter of support from Siemens AG

### Nonbinding Letter of Support for the Development of Accelerator Technology for the use in Healthcare and Nuclear Industries

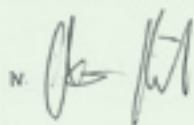
Siemens AG is a global powerhouse in electrical engineering and electronics. The company has over 400,000 employees working to develop and manufacture products, design and install complex systems and tailor a wide range of services to individual requirements. Siemens is an integrated technology company with a clear focus in the sectors Industry, Energy and Healthcare. Each of these sectors supplies a wide range of product solutions including the design and manufacture of many particle therapy centres and energy generation systems.

Siemens is interested in the development and exploitation of accelerator technologies for next generation particle therapy, nuclear processing and energy systems. Looking to the future, in order for accelerators to be more widely available it is important to make them compact, reliable and financially competitive. Therefore, Siemens has considerable interest in the proposed ThorEA project which will focus on developing the underpinning technology to realise accelerator driven subcritical reactor systems, given that the technology cannot be brought to full commercial application without significant advances in technical development and physical demonstration projects. Specifically, Siemens' interest focuses upon the business case, accelerator development, reliability etc. Should the project move forward we can envisage potential collaboration and engagement in the following areas: business case, linear accelerator technology, high power pulsed equipment and productionisation.

Therefore, Siemens believes that the combination of its expertise with ThorEA, could lead to successful development of this technology for the benefit of all parties.

Signed:

On behalf of Siemens AG:



Dr Oliver Heid,  
Head of Healthcare Technology & Concepts

### 3.10 IAEA endorsement of the proposed ADSR programme

The following message of support for the proposed R&D programme was received from Alexander Stanculescu, of the Nuclear Power Technology Development Section of the International Atomic Energy Agency (IAEA), Vienna:

*“During the pioneering years of nuclear energy, from the mid 1950s to mid 1970s, there was considerable interest worldwide to develop thorium fuels and fuel cycles, given the many potential benefits. Indeed, those studies have identified many incentives for the use of thorium fuel. Thorium resources are larger than those of uranium, and neutron yields of  $^{233}\text{U}$  in the thermal and epithermal regions are higher than for  $^{239}\text{Pu}$  in the uranium-plutonium fuel cycle. The introduction of the Thorium-based nuclear fuel cycle would therefore vastly enlarge the fissile resources by breeding  $^{233}\text{U}$ . Large thorium deposits in some countries, coupled with a lack of uranium deposits in those countries is another strong incentive for the introduction of thorium based nuclear fuel cycles.*

*Other reasons identified in past studies are the potential for fuel cycle cost reduction, the reduction in  $^{235}\text{U}$  enrichment requirements, safer reactor operation because of lower core excess reactivity requirements, and safer and more reliable operation of  $\text{ThO}_2$  fuel as compared to  $\text{UO}_2$  fuel at high burnup due to the former's higher irradiation and corrosion resistance.*

*The TMI and Chernobyl accidents, and growing long-lived radioactive waste issues provided new incentives for the use of Thorium-based fuel cycles, given their potential for reducing the*

*production of plutonium and higher actinides, as well as the possibility for a more effective incineration of plutonium and long-lived radiotoxic isotopes.*

*On the other hand, the thorium fuel cycle has some disadvantages when compared with the uranium fuel cycle, which were also recognized from the very beginning of thorium-fuel related activities, more specifically: the thorium- $^{233}\text{U}$  fuel cycle is characterized by a much stronger gamma radiation level than the uranium-plutonium cycle, and therefore handling during fabrication requires more care; nuclear reactions by neutron absorption and decay schemes for Thorium-based fuels are more complicated; longer water storage time for the spent fuel is needed due to higher residual heat; potential difficulties in down stream spent fuel reprocessing.*

*Against this background, the IAEA is supporting interested Member States activities in Thorium-based reactor and fuel cycle technologies. In particular, accelerator technologies to enable the exploitation of such fuels and fuel cycles in accelerator driven subcritical reactors are of particular relevance in this context.*

***IAEA warmly welcomes the proposed accelerator driver development programme embodied in the ThorEA project as a positive contribution to the international effort to secure the eventual global deployment of sustainable thorium-fuelled ADSR power generation systems.”***

## Chapter 4: Value Capture and IP: from ADSRs to Medicine and beyond

### 4.1 Introduction

As innovative devices, thorium-fuelled ADSRs pose a number of technological challenges, the solutions to which will, in turn, lead to significant IP potential and value being captured for the UK. Figure 10 summarises the existing experience and technical challenges along the value chain for the thorium-fuelled ADSR. These challenges are discussed in more detail in Appendix VII.

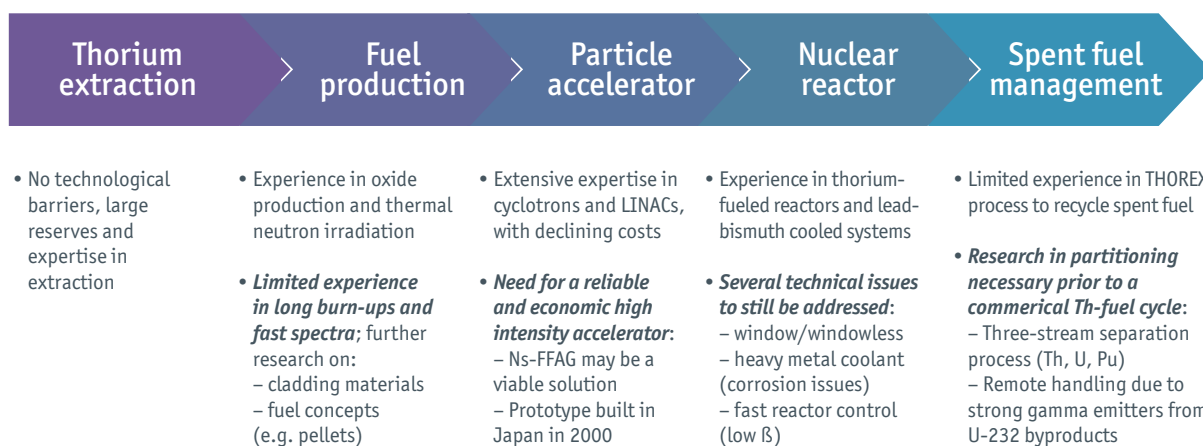


Figure 10. Existing experience and technical challenges along thorium-fuelled ADSR value chain.

### 4.2 Intellectual property landscape

The IP landscape outlined herein concentrates on patented technologies in fields relevant to the thorium-fuelled ADSR programme and gives a strong indication that the position for generating IP is very favourable. On the one hand the programme will be able to use existing patented technologies which have expired or are nearing the end of their life, and on the other it is close enough to market to be able to protect some of the first IP in this field to have real commercial value.

Intellectual Property Rights, resulting from intellectual activity in scientific and industrial endeavours throughout the thorium-fuelled ADSR programme will emerge in a variety of forms:

- Industrial property which includes inventions (patents), trademarks and associated brands, industrial designs in the form of detailed drawings, and know how (tangible and in tangible) trade secrets.
- Copyright and related rights in the form of software, papers, technical specifications, safety and quality documentation, training manuals, process flow documents bill of materials etc.

In exploring the IP landscape indications are that the race for patents and papers in the field of nuclear power generation appears to be taking place largely outside the UK. This project is an ideal opportunity to consolidate the UK's existing knowledge and build the UK's knowledge base and IP portfolio in this key energy field.

In a research sector such as this tacit knowledge, high barriers to entry, and a high potential for tight commercial secrecy are all real and realizable benefits. Copyright and know-how will therefore be at least as relevant and profitable as patents to the UK in terms of valuable IP, creation of technological leadership, skilled staff, facilities and experience that will mark out the UK as global leader in thorium-fuelled ADSR power generation, and hence advanced nuclear engineering.





### 4.3 The patent landscape

Categorization of the technological fields outlined in a patent and the field for which the rights of monopoly are claimed is known as the International Patent Classification (IPC). The International Patent Classification G21C “Nuclear Reactors” covers a wide range of techniques for designing, building and operating nuclear systems, especially for commercial power stations, but additionally for military, maritime and space scenarios. The classification also tends to be applied to a scattering of other nuclear related disciplines such as clinical nuclear therapies. (See Figure 11).

The scale of the patent literature in the G21C area can be judged from a cursory look at this classification using the widely known Esp@cenet service (highlighted in the Appendices), which indicates that a little over 100,000 patent families have been filed in this area over the past few decades. The rate of patenting in this area peaked around 1985, when over 4000 separate patent families were published, so the majority of patents granted will now have expired, but the rate remains at a respectable 1500 or so new patent families being published each year as 2010 approaches.

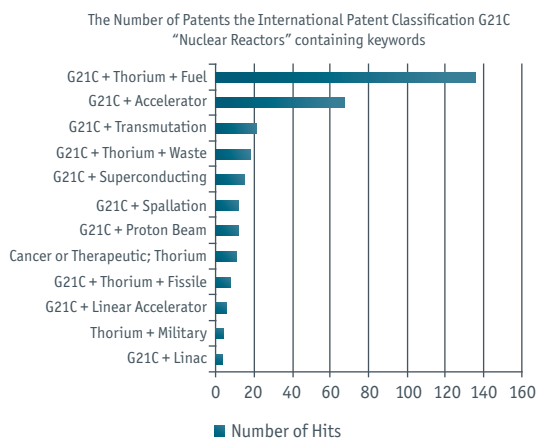
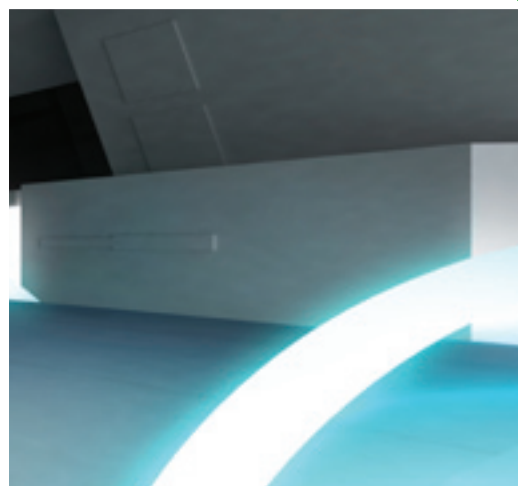
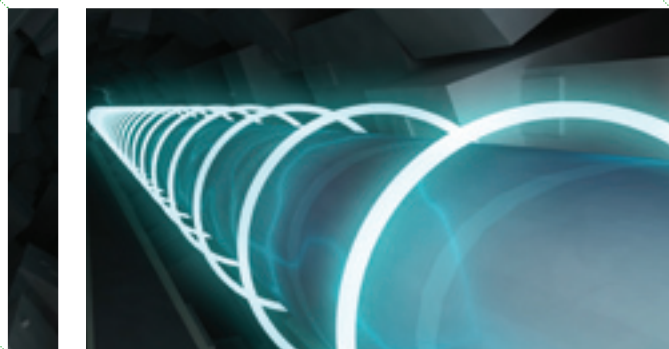


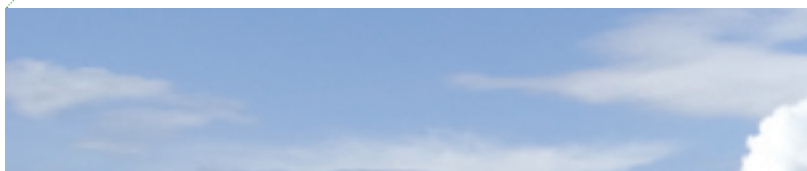
Figure 11. International patents related to Nuclear Reactors and other ADSR components.

The home countries for each patent family, as judged by the country of the priority application, follow trends in other technologies. For 2008 publications, Japan dominates G21C with 386 families, followed by the US with 329. France (151), South Korea (142), China (105), Russia (95) and Germany (85) follow behind. Korea and China are both relatively new players in this patent field and indeed on the international patent stage in general, but both have a very significant future potential.

As for most fields of technology, the patent families in G21C tend to be dominated by modest engineering developments of well established schemes. Thorium, which is little used commercially at present, is mentioned in the title or abstract of only about 380 of the patent families ever categorised in G21C and “accelerator” in only about 70. The International Patent Classification also provides us with a very useful subcategory of “subcritical reactors” G21C1/30, into which the proposed thorium-fuelled ADSR would fall, and historically this categorisation has been assigned to a total of about 1200 patent families. Of these, many relate to fuel preparation and processing. Probably less than ten of these families contain discussions of thorium, while around twice that number contain discussion of particle accelerators.

Significant in this context is the Energy Amplifier (ADSR) patent filed by Nobel Laureate Carlo Rubbia in 1993. This patent is discussed in detail in Appendix VI. However it is noted that the Rubbia patent was initially brought into effect in twelve European countries, but most of these national patents were allowed to lapse in 2003, with only France, Belgium and Italy remaining. The term of a patent is twenty years from the filing date, so these remaining patents, and any others of the family remaining in force, will expire by about 2014. There is little prospect of Rubbia’s system being incorporated in a working Power Station by that time. This reflects a difficulty for early concept patents in fields, such as nuclear power, where the timescales for acceptance and eventual implementation are long.





#### 4.4 IP Management

The patent landscape analysis clearly shows that thorium has been seriously considered as a nuclear fuel for 50 years and there is a considerable quantity of IP in the public domain. Many of the fundamental scientific and engineering principals have been previously explored. This is a huge advantage to the project, as the IP is free to be exploited without fear of litigation. Recent activity in India, Sweden, Canada, US and EU has resulted in publications, designs, processes, procedures, knowledge and methods and patents much of which will contribute to this programme.

This is not to say that there are not challenges and problems, to be solved. Appendix VII provides a clear illustration of where the technological advancements in the project are yet to be made. It is here that valuable IP can be protected to advocate the UK's position as a strong global player in this new market.

A patent's life is 20 years; it may well be at least 8 years before the research stage is complete and the research exception permitting the use of patents for research without risk of infringement is no longer valid. It may then be at least a further 5 years to complete the development stage and the technology be considered 'commercial'. Thus the risks of infringing existing patents will diminish with time.

To ensure that an organised, cost effective IP strategy is implemented, it is proposed that a central IP coordination function should be responsible for monitoring scientific and technical developments across the project, ensuring that suitable measures are in place to guarantee confidentiality of new developments, to maintain a balance between secrecy and academic publication, and to supervise the preparation and review of invention disclosures. The same coordination function will manage the patent process including the preparation of patent searches and specifications, filing and prosecution formalities.

Timing is crucial in deciding what and when to protect IP. The optimum time to patent is when a feasible engineering solution presents itself and has been consolidated in detailed engineering drawings. Regular IP reviews should be integral to the design process when detailed designs have been drawn up and the build has started or is imminent. It is proposed that the ThorEA project is to run to industry standards and will incorporate industrial partners in the collaboration. A project plan for the whole project is taking shape (see Chapter 4: 'ThorEA Proposal'). Prior to commencing the programme detailed project plans with milestones, review points and costing for each phase will be pulled together by the Programme Manager. Regular IP reviews should be tasked at the appropriate times.

A plan to capture IP emanating from the programme through regular audits and due diligence will be defined, providing both knowledge of existing IP that may impact on the projects in the programme and auditing innovations, designs, copyright and know how etc. that are being produced. These two tasks are key to the capture, evaluation and protection of relevant legally sound IP. It should however be recognised that in the nuclear industry, where time horizons are often in decades, conventional IP protection is not the sole convenor of commercial benefits. At times it can be a disadvantage as the registering of a patent reveals details that could otherwise remain hidden.

#### 4.5 Patent strategies for the ThorEA project

It is apparent that a thorium-fuelled ADSR can be constructed using extensive well established technology, for which most or all relevant "basic science" patent applications will have expired. The long development and acceptance times of alternative nuclear reactor schemes are thereby avoided. At the same time the project requires development of much detailed technology, for example for proton beam generation, delivery and spallation which will be highly protectable using the patent system and these patents are expected to be in force for ten or more years after the first commercial operations. Indeed IPR associated with the project has already been filed by ThorEA and STFC.

The ThorEA project will aim to file patent applications in numbers commensurate with the scale of the project. Nine detailed areas of research are outlined in the next chapter, and over a six year time scale an appropriate number of new patent applications across these areas would be between fifty and one hundred. At this level, the project would represent about one percent of the number of new patent families being filed in the nuclear reactor field, for each of the six years. If half of these patent applications stand up to the rigours of patent searching and examination and are entered into ten countries each (for example US, Japan, Russia, China, Korea, India, France, Italy, Germany and the UK), a patent costs budget of about £1.5m-£3m will be required.

Other aspects of Intellectual Property will be brought into play to support ThorEA, including both registered and unregistered design rights, copyright and trademarks where appropriate to support the commercial objectives. The importance of commercial secrets to protect know-how and design aspects which are not easily protected in other ways must not be underestimated.



#### 4.6 Future opportunities facilitated by ADSR accelerator research

Typical engineering patents in the area highlighted in the section 4.2 bear a close resemblance to technologies currently in the patent portfolio held by STFC's world leading accelerator science facilities. This patent portfolio has been largely developed through the design build and use of the Daresbury Laboratories Synchrotron Radiation Source and the ISIS facility at Rutherford Appleton Laboratory. For example, STFC are currently filing a patent on an invention describing an asymmetrical magnet solution as a direct result of the current ns-FFAG.

IP generation is expected to be in fields that are both relevant historically to existing accelerator technologies and looking forward to the thorium-fuelled ADSR project they include advancements in cryogenics, magnet configurations, vacuum technologies, detectors, and imaging devices, laser related technologies, amplifiers, transducers and proton beam generation, delivery, spallation, and spallation targets. These and other new areas to be explored include transmutation of waste, energy production, hydrogen production, pyrolysis. These latter, less explored technologies, are outlined more specifically in the next section.

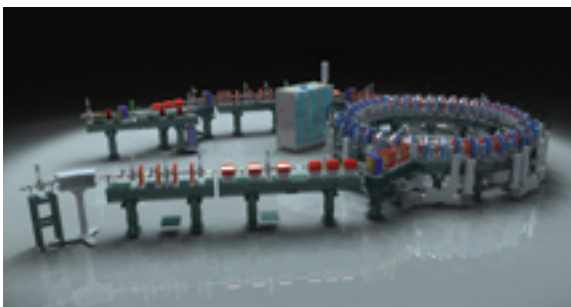


Figure 12. The CONFORM project's EMMA: the world's first non-scaling fixed field alternating gradient (ns-FFAG) accelerator, currently under construction at Daresbury Laboratory

The degree of inventiveness associated directly with CONFORM's accelerator development programme is enormous. A prototype of the world's first ns-FFAG, "EMMA", (Figure 12) is currently being assembled at the Daresbury Laboratory as a key component of the CONFORM project managed in part by authors of this report. The conceptual designs for CONFORM's PAMELA – the next ns-FFAG that may be built at Daresbury – has been designed to have a small footprint. PAMELA will provide the basis for the development of ADSR proton drivers: it will be particularly suitable for both a cellular approach to power generation using multiple accelerators, and for its use in clinical applications based in hospitals where land space is at a premium. PAMELA, presently a conceptual physics design and about to progress to the engineering feasibility phase, demonstrates the synergies of the ADSR programme with other advanced and diverse technologies.

The design and construction of CONFORM's PAMELA is expected to generate fundamental IP as well as regenerating existing STFC IP. PAMELA's novel configuration (two concentric accelerator rings with dual injection and extraction) is set to generate a supply of novel designs in equipment and technologies. Areas of particular relevance include superconducting magnets, cryogenic technologies, and third harmonic cavities, new materials, specialist coatings and LINAC designs. It is expected that IP will be in the form of patents, knowhow and drawings.

Taking advanced particle accelerators from the physics laboratory to real world routine industrial applications is a significant challenge. Meeting this challenge will generate many inventions. Individual components will have to be robust with in-built reliability and it must be possible to track and replace failing components with minimum disruption. Design for bulk manufacture of "off-the-shelf" high power accelerators for exportable ADSR systems will also create a rich source of IP and keep existing IP in the projects portfolio alive through regeneration.

### 4.7 Technological opportunities and benefits available in other fields

Globally there are over 15,000 particle accelerators in operation. Only one hundred or so of these are used in fundamental physics applications, i.e. in the field with which they are most commonly associated. Indeed accelerators are found in areas as diverse as manufacturing industries (e.g. ion beam implantation and lithography) through to medical

applications (cancer therapy and isotope production). Although the research and development programme outlined in this report has, as its final goal, a fully functional thorium-fuelled ADSR power station, the spin-offs, synergies, opportunities and benefits to both related and unrelated technological areas are manifold (see, e.g. Figure 13).

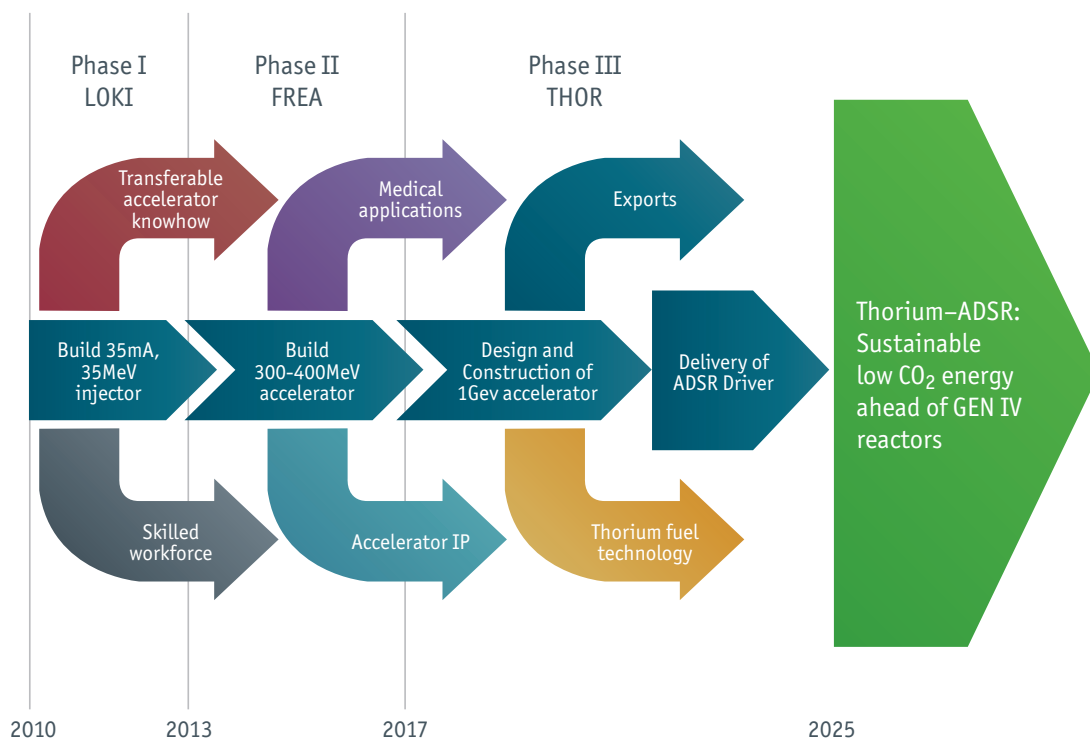


Figure 13. Benefits from the ADSR research programme along the experimental path are multiple



### 4.7.1 Medical applications

Both ADSR systems and medical facilities for proton and heavy ion cancer therapy require particle beams of similar energies. The principal differences, however, are that ADSR accelerators must produce a much higher power (i.e. higher current) proton beam, but do not require quite the flexibility and delicacy in proton extraction as the medical accelerators. IP that addresses the handling of high currents therefore will not spill into the medical sector, whereas that concerned with reliability and, especially, with beam monitoring may well do so. For medical applications it is of paramount importance to know what current (and therefore patient dose) is being delivered, and the diagnostic instrumentation to be developed for ADSR and therapy accelerators are similar.

### 4.7.2 Spallation physics

High intensity proton beams coupled to spallation targets are a highly efficient route to producing intense neutron beams. STFC's ISIS has been at the vanguard of this technology since 1985, producing some of the world's most powerful beams for studies of the structure and dynamics of matter. In 1994 The OECD Megascience Forum predicted a neutron drought, and later recommended the construction of MW class spallation sources (rather than advanced nuclear reactors) in each of the world's regions. The US and Japan have both responded to this call and are currently commissioning the \$1bn 1.5MW SNS and 1MW J-PARC facility respectively. The US already plans an upgrade to 3MW, whilst Europe is still debating its 5MW 1.3 b€ European Spallation Source (ESS) to be sited in Lund, Sweden: both require accelerator and spallation technology not far removed from the planned ADSR driver/target system discussed here. The technology developed as part of this programme could dramatically reduce the cost and increase the efficiency of such spallation sources opening the way for much wider global deployment of this detailed non-destructive fine analysis of materials and their functionality in the fields of physics, chemistry, biology, engineering, pharmacology, geophysics and even archaeology.

### 4.7.3 Transmutation research

The management of radioactive waste is a key issue in the public's perception of nuclear power. The belief that public acceptance may be more easily obtained if the isolation time required for the decay of high level nuclear waste can be reduced to the order of a few hundred years has motivated much research into the partitioning and transmutation (P&T) of such waste. It is in principle possible to reduce the radiotoxic lifetimes of important fission products and actinide wastes by transmuting them into short-lived or

stable nuclei in a fission reactor or an ADSR. Potentially this would obviate the need for geological disposal of nuclear waste arising from commercial power generation and from nuclear weapons programmes.

The main arguments in favour of P&T are that:

- by burning actinides the long-term requirements of final disposal stores are much reduced both in terms of volume and timescale, with both economic and public acceptance benefits;
- the minor actinide waste that undergoes fission becomes an additional source of energy;
- by closing the fuel cycle and recycling the major actinides (U and Pu) and Th much greater use is made of the world's U and Th resources.

The main arguments against P&T are that:

- the inclusion of highly radioactive transuranics makes fuel fabrication more difficult and hazardous;
- many of the technologies and materials involved are proliferation sensitive;
- although transmutation reduces the volumes of high level nuclear waste, it increases the volumes of medium and low level waste.

A number of research programmes investigating transmutation using accelerator-driven systems have been established, including the European Framework EUROTRANS project, the OMEGA programme in Japan and the Accelerator-Driven Transmutation of Waste (ATW) programme in the USA (Appendix IV). Accelerator-driven transmutation appears to offer the potential to yield higher burn-ups than those achievable in fast reactors and to transmute actinides more quickly.

Although much work has been done in this area there still remains much to do. Most of the transmutation research to date has focused on the U-Pu fuel cycle, rather than transmutation within the context of the Th-U cycle. There are currently no facilities capable of performing integrated testing of an accelerator-driven spallation target and a subcritical multiplication system at real power. However, there are plans for such a facility in France and elsewhere. The R&D programme described here would provide a facility for the demonstration of an integrated system performance and an appropriate combination of high-energy protons, spallation neutrons and fission neutrons for testing fuels and materials. There is scope for new IP to arise from the more detailed study of transmutation as part of a closed Th-U fuel cycle and from the experimental development and demonstration of the technology.



Chapter 4: Value Capture and IP: from ADSRs to Medicine and beyond *continued*

#### 4.7.4 Transmutation of waste

There are three distinct classes of “waste” for which transmutation in a thorium-fuelled ADSR might be considered:

- Plutonium arising from decommissioned nuclear weapons;
- Legacy wastes arising from past partitioning activities;
- New wastes arising from continuing nuclear power generation if a closed-cycle strategy is followed in the future.

Plutonium can be used directly as fissile material, alongside bred U-233, in a thorium fuelled ADSR, and thereby burnt or transmuted. It should be noted, however, that transmutation can also be effected by burning plutonium as a component of Thorium-based mixed oxide (MOX) fuel in suitable conventional reactors.

The waste arising from the reprocessing of spent fuel can be subdivided into two categories:

- Minor actinide (MA) waste (isotopes of Am, Np, Cm). (ADSRs are much preferred to critical fast reactors for this application, because of the unfavourable neutronics associated with MAs in the latter);
- Long-lived fission fragments (LLFFs). (Effective transmutation of some LLFFs may require a non-fast neutron spectrum to take advantage of high capture cross-sections in the resonance or thermal regions).

Various so-called multi-tiered approaches to waste transmutation strategies have been proposed, using different combinations of conventional and accelerator-driven reactors to manage specified wastes. Thus, there are potentially a range of options to be considered if the waste transmutation option is pursued.

In addition to developing the capability to manage UK-produced nuclear waste, there is the opportunity to export the technology and know-how. There is a further potential business opportunity, albeit a potentially contentious one, in which the UK could process various forms of waste from other countries in ADSRs. The business cases for using ADSRs (or alternative technologies) to manage these “waste” streams differ.

Legacy wastes and Pu arising from decommissioned weapons exist and have to be dealt with somehow. Arguments in favour of transmutation can be made on environmental (significant reduction of radiotoxic lifetimes), political (especially in respect of eliminating Pu) and, potentially, economic grounds.

Transmutation of waste yet to be produced is only an option if a commitment is made to closed-cycle reactor operation. Arguments in favour of future closed-cycle operation can be made on sustainability (much greater utilisation of natural resources), environmental (as above) and economic grounds, particularly in scenarios where the price of uranium or thorium increases significantly due to market forces. Note that it can be estimated that it currently costs the UK of the order of £100m to manage (in perpetuity) the waste arising from each year’s operation of our existing nuclear power stations. It is notoriously difficult to assess reliably the economics of reprocessing nuclear fuel, with studies tending to support the political positions of the government or organisation by whom they were commissioned.



#### 4.7.5 From megatons to megawatts: Weapons decommissioning

Since its development for commercial purposes, civil nuclear power has raised concern about its diversion for military purposes and the threat of nuclear weapon proliferation. However, since the end of the Cold War attention has shifted towards the use of military uranium as a source of fuel for commercial nuclear reactors. Since 1987 the United States and countries of the former USSR have signed a series of disarmament treaties to reduce the nuclear arsenals by about 80%.

Fissile nuclear materials can be converted into nuclear fuel, since the main material is highly enriched uranium (HEU), containing about 90% U-235. HEU can be blended with natural uranium (0.7% U-235) to produce commercial reactor-grade nuclear fuel. The global stockpile of HEU amounts to 2,000 tonnes, equivalent to twelve times annual world mine production. World stockpiles of weapons-grade plutonium are reported to be some 260 tonnes, which if used in mixed oxide fuel in conventional reactors would be equivalent to over a year's world uranium production. As previously mentioned, military plutonium can be blended with uranium oxide to form MOX fuel.

After low-enriched uranium (LEU) or MOX is burned in power reactors, the spent fuel is not suitable for weapons manufacture. Since the late 1980s and by 2009 a total of 367 tonnes of HEU had produced some 10,621 tonnes of low-enriched fuel, equivalent to 14,686 nuclear warheads.

Using Thorium-based fuels to eliminate weapons-grade nuclear material presents significant advantages over the use of MOX: such system is significantly more proliferation resistant, the fuel can be easily made with existing technology and a lot more plutonium can be put into a single fuel assembly than with MOX, so that three times as much can be disposed of as when using MOX, at a much faster rate. Finally, the spent fuel amounts to half the volume of MOX and is even less likely to allow recovery of weapons-useable material than spent MOX fuel, since less fissile plutonium remains in it. Since the 1990s, Russia has had a programme to eliminate its nuclear stockpile through Thorium-based fuels.

Since 1996, the UK has been systematically reducing its nuclear weapon stockpile, from 300 warheads (about 45

tonnes of weapons-grade material; of those, 70% HEU and 330% Pu) to "less than 200" by 2001. Current plans aim at a further 20% reduction to 160 warheads. This implies a total of approximately 20 tonnes of weapons-grade material to eliminate, not including the upgrade to UK's nuclear arsenal.

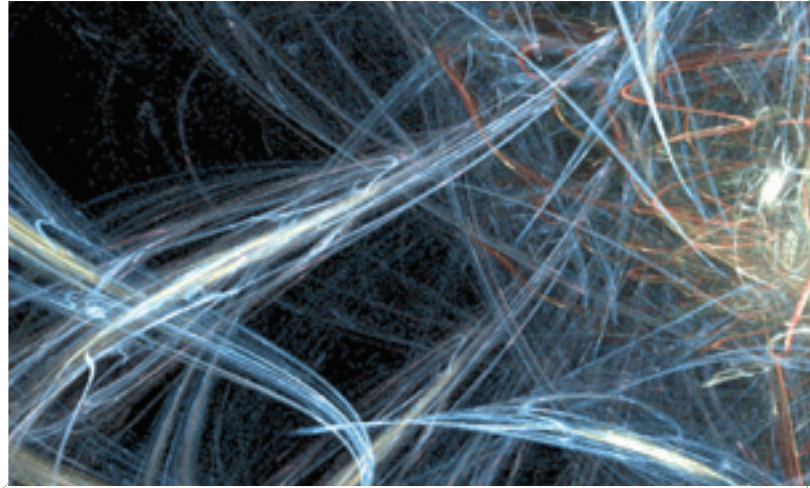
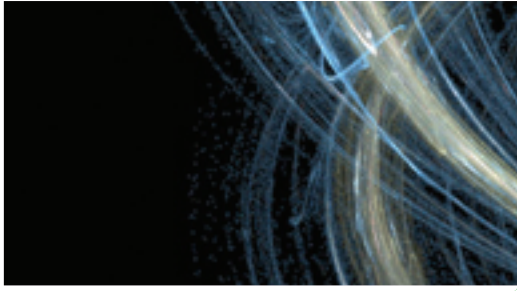
This nuclear material could be incorporated in ADSR fuel, and thereby effectively eliminated UK's. Given the very low fraction of plutonium and higher actinides produced in the thorium fuel, and the ADSRs fuel flexibility, weapons-grade material could serve as a seed for the breeding process, with concentrations being reduced to marginal and non-weapons grade amounts.

Additionally, the UK would be developing a system to effectively eliminate military nuclear stockpile for other countries such as the US and former Soviet states. ADSR technology could help to eliminate such material producing electricity as a by-product.

#### 4.7.6 Opportunities for hydrogen production

High temperature reactor (HTR) systems operating at above 750C are possible process heat sources for thermo-chemical hydrogen production using the sulphur iodine cycle. HTR systems pose particular materials challenges as neither austenitic or ferritic martenistic are suitable at such high temperatures (e.g. problems of cyclic softening). Oxide Dispersion Strengthened (ODS) steels may be suitable for high temperature nuclear applications, but much further work is required and it is noteworthy that no European facility exists for the bulk production of ODS steels. Much useful work will be done by those working on critical HTR research.

Alternatively hydrogen can be produced by electrolysis. High temperature steam electrolysis is especially attractive. Such capabilities could complement the intrinsic flexibility of a Thorium ADSR power station. Such flexibility and the ability to load follow with grid supplied power is likely to be of great importance in future decarbonised electricity systems comprising renewables and nuclear power.



## Chapter 5: The economics of thorium-fuelled ADSR technology

The returns on investment in an R&D programme to deliver thorium fuelled ADSR technology are diverse and manifold and include, for example, cost competitive low carbon electricity, export of IP and facilities, inward investment, education and training, skilled workforce, new businesses, new products and service, regional development & UK reputation and leadership. Some of these benefits are discussed in this Appendix.

### 5.1 ADSRs as a cost competitive, low carbon technology

ADSRs excel when considering social and environmental benefits such as diversifying the fuel mix, reducing radioactive waste products, increasing proliferation resistance and avoiding carbon emissions. However, alongside these benefits it is necessary that ADSRs are cost competitive with alternative forms of electricity generation. The following preliminary cost benefit analysis indicates firstly, how an  $n^{\text{th}}$ -of-a-kind 600MW<sub>e</sub> ADSR competes with a contemporary  $n^{\text{th}}$ -of-a-kind 600MW<sub>e</sub> uranium cycle nuclear power station, and secondly calculates the carbon price above which ADSRs outperform gas fired power generation. In the analysis both conventional Linac and ns-FFAG driven thorium fuelled ADSRs, are considered.

The study is an extrapolation from the analysis performed by (Kennedy, 2007). It is assumed that the cost of a uranium cycle power station is the same as that of an ADSR, except for fuel and accelerator costs. Costs are divided into six categories: capital expenditure for the nuclear power station (Nuclear CapEx) and the accelerator complex (Accel. CapEx); Fuel; Operations and Maintenance for the nuclear power station (Nuclear O&M) and the accelerator complex (Accel. O&M); and finally the geological disposal and site decommissioning funds.

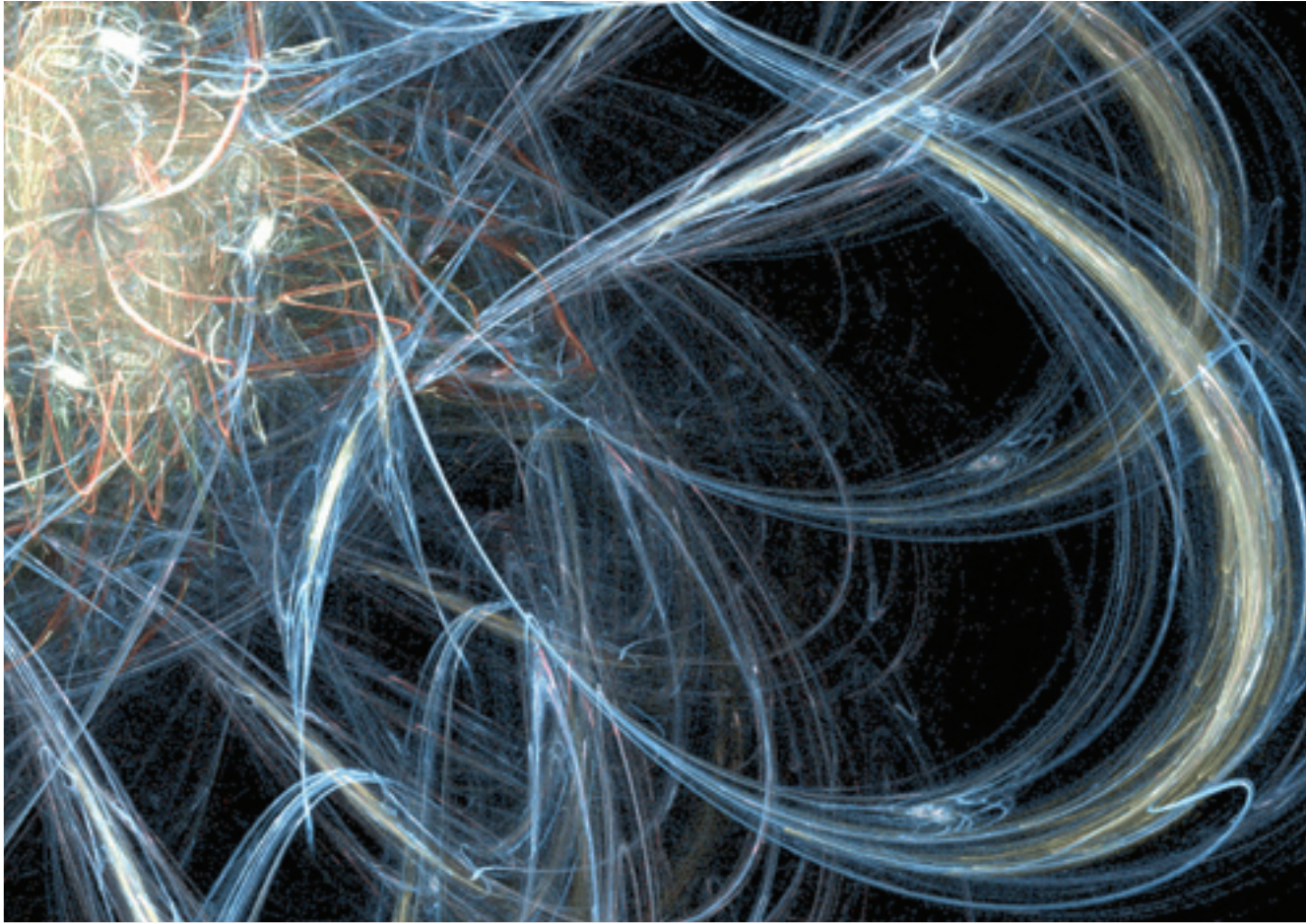
The LINAC accelerator complex cost is based on predictions performed under the Euratom programme (European Commission, 2001). A 600MeV 20mA accelerator is predicted to cost €210 million, assuming zero cost increase for cryogenics, the superconducting LINAC cost has been linearly scaled (Ruggiero, 1997), accounting for increasing the beam energy from 600MeV to 1 GeV. This gives cost of construction of €290 million (excluding the cost of financing) for a LINAC accelerator complex. An exchange rate of €1=£1 has been used. Preliminary projections indicate that the cost of ns-FFAGs will be £60 million (excluding the cost of financing). It is considered that it might be advantageous to employ three ns-FFAGs to drive an ADSR. Accelerator O&M costs for LINACS and ns-FFAGs are derived from those reported by the existing high-powered accelerator facilities, the Spallation Neutron Source at Oak Ridge and the European Synchrotron Radiation Source.

The added costs of the accelerators are estimated to be £14/MWh for a LINA and £10/MWh for the ns-FFAG option.

In terms of the fuel costs, uranium mining makes up approximately a quarter of the uranium cycle fuel cost (WNO, <http://www.world-nuclear.org/info/inf22.html>). It requires enrichment, which accounts for approximately 50 % of the uranium cycle fuel cost (WNO, <http://www.world-nuclear.org/info/inf28.html>); the remaining fuel cost is dominated by fuel rod fabrication. The efficiency of the thorium once-through fuel cycle is greater than for uranium. Over 8 times more uranium ore is required per MWe of electricity produced compared to thorium (Bryan, 2009). Thorium does not require enrichment. The contemporary uranium fuel cycle costs £3.9/MWh, thorium is expected to cost only £1.1/MWh.

The savings associated with a thorium fuel cycle therefore amount to almost £3/MWh.





For an operational lifetime of 40 years and a real discount rate of 10%, the levelised cost per MWh for nth-of-a-kind uranium cycle, LINAC and ns-FFAG ADSR nuclear power stations are presented in the below figure. The analysis shows that a LINAC ADSR costs £12 /MWh more than a uranium cycle nuclear power station. The ns-FFAG design is predicted to achieve a £4/MWh cost saving over the LINAC accelerator, making it £7/MWh more expensive than the uranium cycle, at current uranium prices.

A cost comparison of the thorium ADSR and conventional uranium systems is shown in Figure 14. This comparison would of course be significantly modified if:

- ◆ The predicted escalation of uranium prices over the coming decades;
- ◆ A potential reduction in the cost of accelerator drivers are taken into account.

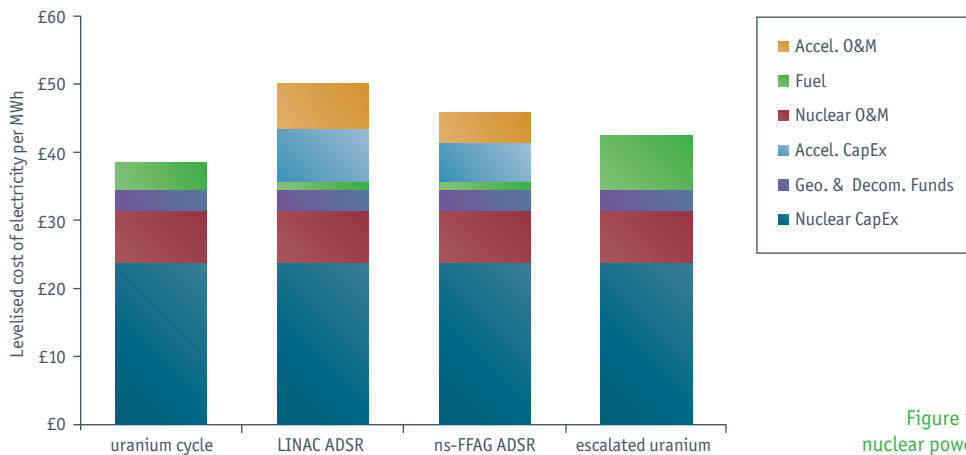


Figure 14. Cost structure for different nuclear power options, per MWh produced.

During 2004–2008, inclusive, the average spot price of uranium was \$113/kgU (2006 prices). This is over double its price from the preceding 20 years, \$46/kgU (2006 prices). The report: “Uranium 2007: Resources, Production and Demand” (ref: OECD, International Atomic Energy Agency. Published by: OECD Publishing) finds that, at 2006 consumption rates, the supply of uranium that can be extracted for a price of <\$130/kgU is sufficient to last 100 years. However, it has been predicted by the IAEA that the world nuclear capacity will raise into the range 473–748 GWe by 2030 (ref: IAEA bulletin :<http://www.iaea.org/Publications/Magazines/Bulletin/Bull50150104722831.pdf>).

Assuming that new power stations consume mined uranium at a rate equal to existing ones, this suggests that all of the <\$130/kgU uranium will have been consumed by 2061–2086 (see figure 15 below). The inflexibility of nuclear fuel consumption may mean that an aggressive world-wide nuclear build will cause demand to exceed supply. The predictability of nuclear fuel consumption may cause pre-emptive price escalation. Assuming that uranium price increases by a factor of five beyond 2030 compared to contemporary prices, the cost per MWh for fuel will increase by £4/MWh. The expected cost per MWh of electricity generation for a uranium cycle generator beyond 2030 in a uranium price-escalated scenario is presented in the above figure. It indicates that in a world where uranium demand exceeds supply, thorium fuelled ADSRs will be economically competitive.

What has not been factored into this cost comparison is the observation that estimated costs of both the Linac and ns-FFAG accelerators have been taken from existing build programmes. These costs are based upon one-of-a-kind prototypes. It might be expected that production models of both accelerator types could cost significantly less than such prototypes.

**It is apparent that in an expanding nuclear market thorium fuelled-ADSR and conventional nuclear systems are cost competitive.**

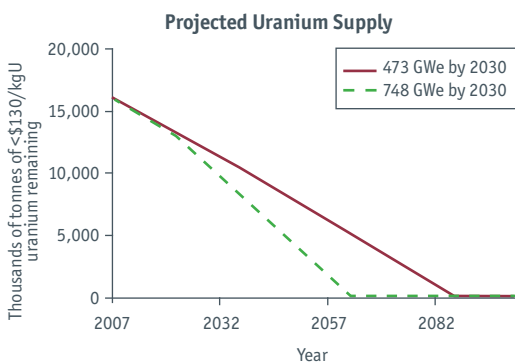


Figure 15. Global uranium reserve decrease for the two different IEA (IEA, 2007) global energy mix scenarios.

The competitiveness of Generation III+ nuclear power has previously been compared to gas powered electricity generation by D.Kennedy (ref: Kennedy, *Energy Policy*, 35, 2007, 3701). In D.Kennedy’s study a range of gas and nuclear production costs are considered (Low, Central and High). In each scenario the minimum price of carbon for which ADSRs become more profitable than gas powered electricity has been identified. For the current analysis, ns-FFAG ADSRs are compared to gas. The carbon price is identified for which ADSRs are more competitive than gas, this has been calculated for all combinations of the cost scenarios, see the figure below. Figure 16 shows that, for example in the central nuclear and central gas costs scenario, ADSRs are more profitable than gas when the carbon price exceeds €43/tCO<sub>2</sub>.

In conclusion, and aside from the social and environmental benefits associated with ADSRs, the technology has the potential to become independently economically competitive with other nuclear and alternative forms of energy generation. This independent competitiveness requires a future where the widely anticipated commitment to CO<sub>2</sub> pricing is sustained over the 21<sup>st</sup> century, and also that the recent world-wide renaissance of nuclear power generation, causes the demand for uranium to exceed production rates.

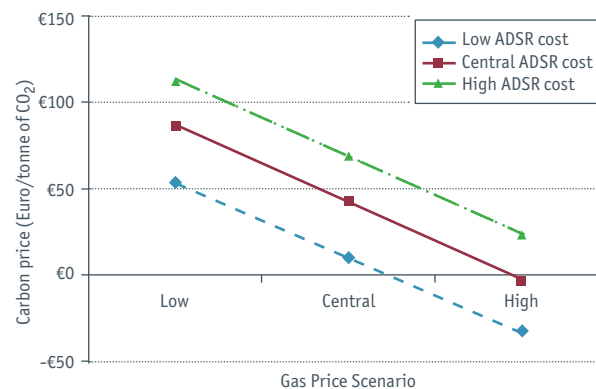


Figure 16. Switching costs for varying gas prices/carbon prices/ADSR costs.

## 5.2 Inward investment

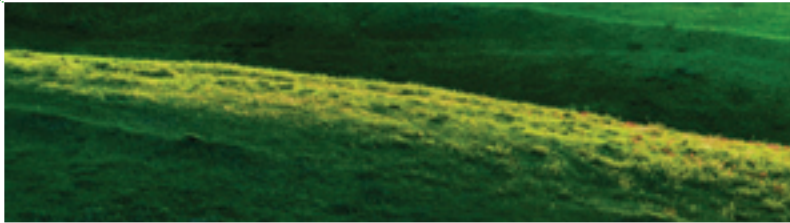
The delivery of a thorium based ADSR system in advance of conventional Generation IV reactors would place the UK at the forefront of nuclear energy generation. Such international leadership will inevitably result in inward investment opportunities for the UK. Indeed, the proposed accelerator-based technology outlined in this report has already generated considerable interest from the Norwegian owned engineering company Aker Solutions which has a UK base in the North East of England. Aker Solutions level of commitment to develop a thorium fuelled ADSR is significant and the company has indicated that if suitable partners can be found (public or private), it would aim to design, build and commission a full-scale reactor within the UK by 2030.

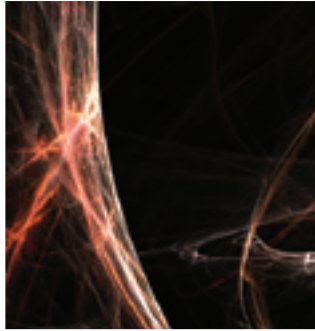
Aker Solutions is in the process of seeking development partners within the UK including accelerator science and technology developers, as well as industrial partners from the nuclear engineering sector. If such a reactor was to be built, Aker Solutions has indicated that the UK would be a preferred location. This level of engagement already demonstrates the potential inward investment opportunity which the project would attract, from both the nuclear reactor perspective and the leading-edge platform technologies which would have to be developed to achieve the ambitious aims detailed in this report.

## 5.3 Regional development

The regional development agency Yorkshire Forward, at the request of the then Science Minister, Lord Sainsbury, commissioned a report by Arthur D. Little on the economic impact of large scale facility, i.e. the European Spallation Source, on the Yorkshire region, (Little, 2005). The socioeconomic analysis showed that not only did the majority of the investment stay within the region during construction, a large percentage also remained during operation. The on-going benefit and legacy was found to be many multiples of the investment with a 'cluster' of companies following such investment. The report demonstrates this through reference to other large scale projects around the world (SNS – USA, ANSLS – Australia, CLS – Canada).

Given that the culmination of the AESIR accelerator development programme would be a "large scale facility" similar in scope and application to those at TRIUMF (Vancouver, Canada) and PSI (Villigen Switzerland) the socioeconomic advantage to the host region could be significant, although Little cautioned that such benefits would be much reduced if the facility was located in an economically heated region (e.g. the Thames Valley).





Chapter 5: The economics of thorium-fuelled ADSR technology *continued*

**5.4 Public acceptance of nuclear power**

One of the political challenges of climate change is that although nuclear power is clear an option for reducing carbon emissions, it is unpopular with the electorate. There is still considerable opposition to nuclear power in the UK. Climate change is pressing some towards ‘grudging acceptance, however there is a long way to go before the nuclear option is widely welcomed. Depending on the path taken (once-through vs reprocessing and pure thorium vs enriched fuel) thorium fuelled ADSR has the opportunity to be marketed as a distinctly better technology; lower risk, waste reducing and proliferation resistant; in many respects thorium-fuelled ADSR technology could be ‘the acceptable face of nuclear’.

**5.5 UK reputation and leadership**

For a small island on the edge of Europe the UK holds a significant position in the world. Politically the UK has considerable international influence, commercially it strong (is still the 6th largest economy globally (International Monetary Fund, 2009), and is the world’s 9th largest exporter (CIA).

There are clearly both historical reasons for this (natural resources, technological leadership gained during the industrial revolution) and more recent developments (the dominance of English as the international language of commerce and politics, for example). However, if Britain is to maintain its position of strength there is a need to create new wealth in ways aligned with the 21st century. Innovation is a key driver of future success yet this is an area where the country is not currently excelling. The World Economic Forum’s ‘Global Competitiveness Index’ (World Economic Forum, 2008) assesses the Innovation capabilities of countries using seven criteria, see Figure 17.

12th pillar: Innovation		
12.01	Capacity for innovation	14 ■
12.02	Quality of scientific research institutions	7 ■
12.03	Company spending on R&D	12 ■
12.04	University-industry research collaboration	9 ■
12.05	Gov’t procurement of advanced tech products	32 ■
12.06	Availability of scientists and engineers	32 ■
12.07	Utility patents	18 ■

Figure 17. The UK’s ranking in the components of the 12<sup>th</sup> pillar of innovation (World Economic Forum, 2008)

Although the ‘Quality of scientific research institutions’ and ‘University-industry research collaboration’ are commensurate with the UK’s economic standing the UK is lagging in areas critical to the future; the ‘Availability of scientists and engineers’ and ‘Utility patents’ (the number of patents per m population) are judged to be poor.

These, and other indicators, would be greatly improved by a large scale innovative R&D programme such as that proposed for the thorium fuelled ADSR systems. This would not only strengthen the UK economically, but keep it at the forefront in areas that are becoming ever more critical politically – energy, carbon reduction and the scientific innovations that will lead to the solutions the world is waiting for.

Much of the above is predicated on the UK securing a position at the forefront of the technological innovation. Once others have developed the technology, and secured the IP, the UK will have lost the lead at which point much of the value could be lost. This is more than a “make vs buy” situation, it is a unique “make, patent and sell vs buy” opportunity.

## Chapter 6: The way forward

In this report the significant scientific, technological, environmental and economic benefits of a nuclear future in which thorium-fuelled ADSR systems play a significant role have been considered and discussed. The report presents a comprehensive assessment of the commercial opportunities and advantages available to the UK in pursuing a world-lead in thorium-fuelled ADSR technology. It also introduces a UK roadmap for securing such a lead, and addresses the challenges associated with realising the enabling science and technology necessary to underpin this secure, stable-priced, low-carbon and proliferation resistant nuclear energy option for the future.

The principal conclusions of the report are:

1. Accelerator Driven Subcritical Reactor systems are a realistic, achievable and cost effective near- to mid-term technological alternative to conventional current and future nuclear fission reactors for power generation, offering potential deployment as early as 2025. Operating in a subcritical configuration, ADSR systems may additionally afford intrinsically wider safety margins than those of current and proposed critical reactors.
2. The ADSR principle is ideal for exploiting the relatively untapped potential of fertile thorium as a nuclear fuel. Thorium presents numerous advantages over uranium as a sustainable fuel for power generation: it is abundant in nature, needs very little processing, and plutonium is absent from a low waste thorium fuel cycle which is intrinsically proliferation resistant.
3. Thorium-fuelled ADSR technology will command a pivotal role in a rapidly expanding global energy market charged with significantly reducing carbon emissions. The technology promises an environmentally acceptable, inexhaustible source of nuclear energy. Moreover, this technology, because of its intrinsic proliferation-resistance, could sustain a multibillion pound international nuclear export market from which both conventional uranium- and plutonium-based nuclear technologies have been historically excluded.
4. Although the ADSR concept is not new, it has not advanced beyond simple technical demonstrations and no functional ADSR energy source has yet been developed. This is a consequence of identifiable and rectifiable limitations of the underpinning technology, notably those associated with the reliability of appropriately powerful proton drivers based on current accelerator technology.
5. The UK has a particularly strong and experienced accelerator science and technology base. Indeed, recent developments in advanced and innovative accelerator concepts, such as those promoted by the CONFORM project (funded by the Research Councils UK (RCUK) Basic Technology Programme) and by other advanced linear accelerator developments supported by STFC, place the UK in a unique and timely position to seize the initiative in progressing ADSR proton driver technology to the point of deployment. If accompanied by a parallel optimisation of complementary ADSR technologies (e.g. spallation neutron targets, reactor core design and thorium fuel cycles, all of which draw upon existing and acknowledged UK strengths) such an initiative would secure a UK global lead in ADSR design and the potential for the UK to deliver ADSR systems within fifteen to twenty years.
6. An extensive and coherent research and development (R&D) programme could secure all underpinning technology necessary to facilitate construction and operation of the world's first thorium-fuelled ADSR power station by 2025. In order to achieve this, the R&D strategy should ensure that several technological options are incorporated and evaluated from the start, with the whole programme reviewed at specific key points to ensure a smooth route to a timely and simultaneous delivery of all final project objectives.
7. It is apparent that such a UK thorium/ADSR R&D programme should be established as a matter of urgency, enabling the programme to capitalise upon the momentum of the CONFORM accelerator programme and other UK advanced accelerator programmes. R&D will build directly upon UK scientific and technological leadership afforded by, for example, The Cockcroft Institute (national centre of excellence for accelerator science), The National Nuclear Laboratory, STFC and its laboratories, and recognised academic HEI expertise in nuclear physics and chemistry, accelerator science, and materials science. Additionally the programme would aim to engage as partners key industrial companies which have already expressed specific interest in such R&D and its stated goals (e.g., Aker Solutions, Siemens).
8. The route to the design and deployment of functional thorium-fuelled ADSR power generation systems is not without challenges. It is therefore inevitable that an R&D programme focused upon meeting these challenges will generate a plethora of innovative technology. Indeed, IP has been identified as a significant value capture mechanism for the programme: it is anticipated that a suitably focused R&D effort would generate up to twenty patents per year. Additionally, the development of processes, know-how, skills and experience would also be highly valuable, consolidating a considerable competitive advantage in new ADSR and associated industries for the UK. (It is noted that a patent already exists on the underlying ADSR, or energy amplifier (EA), concept, but that this patent will have expired well before the anticipated deployment of the first ADSR system.)
9. Whilst the proposed programme is aimed specifically at meeting global requirements for clean, sustainable electricity generation, ADSR-related technology developed through the programme has synergies and applications in other fields, including heavy ion cancer therapy, medical isotope production, weapons decommissioning and nuclear waste management. IP may emerge from these ancillary applications. Additionally a project of this scale has both direct and indirect socioeconomic benefits for the UK as a whole and for the region in which it is located.



## Chapter 6: The way forward *continued*

There is a compelling case for the UK to invest now in the R&D to secure the technology necessary to build the world's first fully operational thorium-fuelled ADSR power station by 2025. Such an investment builds upon existing and acknowledged UK strengths in accelerator development, spallation physics and nuclear science.

The commercial advantages of such an investment to the UK are:

- Global leadership in an advanced nuclear technology;
- A reinvigoration of Britain's nuclear industry;
- The capture of IP and knowhow from nuclear and other innovations (e.g. in medicine);
- The creation of an export market for nuclear power stations, which would include those regions historically closed to the export of conventional fission reactors;
- A shift from nuclear dependency on uranium (a limited resource) to thorium (an unlimited resource).

The environmental advantages include

- A new and sustainable route to low carbon energy;
- A nuclear technology in which the reactor operates well below criticality levels;
- A nuclear fuel cycle which does not include plutonium as either fuel or waste;
- A fuel cycle with relatively low radiotoxic and low volume waste;
- A system which can potentially burn legacy plutonium and minor actinide waste as fuel;
- A system which is intrinsically proliferation resistant.

Not only is this vision for a future energy source entirely commensurate with the goals of the Government's "Road to 2010" and preceding 2008 White Paper on nuclear power "Meeting the energy challenge", it also exploits science and technology in which Britain has a clear competitive advantage and provides significant opportunities for growth over the next two decades.

Analysis suggests that this can be achieved by a public investment of £300m over 5 years. The investment would fund an extensive R&D programme in advanced accelerator technology, spallation physics, reactor core design and thorium fuel cycles in collaboration with higher education institutes, national laboratories (e.g. the National Nuclear Laboratory) and private industry.

The programme would progress as a public-private partnership, managed by a limited company (ThorEACo) which would be responsible for delivering the technology, capturing IP and subcontracting and commissioning additional R&D where appropriate. It is envisaged that in the initial phases the research and development programme would be sourced principally from public funding and as the appropriate ADSR knowledge and technology become available for exploitation and transfer, private funding would increase, and pay for the design and ultimately the construction of a 600MWe thorium fuelled ADSR power station ready which could be ready for commissioned and ready for operation by 2025.

By this time the UK will lead the world in thorium-fuelled ADSR technology and will be poised to benefit from a multibillion pound market for that technology.



## Appendix I: ADSR Accelerator Requirements

### A1.1 Proton beam energy

The average number of useful spallation neutrons produced in a collision depends on the energy of the incoming particle. (It also depends on the nature of the incoming particle, the target nucleus, and the target geometry, but for the present purpose we will assume that protons are used, and the target will be chosen and optimised in later studies). The number of neutrons produced per unit beam energy is fairly flat at 1 GeV and above; below 1 GeV this number decreases rapidly.

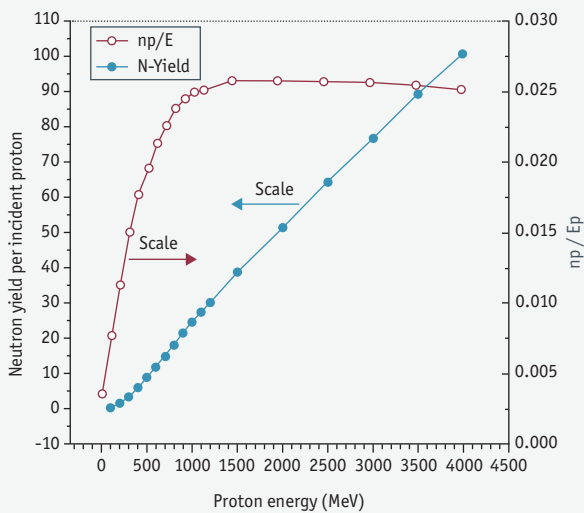


Figure 18. Neutron yield from protons of a given energy impacting a lead spallation target

Although doubling the energy would facilitate operation of the accelerator driver at half the proton beam current, higher currents are, broadly speaking, easier to achieve than higher energies. Correspondingly, halving the proton energy would require approximately four times the beam current to produce the same number of spallation neutrons, and the difficulties in operating at these currents would outweigh the gains. 1 GeV as therefore an appropriate design energy for a proton driver for an ADSR.

### A1.2 Beam current and power

The thermal power output of an ADSR ( $P_{th}$ ) generated by the can be calculated quite simply from the effective criticality,  $K_{eff}$  ( $<1$ ) of the core, the energy released per fission  $E_{eff}$  ( $\sim 200$ MeV), the mean number of neutrons released per fission  $\nu$  ( $\sim 2$ ) and the number of spallation neutrons per second,  $N$ , produced by the proton driver:

$$P_{th} = \frac{N \times E_f}{\nu} \cdot \frac{K_{eff}}{1 - K_{eff}}$$

For a thermal power output of 1550MW, equivalent to an electrical power output of  $\sim 600$ MW the number of spallation neutrons required,  $N$  is therefore:

$$N = 9.6 \times 10^{19} \cdot \frac{1 - K_{eff}}{K_{eff}} \quad \text{neutrons per second}$$

Given that a 1 GeV proton discussed in the previous section produces 24 spallation neutrons (in a lead target), we can therefore estimate the required proton beam current necessary (in milliAmps) to generate 1550MW thermal power for a given ADSR core design with effective criticality of  $K_{eff}$ , as shown in the graph in figure 19.

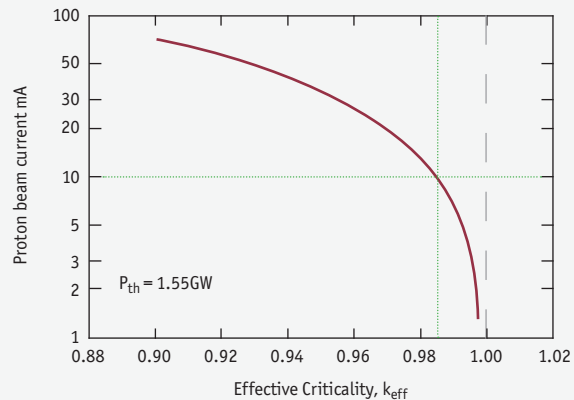


Figure 19. The current (in mA) of a 1 GeV proton beam necessary to generate 1550MW thermal power in a thorium-fuelled ADSR as a function of the effective criticality parameter  $K_{eff}$ .

It can be seen that if the ADSR operates at safe effective criticality of 0.985, then a proton current of 10mA is required to produce a thermal power of 1550MW. With a beam energy of 1 GeV, this implies an accelerator power of 10MW.

It should be noted that, for an effective criticalities closer to unity, a substantially reduced proton beam current, and hence beam power could be deployed.

Although a 1 GeV, 10 mA (10MW) proton accelerator has yet to be built, such a design is not far beyond the limits of existing machines. The PSI cyclotron delivers 2 mA at 590 MeV, (1.2 MW). The ISIS synchrotron delivers 0.2 mA at 800 MeV (0.16MW). The US Spallation Neutron Source (SNS), currently being commissioned at Oak Ridge National Laboratory is designed to deliver 1.4 MW of 1 GeV protons, and there are already firm plans to increase this design performance to 3MW. The initial design of the European Spallation Source was initially planned to deliver 10 MW (at 1.3 GeV) into two spallation targets, but the more recent and more modest design accepted by ESFRI for their European Large Scale Facilities Road Map, plans to deliver 5MW of beam power into a single lead-based liquid metal spallation target.



### A1.3 Accelerator reliability

Accelerator drivers for ADSR systems must meet stringent reliability requirements. If the beam current stops for any reason then heat-generating fission reactions will also cease, and the loss of a thermal output of up to 1.5GW could result in a matter of milliseconds. Such thermal transients will produce stresses in components of the spallation target and ADSR core sub-structures which could lead to mechanical failure. While such effects can be mitigated by appropriate design considerations it is clear that repeated beam loss must be minimised.

The effects of beam loss are not restricted to engineering considerations. If the accelerator beam loss is sufficiently long to affect the electrical output from an ADSR power station then this will have severe financial consequences for the generating company who, to fulfil contractual obligations, will have to find alternative supplies of electricity on the open market to cover their contracts to sell. The price premium for this is typically prohibitive. Outline estimates suggest that an ADSR accelerator should not be permitted to trip more than a few times in every year. This is some way beyond the performance even of well-established and well-understood accelerators.

Nevertheless reliability can be achieved: although an accelerator is a complicated machine it is no more so than, for example, commercial airliners, which out of necessity are engineered to achieve the highest standard of reliability. Nevertheless a similar reliability analysis cannot readily be applied to accelerators: whilst the overall reliability of an accelerator might exceed, say, 99%, a 1% down time might not be a serious concern if it corresponded to a single extended beam loss, but could result in serious mechanical damage from thermal cycling if it corresponded to frequent short (ms) periods of beam loss.

Whilst not aggressively applied to accelerators, which are currently designed for ultimate peak performance rather than absolute reliability, there are standard techniques for achieving reliability through engineering: redundancy, under-rating components, graceful failure, and planned preventative maintenance. Such techniques are all costly and it is vital to understand the complete accelerator system and ensure that reliability engineering is used where appropriate.

Fortunately a wealth of data has been collected on the performance of numerous existing accelerators throughout their lifetime, and from their operational characteristics the likely causes of failure and how to prevent them can be ascertained and ameliorated.

The current generation of linear accelerators (linacs) and cyclotrons are not sufficiently reliable for deployment as ADSR drivers, although a substantial R&D programme, such as that outlined in this report, would be expected to deliver appropriate reliability parameters. It may well be more productive to focus R&D resources on the development

of Fixed Field Alternating Gradient (FFAG) accelerator technology which, although still at an early stage of development, promised to deliver more reliable, cheaper and more compact accelerator systems. This would have the advantage of not only providing an intrinsically more reliable driver, but also of providing an opportunity to use several lower current 1 GeV drivers to spallate neutrons from multiple distributed targets with the core, thereby considerably minimising the effects of a transient beam loss associated with a single driver.

### A1.4 Considerations of potential acceleration technologies for ADSRs

#### Cyclotrons

The classical cyclotron – as originally conceived and built by Ernest Lawrence – is restricted to operation at non-relativistic energies where the revolution frequency is constant. Simple cyclotrons can only accelerate protons to energies much less than the proton rest mass of 938MeV, and 1 GeV cannot be reached.

Variants of the cyclotron principle, for example the separated-sector method, may be used to increase the output energy somewhat: the SINQ cyclotron at PSI attains 590 MeV. Nevertheless, although cyclotron technology is mature, appropriate designs to take energies as high as 1 GeV have proved elusive. Compromise ADSR designs using lower-energy cyclotrons are possible, but the loss of spallation output and consequent increase in required current mean that the cyclotron option is inadequate for ADSR deployment.

#### Synchrotrons

Synchrotrons were invented to overcome the cyclotron energy limit and proton energies of 1 GeV are easily attained. However, synchrotrons require their dipole fields to be cycled whilst the charged particles are accelerated. This strongly limits the duty factor of the accelerator: whilst cyclotrons produce a quasi continuous beam of particle, the synchrotron current is tightly bunched. This bunching, because of “space charge effects” arising from the intrinsic coulomb repulsion between charged particles of the same polarity within the bunch, in turn limits the output current of the accelerator which is therefore also inherently pulsed.

Such a pulsed high energy proton beam leads to a high instantaneous deposition of energy as each proton pulse impacts the spallation target. This can cause problems with the mechanical integrity of the spallation target and vessel. Developments such as the Rapid Cycling Synchrotron (RCS) seek to overcome the limited cycling rate (~50 Hz) of conventional synchrotrons by exploiting recent developments in magnet and power supply technology. In particular, accelerator research groups in the US are re-examining the RCS option, although space-charge expansion of the bunches whilst accelerating is still a concern.

### FFAGs

The Fixed-Field Alternating-Gradient (FFAG) accelerator combines many of the advantages of the synchrotron and cyclotron. Similar to cyclotrons, FFAGs have fixed dipole fields allowing high duty factors and rapid accelerations, but provide a synchrotron-like focusing of the beam. The beam current is only limited by the accelerating radio-frequency power that can be fed to the particle beam.

To minimise the size and complexity of a FFAG a so-called non-scaling design can be used. The UK is uniquely placed in FFAG development since the world's first non-scaling FFAG, EMMA, is presently under construction at Daresbury Laboratory as part of the CONFORM project. The provision of an experimental prototype, as a focus for UK accelerator experts to test the ns-FFAG principle will secure the expertise for the UK to develop ns-FFAG designs for nuclear, medical, and scientific applications.

### Linacs

Linear accelerators (linacs) are a relatively straightforward and well understood technology that can deliver high currents at high energies – but at a high price. Rather than recirculating particles through just a few accelerating cavities to provide the acceleration, a much longer sequence of cavities each accelerate the charged particles only once.

Circular accelerators designed to accelerate protons to energies of the order of 1 GeV generally have diameters of a few tens of meters, the equivalent linac must be several hundred meters long containing a sequence of accelerating cavities each of which are much more expensive than the simple magnets which constitute the bulk of the circular accelerator.

In the absence of cheaper, viable alternatives Linear accelerators are deployed in one-of-a-kind major large scale scientific facilities such as the SNS or ESS, where high energy, high current beams are required. Without significant technological advanced it may not be cost effective to exploit such linear accelerator technology as drivers for a commercial fleet of ADSR power stations.

## Summary

The characteristics of the potential accelerator technologies available for ADSR deployment is summarised in the following table.

	Cyclotron	Synchrotron	ns-FFAG	Linac
<b>Plus points</b>	High current	High energy	High current and high energy	High current and high energy
<b>Minus points</b>	Energy limited	Current limited	Not yet proven	Expense
<b>Examples</b>	PSI	CERN PSB	EMMA	ESS, SNS

Clearly there are several options, with different consequences and risks. Whilst the ns-FFAG holds the greatest potential in terms of current, energy, cost and size, should it prove impossible to secure ns-FFAG technology on the appropriate time scale the other technologies provide a proven fallback.

It should also be emphasised that the R&D work necessary to establish the necessary levels of accelerator reliability is independent of the type of accelerator.

## Appendix II: Thorium as a nuclear fuel

As a nuclear reactor fuel, thorium presents numerous advantages in terms of availability, proliferation resistance, nuclear waste management and reactor performance. In a 2005 status report the IAEA concluded that “...in recent times, the need for proliferation-resistance, longer fuel cycles, higher burn up, improved waste form characteristics, reduction of plutonium inventories and in situ use of bred-in fissile material has led to renewed interest in Thorium-based fuels and fuel cycles in several developed countries.....”

The following points briefly summarise the main advantages of thorium fuel.

### A2.1 Thorium: an abundant resource

Thorium is present in the Earth's crust in large quantities (similarly abundant as lead and about three times more abundant than uranium) and widely distributed, with an average concentration of 10 ppm. This resource has barely been exploited commercially. Present in many phosphates, silicates, carbonates and oxide minerals, thorium generally occurs in association with uranium and rare earth metals in diverse rock types. Monazite, a mixed thorium-rare-earth-uranium phosphate, is the most common source of thorium, available in many countries in beach and river sands.

### Estimated thorium resources by country

Country	Total Identified Thorium Resources ('000 t TH) <USD 80/kg TH	%
Australia	420	17
United States	400	16
Turkey	344	14
India	319	13
Venezuela	300	12
Brazil	221	9
Norway	132	5
Egypt	100	4
Russian Federation	75	3
Greenland	54	2
Canada	44	2
South Africa	18	1
Others	33	1
<b>Total</b>	<b>2460</b>	

Sources: Data for Australia compiled by Geoscience Australia; estimates for all other countries are from: OECD, 2006: Red Book Retrospective. A review of Uranium Resources, Production and Demand from 1965 to 2003.

Extraction of thorium from the minerals forms, and in particular from monazite, is significantly simpler than extracting uranium from its ores. The overburden during mining is much smaller and the radioactive waste production during the mining operation is about two orders of magnitude lower than that of uranium. The radon impact is also much lower and public and occupational doses are therefore much smaller. There has been sustained interest in India in thorium fuels due to India's large deposits (319,000 tonnes), compared to its limited mineral uranium reserves (92,000 tonnes). The long-term sustainability of India's civil nuclear programme greatly depends on the industrial deployment of the thorium fuel cycle.

### A2.2 Proliferation resistance of thorium fuel

Thorium occurs naturally only as Th-232. This thorium isotope is fertile (like U-238) rather than fissile (like U-235). However Th-232 is more considerably more fertile than U-238 due to its larger absorption cross section. It is therefore easier to convert natural thorium into a usable fuel during a breeding cycle than it is to convert uranium to plutonium. The resulting fissile component is U-233 as shown in the thorium fertile-fissile conversion (Figure 20).

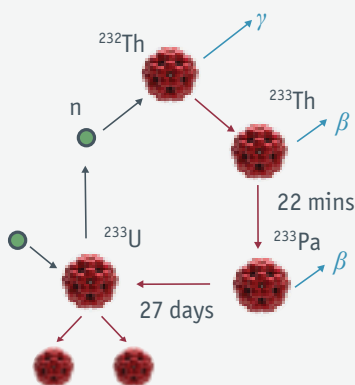


Figure 20. Neutron induced fertile to fissile conversion of thorium: from fertile Th-232 to fissile U-233

U-233 has a significantly higher fission cross-section and fission-to-capture ratio than any of the other conventional fissile element fuels, i.e. U-235, Pu-239 and Pu-241, for both thermal and fast neutrons. Less fissile material is therefore needed to sustain the reaction, and the production of unwanted isotopes is lower.

The potential fuel material, thorium oxide (ThO<sub>2</sub>), is chemically more stable and has a higher radiation resistance than uranium oxide (UO<sub>2</sub>), the chemical form of uranium usually used in reactor fuel rods. The fission product release rate for ThO<sub>2</sub>-based fuels is around ten times smaller than that of UO<sub>2</sub>. ThO<sub>2</sub> also has favourable thermo-mechanical properties because of its lower thermal expansion coefficient, and higher thermal conductivity, relative to UO<sub>2</sub>. Additionally ThO<sub>2</sub> is relatively inert and does not readily oxidise, unlike UO<sub>2</sub> which oxidises easily to U<sub>3</sub>O<sub>8</sub> or UO<sub>3</sub>: interim storage and permanent repository disposal of spent ThO<sub>2</sub>-based fuels are simpler. ThO<sub>2</sub>-based fuels have shown excellent performance during (thermal neutron) irradiation and in post-irradiation tests, and offer great potential in both pressurised water reactors (PHWRs) and in ADSRs.

The public concerns about nuclear power are often associated with the long-term toxicity of its waste streams; in a uranium-based open fuel cycle, the waste hazard is predominantly due to plutonium and other minor actinides. The Th-232/U-233 fuel cycle produces virtually no plutonium and fewer minor actinides (MAs: Neptunium, Americium and Curium) compared to the uranium fuel cycle, thereby potentially minimising proliferation threats, waste radiotoxicity and decay heat problems.

The potential proliferation of weapons' material from the nuclear fuel cycle is a further cause for public concerns over nuclear power, and may be one of the major obstacles to the worldwide exploitation of nuclear technology. These concerns have led to the abandonment of reprocessing in the USA despite its advantages in utilizing fuel resources and reducing waste streams. For nuclear energy to be accepted as a future major global energy contributor it should be based on a highly proliferation-resistant fuel cycle. This barrier should be supported by safeguard measures and administrative control, as well as by the inherent properties of the fuel cycle itself. Any fuel cycle should produce as little weapon-grade material as possible, both terms of quantity and quality.

In this regard, the thorium fuel cycle presents an intrinsic proliferation barrier due to the parasitic production of U-232 (73.6 years half-life), a strong gamma emitter and its short-half-life daughter products. This isotope is produced through (n, 2n) reactions (mostly occurring due to fast neutrons) in U-233 and Pa-233 (with subsequent β<sup>-</sup> decay).

The presence of U-232 creates an important barrier to proliferation, making it very difficult to handle the fissile uranium within the Thorium-based spent fuel rod after its withdrawal from the reactor. Moreover, this cycle offers the possibility of incorporating civilian and weapon-grade plutonium in the fresh fuel for its incineration during the burn-up.

Ironically, it is very likely this proliferation resistance that led to an almost comprehensive abandonment of proven thorium fuel cycles in commercial systems in the 1970s and early 1980s.

## Appendix III: International research on thorium fuels and fuel cycles

Since the early 1960s, extensive studies on the thorium fuel cycle and its deployment have been conducted in Germany, India, Japan, the Russian Federation, the United Kingdom, and the USA. These included studies in material data, fabrication tests, irradiation of Thorium-based fuel in material test reactors with post-irradiation examinations, and investigations into the use of thorium based fuel for Light Water, Liquid Metal Fast Breeder, and High Temperature Gas Reactors. Test reactor irradiations of thorium fuel to significant burn-ups (up to 150 GWd/t) at high specific heat loads (up to 680 W/cm) have also been conducted. Additionally, several test reactors have been either partially or completely loaded with Thorium-based fuel.

### A.3.1 Experimental reactors

#### Dragon reactor, United Kingdom:

In this 20 MW<sub>th</sub> HTGC reactor, which started operation in 1966, thorium fuel elements (10:1 Th:HEU ratio) were irradiated for 741 full power days.

#### MSRE ORNL, USA:

The Molten Salt Reactor Experiment (MSRE) at Oak Ridge National Laboratory (ORNL) was a 7.4 MW<sub>th</sub> graphite-moderated reactor operated from 1960 for 5 years. The molten salt was LiF-BeF<sub>2</sub>-ZrF<sub>4</sub>-UF and the fuels were Pu-239, U-235 and U-233. The operation successfully completed its objectives, including the study on U-233 operation at high power.

#### Peach Bottom HTGR, USA:

The Peach Bottom reactor was a high-temperature, graphite-moderated, helium-cooled reactor experiment operating at 110 MW<sub>th</sub> with HEU/Th coated-particle fuel, from 1966 to 1972.

#### Power Reactors

Considerable experience has been gained in thorium based fuel in power reactors worldwide. The following reactors have either irradiated thorium fuel or are preparing test irradiations:

#### THTR, Germany:

300 MW<sub>e</sub> reactor operated with 675,000 pebbles containing Th-HEU fuel from 1985 to 1989. Fuel fabrication was on an industrial scale.

#### Fort. St. Vrain, USA:

The Fort St. Vrain reactor was a HTGR (graphite moderated, helium-cooled) reactor with thorium and HEU fuel designed to operate at 842 MW<sub>th</sub> (330 MW<sub>e</sub>). The fuel was in microspheres of thorium carbide and Th/U-235 carbide. Almost 25 metric tons of thorium fuel was manufactured for this reactor. Excellent results in matching reactor physics calculations (e.g. temperature coefficients, control rod worth, reactivity evolution as a function of burn-up) with measurements (ref).

#### Indian Point & Shippingport, USA:

Thorium based fuel for PWRs was investigated at the Indian Point reactor (285 MW<sub>e</sub>) using both U-235 and plutonium as the initial fissile material and it was concluded that it would not significantly affect operating strategies or core margins (ref). A Thorium-based plutonium-burner was proposed for the LWR fuel cycle. The LWBR concept was also tested in the Shippingport reactor (100 MW<sub>e</sub>, largest breeder in the World) using thorium and U-233 fuel in zircaloy clad. The core was operated from 1977 for 5 years without fuel failure, achieving a maximum burn-up of 60 GWd/t and successfully demonstrated breeding of U-233 using the seed/blanket concept.

#### BWR, Lingen, Germany:

Th/Pu-based fuel test elements were used in this 60 MW<sub>e</sub> reactor.

### A3.2 The Special Case of India: Thorium-Fuel Reactors and Experiments

There has been sustained interest in India for the thorium fuels and fuel cycles due to its large deposits of thorium (518,000 tonnes; mostly as monazite in beach sands), compared to its limited mineral Uranium reserves (92,000 tonnes). The long-term sustainability of India's civil nuclear energy programme greatly depends on the large-scale utilization of its vast thorium resources for breeding and recycling fissile U-233 in a self-sustaining Th-232/U-233 closed fuel cycle.

Therefore, the case of India is of particular interest given its current leadership in thorium research programs. Since its inception, India's nuclear power program, contemplated three phases, namely i) the use of heavy water reactors; ii) the development of fast breeders; and iii) the development of thorium based reactors to utilise its vast reserves.

Intense work on the thorium cycle began in the 80s when this cycle was analyzed for all possible reactor configurations. MSRs were proposed as theoretically optimal for this cycle although PHWRs appeared as the natural option to develop this fuel cycle, given the well-proven technology and availability. Several power reactors are currently in operation in this country:

#### CIRUS, KAMINI and DHRUVA Reactors, India:

CIRUS is a 40 MW<sub>th</sub> PHWR in BARC, near Mumbai, where fuel fabrication, irradiation and examination of spent Th-fuel (up to 18 GWd/t burn-up) has been carried out.

Reaching criticality in 1996, KAMINI is a 30 kW<sub>th</sub> light water experimental reactor, specifically designed to use metallic uranium-233 as fuel.

Largest research reactor in India, DHRUVA is a 100 MW<sub>th</sub> PHWR similar to CIRUS, also based in BARC. Work to optimise and confirm the physics design parameters of the AHWR using (Th-Pu)O<sub>2</sub> and (Th-U-233)O<sub>2</sub> fuels has been carried out.

#### KAPS Units 1 and 2, KAIGA Units 1 and 2, and RAPS 3 and 4, India:

All units are 220 MW<sub>e</sub> PHWRs. Each KAPS unit is loaded with 500kg Th-fuel; in June 1995, Unit 1 had achieved about 300 days of full power operation, Unit 2 about 100 days. More units in the KAIGA and RAPS power stations are under construction. The use of Th-based fuel is planned for power flattening. Work on post-irradiation examinations, reprocessing (laboratory scale and pilot-scale) and re-fabrication (laboratory scale) continues and has been enlarged based on these experiments.

**FBTR, India:**

India's first fast power reactor, based on the design of Rapsodie, in Cadarache, France. It is a sodium-cooled 40 MW<sub>th</sub> reactor using MOX fuel and a thorium breeding blanket. Considerable work has also been done on the **recovery and final purification of U-233 from irradiated thorium via**

**the THOREX process.** Reprocessing was done using tributyl phosphate as the extracting chemical. In the initial stages, the emphasis was on the recovery of U-233. An engineering scale facility is in operation in BARC for the processing and recovery of U-233 from CIRUS and Dhruva irradiated thorium fuel rods on a regular basis.

**A.3.3 Summary**

The table below shows the experimental and power thorium reactors. Fuel for these reactors falls generally within two categories: i) coated fuel particles in graphite matrix, for HTGRs; ii) zircaloy/stainless steel-clad fuel pin assemblies, for water-cooled reactors.

Name and country	Type	Power	Fuel	Operation period
AVR, Germany	HTGR Experimental (Pebble bed reactor)	15 MWe	Th+U-235 driver fuel coated fuel particles oxide & dicarbides	1967 – 1988
THTR-300, Germany	HTGR Power (Pebble bed reactor)	300 MWe	Th+U-235 driver fuel coated fuel particles oxide & dicarbides	1985 – 1989
Lingen, Germany	BWR Irradiation-testing	60 MWe	Test fuel (Th,Pu)O <sub>2</sub> pellets	Terminated in 1973
Dragon, UK OECD-Euratom also Sweden, Norway & Switzerland	HTGR Experimental (Pin-in-Block design)	20 MWth	Th+U-235 driver fuel coated fuel particles dicarbides	1966 - 1973
Peach Bottom, USA	HTGR Experimental (Prismatic Block)	40 MWe	Th+U-235 driver fuel coated fuel particles oxide & dicarbides	1966 – 1972
Fort St Vrain, USA	HTGR Power (Prismatic block)	330 MWe	Th+U-235 driver fuel coated fuel particles dicarbides	1976 - 1989
MSRE ORNL, USA	MSBR	7.5 MWth	U-233 molten fluorides	1964 - 1969
Shippingport & Indian Point 1, USA	LWBR PWR (Pin assemblies)	100 MWe 285 MWe	Th+U-233 driver fuel oxide pellets	1977 – 1982 1962 – 1980
SUSPOP/KSTR KEMA, Netherlands	Aqueous homogenous suspension (Pin assemblies)	1 MWth	Th+HEU oxide pellets	1974 - 1977
NRU & NRX, Canada	MTR (Pin assemblies)		Th+U-235 test fuel	Irradiation-testing of few fuel elements
KAMINI; CIRUS; & DHRUVA, India	LWR PHWR PHWR	30 kWth 40 MWth 100 MWth	Al+U-233 driver fuel 'J' rod of Th & ThO <sub>2</sub> , 'J' rod of ThO <sub>2</sub>	All three research reactors in operation
KAPS 1 & 2; KAIGA 1 & 2; RAPS 2, 3 & 4, India	PHWR (Pin assemblies)	220 MWe	ThO <sub>2</sub> pellets (For neutron flux flattening of initial core after start-up)	Continuing in all new PHWRs
FBTR, India	LMFBR (Pin assemblies)	40 MWth	ThO <sub>2</sub> blanket	1985 – in operation

## Appendix IV: Current international ADSR R&D programmes

### A4.1 Examples of recent and current international R&D studies of ADSR systems and their components

#### Europe: EUROTRANS Project

A consortium of 29 partners (17 Universities represented by ENEN) Working towards a reliable basis for the assessment of the technical feasibility of transmutation by ADS and a first estimate of cost.

#### Belgium: SCKCEN

MYRRHA is an Accelerator Driven System (ADS) under development at Mol in Belgium. It aims to serve as a basis for the European XT-ADS (eXperimental demonstration of Transmutation in ADS) and to provide protons and neutrons for various R&D applications. It consists of a proton accelerator delivering a 600 MeV – 2.5 mA (or 350 MeV – 5 mA proton beam) to a liquid Pb-Bi spallation target that in turn couples to a Pb-Bi cooled, subcritical fast nuclear core. The project started in 1997 and the aim is to have MYRRHA fully operational around 2022-2023. On March 4th, 2010 Belgian Prime Minister Leterme announced that the Belgian government will give its go ahead for the MYRRHA project, supporting 40% (M€384) of the total budget (M€960).

#### Switzerland: Paul Scherrer Institute (PSI)

MEGAPIE (Megawatt Pilot Target Experiment) is an initiative launched by Commissariat à l'Énergie Atomique, Cadarache (France) and Forschungszentrum Karlsruhe (Germany) in collaboration with Paul Scherrer Institut (Switzerland), to demonstrate, in an international collaboration, the feasibility of a liquid lead bismuth target for spallation facilities at a beam power level of 1 MW. It has served to demonstrate the feasibility, potential for licensing, and long-term operation under realistic conditions, of a high-power spallation target.

The MEGAPIE target has been tested using the world's highest proton current cyclotron at PSI. This cyclotron delivers a proton energy of 590 MeV and a continuous current of 1.8 mA, currently being upgraded to 2 mA. It is used for a large range of scientific research tools, the most prominent one being a spallation neutron source (SINQ) with its large number of different user facilities. This facility is designed as a neutron source mainly for research with extracted beams of thermal and cold neutrons, but hosts also facilities for isotope production and neutron activation analysis.

#### Germany: Forschungszentrum Karlsruhe (FZK)

The FZK is investigating an ADS for transmutation of minor actinides and long lived fission products. The study considers core design, neutronics, safety systems materials and corrosion. Experiments are underway to study corrosion mechanisms, surface treatment, oxygen sensor development and oxygen control systems. Further experiments are planned to study thermohydraulics under normal and decay heat conditions.

#### Sweden: European Spallation Source (ESS)

ESS is a proposed 5 MW spallation source with extremely high flux and pulses of 2 ms. ESS, which has been highest priority of almost all neutron centres and scientists since the early nineties, will be the world's leading neutron source, providing a combination of the highest neutron intensity (factors of 10 to several 100s compared to current and planned facilities) and novel instruments, to form a unique tool for research into structure, characteristics, functions and dynamics of matter. The initial long pulse configuration of ESS provides maximum complementarity to existing and the largest instrument innovation potential. Its unique upgradeability guarantees a long-term world leading status. ESS will offer new modes of operation and user support to facilitate industrial and academic exploitation of neutron beams. Authors of this report have played a leading role in the ESS R&D and political programme for almost two decades.

#### Japan: Japan Nuclear Cycle Development Institute (JNC)

JNC is assessing the prospects for the commercialization of a prototype fast breeder reactor. A promising candidate is a Pb-Bi cooled, modular system with natural circulation. JNC is currently working on corrosion phenomena in Pb-Bi melts, assessing corrosion resistant methodologies, performing additional research on advanced alloys for Pb-Bi cooled systems.

#### Japan: Central Research Institute of the Electric Power Industry (CREIPI)

CREIPI is engaged in R&D on the Pb alloy cooled fast reactor concept and ADSR systems for processing of transuranic waste. Studies are being conducted into feasibility of FBR systems with innovative Pb-Bi heat exchanger, direct contact heat transfer between Pb-Bi and water, fundamental aspects of liquid metal-water vapor explosions and system thermohydraulics.

#### Japan: High Energy Accelerator Research Organization (KEK)

The world's first proton FFAG accelerator, the Proof-of-Principle FFAG (POP-FFAG) was built at KEK in Japan in 2000. At approximately the same time, researchers recognized that FFAG accelerators can feature rapid acceleration with large momentum acceptance. These are exactly the properties required for the production of medical proton beams and for accelerator-driven sub-critical reactors (ADSR) for nuclear energy and for muon acceleration. To investigate this potential, a team at KEK developed the first prototype of a large-scale proton FFAG accelerator. In 2004, it successfully accelerated a proton beam up to 150 MeV with a repetition rate of 100 Hz. Since then, intensive studies and discussions have taken place and various novel ideas have emerged that have led ultimately to new application projects for FFAG accelerators at several institutes in Japan.

A team at the University of Kyoto has developed a proton FFAG accelerator for basic research on ADSR experiments, whereby beam is delivered to the existing critical assembly of the Kyoto University Research Reactor Institute (KURRI). The whole machine is a cascade of three FFAG rings. The beam was recently successfully accelerated up to 100 MeV and the first ADSR experiments began in 2009, but only at very small (nanoamp) currents.

**Japan: Mitsui Engineering & Ship Building Co (MES)**

MES has worked cooperatively with IPPE in Russia to develop Pb-Bi technology for neutron source target systems and coolants for ADSR. MES also conducted independent Pb-Bi flow loop research on corrosion behaviour of Japanese Steels, Pb-Bi interaction with air and water, coolant conditioning techniques and sensor development, and engineering feasibility studies of ADSR and fast reactor designs.

**Israel: The Ben-Gurion University of the Negev, Center for Magnetohydrodynamic Studies (CMHDS)**

CMHDS have conducted extensive R&D on liquid metal thermal sciences They have two large scale facilities and have conducted Pb and Pb-Bi circulation tests when propelled by steam bubbles Also studies on the oxidation of steels by Pb high temperature alloy.

**Lead Fast Reactor - USA: Idaho National Laboratory (INL)**

INL has obtained corrosion data from both Pb and Pb-Bi operations at an experimental facility.

**USA: Los Alamos National Laboratory (LANL)**

LANL has conducted Pb alloy research and is investigating kinetic modelling of corrosion with Oxygen control, Oxygen sensor development, the operation of a materials test loop and the corrosion test of US standard steels.

**USA: Massachusetts Institute of Technology (MIT)**

MIT has supported Pb and Pb-Bi reactor concepts for actinide burning and electrical generation Research activities include reactor physics, fuel management, reactor thermal hydraulics, nuclear materials, structural engineering and coolant chemistry.

**USA: SNS (Oak Ridge)**

SNS: is an accelerator-based neutron source built by the US Department of Energy. The pulsed proton beam is directed onto a liquid mercury target.

**Russia: Institute of Physics and Power Engineering (IPPE)**

The IPPE has carried out a number of comparisons between reactor designs using Na, Pb and Pb-Bi coolants.

	Accelerator	Spallation target	Reactor core	Coolant technology	Fuel management
<b>European Union</b>	EUROTRANS Project: Partnership for assessing the feasibility of ADSR transmutation				
<b>Belgium (SCK - CEN)</b>	MYRRHA: Multi-purpose hybrid research LBE cooled 50 MW ADSR				
<b>Switzerland (Megapie)</b>		Construction and operation of a 920 kg LBE spallation target for 1 MW of beam power			
<b>Germany (FZK)</b>			Studies on core design, neutronics and safety systems	materials and corrosion studies	
<b>Sweden (Lund - ESS)</b>		State-of-the-art facility, 5 MW pulsed spallation source with extremely high flux			
<b>Japan (CREIPI)</b>				Feasibility studies of FBR systems with innovative Pb-Bi heat exchanger, corrosion studies and system thermohydraulics	
<b>Japan (JNC)</b>				Assessment of corrosion resistant methodologies & research on advanced alloys for Pb-Bi cooled systems	

Appendix IV:  
Current international ADSR R&D programmes *continued*

	Accelerator	Spallation target	Reactor core	Coolant technology	Fuel management
Japan (KEK)	World's first proton FFAG accelerator; 5 MHz RF cavities and 200 kV/m gradient; proton pulses at 150 MeV and 100 Hz				
Japan (MES)		Pb-Bi technology for neutron source target systems		Pb-Bi technology for ADS cooling systems	
Israel (CMHDS)				Pb and Pb-Bi circulation tests; and studies on the oxidation of steels by Pb high temperature alloy	
US (INL)				corrosion data from both Pb and Pb-Bi operations at an experimental facility	
US (LAN)				alloy research, Kinetic modelling of corrosion of US standard steels	
US (MIT)			reactor physics thermal hydraulics nuclear materials and structural engineering	chemistry	fuel management studies
US (SNS)		accelerator-based neutron source (liquid mercury target)			
Russia (IPPE)			comparisons between reactor designs using Na, Pb and Pb-Bi coolants		

#### A4.2 Activities supported by the European Commission

For more than ten years the European Commission's Euratom team has funded research into the partitioning and transmutation of nuclear wastes and spent nuclear fuel via the European Framework programmes. Significant attention has been devoted to accelerator driven systems for transmutation of spent fuels and partitioned radioactive wastes. European Commission emphasis has been given to issues relating to waste management rather than nuclear power station new build because of political and constitutional considerations within the European Union.

Nuclear research is governed by the 1957 Euratom Treaty rather than by the sequence of European Economic Community treaties. Under the terms of the Euratom Treaty activities require unanimous member state approval. Such

unanimous support has thus far proved difficult to achieve in matters relating to nuclear power generation and its possible expansion. Radioactive waste management, as a legacy issue, has been an easier issue on which to agree.

A major overview comparing the relative merits of various approaches was conducted in sixth Framework Programme by the Red-Impact collaboration. Five fuel cycles were analysed: UO<sub>x</sub> once through; Monorecycled Pu MOX in PWR; Multi-recycled Pu in Fast Reactors; Multi-recycled Pu and minor actinides in Fast reactors and an approach combining PWRs and ADSR transmutation. Euratom has also funded a series of experimental initiatives directly addressing the potential for ADSR based radioactive waste transmutation. Recent efforts have centered upon a European Framework Project known as 'EUROTRANS'. This is dedicated to achieving ADSR-based transmutation demonstration devices of industrial interest.



EUROTRANS has proposed a route to an industrial prototype in which two early stage machines are proposed. These are: a 50-100MWth experimental facility known as XT-ADS and a larger 400MWth European Facility for Industrial Transmutation known as 'EFIT'. The EUROTRANS coordinator, Joachim Knebel, reported at the 2009 FISA Prague Euratom conference in Prague in June 2009 that no technological showstoppers had been identified and the approximate costs of the way ahead were known. With integral multiple recycling it was envisaged that the radiological hazard associated with nuclear energy production could be brought down to a few hundred years.

Relevant to future developments in this area is the European Industrial Initiative of the EC Sustainable Nuclear Energy Technology Platform.

EUROTRANS research has already identified the following challenges to progress: a lack of European experience in heavy liquid metal handling; a lack of suitable thermal hydraulics knowledge; a need to understand the build up of oxide layers that impair heat transfer; liquid metal induced

corrosion; a need for a better understanding of decay heat; better understanding of flow rate recovery after a reactor SCRAM; and a need properly to understand the effects of a heat exchanger blockage. All of these challenges are also potentially faced by thorium-fuelled ADSR systems.

It is important to emphasise that almost all European ADSR interest has been motivated by the possibility of waste transmutation.

It has been asked recently: 'might we (i.e. Europe) do transmutation without ADSR?' The answer to that question is most probably 'yes'. The proposed thorium-fuelled ADSR project instead asks the opposite question 'might we do ADSR without transmutation?'. For political reasons, thus far, the EU has been unable directly to address that question. That omission places the proposed UK thorium-fuelled ADSR R&D programme at a significant strategic advantage. The UK now has the opportunity to build upon much prior and parallel EU work and to take it in the direction of exportable power generation.

## Appendix V: Placement of ADSR technology in the nuclear power market

The first commercial nuclear power plants were commissioned in the UK, USA and USSR in the mid 1950s and by the mid 1980s, nuclear power was accepted as a mature industrial technology, with a successful track record and good prospects for the future. However, the growth of the nuclear industry dramatically slowed after the Chernobyl catastrophe in 1986. Nevertheless, concerns about global warming have rekindled the national and international appetites for the nuclear option: It is widely argued that future energy demands cannot be met solely through the burning of fossil fuels, and an increase in installed nuclear capacity, as a low carbon option, maybe required. Currently, the reactors in operation are mostly Gen II technology<sup>1</sup>, with several Gen III PWRs under construction.

In such context, the five forces analysis of the nuclear power industry, presented in Figure 21, qualifies the potential business opportunity for the entry of thorium-fuelled ADSR technology into a nuclear power market within which competition is limited to only a few power plant vendors of mature technology (e.g. Areva, Westinghouse, GE, Toshiba). The ADSR could facilitate a smooth transition from a PWR technology which is rapidly consuming limited uranium reserves to a innovative nuclear system fuelled by thorium, a widely available commodity. The price premium of the ADSR accelerator is therefore fully justified by a fully differentiated system with relevant additional features, such as inherent proliferation resistance and low waste. Future generations of nuclear reactors, such as those proposed by the Generation IV International Forum, or GIF (created in 2001) would afford some of the features of the thorium ADSR systems such as high temperatures/efficiency, long burn-ups or favourable economics. Nevertheless, no Gen IV design<sup>2</sup> explicitly proposes the use of thorium as base fuel or provides the added safety feature of sub-critical operation.

The **high barriers of entry** into the nuclear market, linked to high R&D and capital investment costs and very specific capabilities deter new entrants. As with any other technological innovation, thorium-fuelled ADSR systems would have to overcome these barriers. Nevertheless, it is likely that partial government support for an R&D programme would be necessary only until the competition of a full scale prototype that adequately demonstrates the technology to the market. It is also recognised that such public investment, coupled with a public appreciation of the ADSR as an acceptable low carbon but relatively safe nuclear option, would undoubtedly influence clients for the new technology.

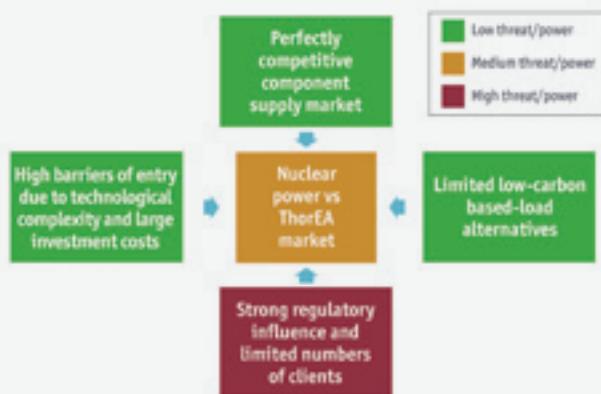


Figure 21. Five forces analysis of the nuclear power market in which ThorEA would compete.

<sup>1</sup> Most reactors in operation are based on technology developed up to the 1970s during the height of nuclear deployment. Most nuclear power plants are based on light-water reactors (LWRs, 87% of the installed capacity): mostly pressurised light-water reactors (PWRs and VVERs, 65%) and boiling water reactors (BWRs, 22%). The World nuclear landscape is completed by pressurised heavy water reactors (PHWRs also known as Candu – 6% of the total installed capacity), gas-cooled reactors (AGR and the British Magnox; 3%) and light-water graphite reactors (RBMK; 3%). Source: <http://www.world-nuclear.org/info/inf32.html>

<sup>2</sup> Six reactor designs have been proposed, namely: Gas-cooled Fast Reactor (GFR), Lead-cooled Fast Reactor (LFR), Molten Salt Reactor (MSR), Sodium-cooled Fast Reactor (SFR), Supercritical Water-cooled Reactor (SCWR) and Very High Temperature Reactor (VHTR).

## Appendix VI: The Carlo Rubbia ADSR Patent

Probably the first patent application relating to the particular concept of an accelerator driven subcritical reactor was EP 93117587.1 filed by the Italian Nobel prize winner Carlo Rubbia in October 1993 in a personal capacity, during his term as Director-General of CERN. This priority application formed the basis of a PCT application PCT/EP94/02467 filed in July 1994, which was pursued into a variety of jurisdictions including the US, Russia, Japan, China, Brazil, Australia and Europe. The consequent European patent application EP 94925396.7 granted in February 1999, but was opposed by the French public company Framatome, which was merged with Cogema in 2001 to form Areva, the French public industrial conglomerate mainly known for its interests in nuclear power. Areva currently files around 200 patent families a year, many in the area of nuclear power.

The Rubbia PCT patent application contained a claim 1 particularly directed to **“A method of producing energy from a nuclear fuel material contained in an enclosure, through a process of breeding of a fissile element from a fertile element of the fuel material via a beta-precursor...”**. It is notable that the claim is not limited to any particular chemical elements, although in the patent description the particular example of Thorium 232 as a fertile element, leading to Protactinium 233 as the beta-precursor, leading on to Uranium 233 as the fissile element is used. Other schemes such as using U238 to breed Pu239 are also discussed. Of course, the various possible nuclear reactions which could have been used were very well known by 1993, and it is the way in which the two stage reaction is used later in claim 1 which is interesting.

The claim 1 of the PCT application went on **“...characterised in that a high energy particle beam is directed into the enclosure for interacting with heavy nuclei contained within the enclosure so as to provide high energy neutrons...”**. In the patent description a number of accelerator types and techniques are discussed, including LINACs and Isochronous synchrotrons, one such mentioned type of synchrotron being

an FFAG. When the patent application was being written in 1993 the concept of an FFAG accelerator was well established, and would have been familiar to Carlo Rubbia as a leading scientist in the field of particle physics, but there was no real prospect of any such accelerator being built within the next decade, and certainly not having the beam power required to build a plausible nuclear power plant. Although the patent description mentions various accelerator types, claim 1 doesn't require any particular one to be used, although he clearly appreciates the serious difficulties of successfully delivering a proton beam of sufficient power and stability. Rubbia spends more time in the patent application discussing different possibilities for the beam target, for example whether to use a specific lead based target, or the thorium fuel itself.

The claim finishes with a final statement **“...the neutrons thereby being multiplied in sub-critical conditions by the breeding and fission process, said breeding and fission process being carried out inside the enclosure”**. This ties the rest of the claim up into the whole “Energy Amplifier” concept which Rubbia introduces, whereby initial electrical energy for the particle accelerator drives the chain of converting fertile Thorium to fissile Uranium which burns to provide an *amplified* amount of heat energy product, a process which can continue for many years without refuelling the reactor core, if the accelerator beam and spallation target system can be sustained.

The Rubbia European patent was granted with little change, but the scope of the claims was challenged during the subsequent European Opposition proceedings. Faced with the challenge from Framatome, the European Patent Office decided that the claim 1 as granted was already known, especially from an academic paper published in 1983 which described a “Linear Accelerator Driven Reactor” using natural Uranium fuel which would be economically viable when the power produced from fission was at least five times the power needed to drive the particle accelerator. The patent was maintained, but in a narrower form in which the ratio of the fertile and fissile materials remains stable during operation.

## Appendix VII: Technical challenges of the thorium-fuelled ADSR concept

In addition to the very clear challenges associated with accelerator technology for ADSR deployment, outlined in Appendix II of this report, several other technical challenges remain to be solved. It is noted, however, that many if not all of these challenges offer the potential of precipitating IP for the thorium-fuelled ADSR project.

### Thorium extraction

Due to its limited use other than as nuclear fertile material thorium resources are not yet well-known, but significant deposits have been found in many regions of the World. The most important source of thorium is the mineral monazite and the largest reserves of thorium are in deposits of heavy-

mineral sands deposited by moving water. The UK could develop the technology to efficiently extract thorium from monazite as well as from other minerals. As a cost-efficient alternative to uranium, the development of a competitive advantage and economies of scale in the extraction process could grant the UK the key to the industrial deployment of this technology and open the use of thorium for different industrial purposes.

### Fuel fabrication technology

Thorium fuel fabrication technology is similar to that used for uranium oxides. Nevertheless, widespread industrial manufacturing processes for thorium, thorium oxide or

thorium oxide mixed fuels is accessible. Additionally there is a need for a large-scale thorium-fuel irradiation study, particularly as thorium fuel elements will spend substantially longer in the high fast neutron fields of the ADSR core (years) than uranium based fuel spend in the core of a thermal reactor (months). The materials research associated with these issues could be performed by collaborative programmes between UK HEIs and nuclear fuel manufacturers; it will require specialists in metallurgy, chemistry, physics and mechanical engineering. Collaboration with the National Nuclear Laboratory and exploitation of their extensive experience and world class facilities would be of particular value.

### Coolant selection

Much of the research hitherto undertaken to date ADSR systems has assumed the use of either lead or lead-bismuth coolant. The use of such a coolant has many potential advantages; however corrosion of sub and superstructures remains a concern. In Russia Pb-Bi coolants have been successfully deployed in the reactors of nuclear submarines.

The resolution issues associated with molten metal coolants will require expert metallurgical input from HEIs and other research organizations; it will require an understanding of the mechanisms leading to the cause of corrosion and proposals to overcome them. The eventual solution should be demonstrated in near operational conditions. The R&D necessary to overcome these issues could in part be carried out in collaboration and participation with, in the European Spallation Source (ESS) project, for which the search for new liquid metal target systems, as an alternative to mercury, is already underway.

It is considered possible that the molten metal coolant and the molten metal spallation target could be contiguous, simplifying the circulation system and the core design. Such a system would be particularly advantageous if the multiple spallation target option proved optimal. Complex fluid dynamics calculations and simulations will be required to demonstrate the efficacy and feasibility of such a system.

### Reactor core principles

The construction of the world's first thorium fuelled ADSR will set new standards in nuclear reactor technology, not least because of the sub-critical operation, the coupling of a monolithic external device to the core (i.e. the accelerator complex) and the deployment of thorium fuel in what is essentially a fast reactor mode. Considerable work on calculation, simulation and modelling of the configuration and performance of the reactor core will therefore be required ahead of deployment in order to qualify and quantify both performance and safety, and to establish licensing protocols.

Much of the basis upon which future performance is predicted has been undertaken by Prof Carlo Rubbia at CERN. Further work will be needed to confirm that the initial principles and suppositions are valid, and also to investigate and select the optimum fuel configurations and coolants etc to optimise fuel burn-up and minimise waste. Members of ThorEA are already undertaking such studies at The University of Cambridge.

### Spent fuel management

ADSRs afford the potential of using alternative fuel configurations with the benefit of providing reduced production of long-lived, high level waste and extended fuel burn-ups without the need for fuel movements during operation. However it is in the long-term operation of the reactor that the real benefits of waste reduction become compelling. To fully exploit these advantages repeated re-processing of the fuel will be necessary. Re-processing technologies for uranium/plutonium fuel already exist however, technologies to deal with thorium fuel mixtures will need to be developed.

For both open and closed fuel cycles and as opposed to uranium, the back-end of the thorium fuel cycle presents several unique challenges that need to be resolved at a commercial, rather than demonstrational, level. For example, as part of this process the isotopic inventory of spent thorium fuel needs further investigation. The challenges in the chemistry of the back-end of the thorium fuel cycle offer several R&D opportunities for the UK:

- development of alternative extraction;
- development of two stream (for mixed Th-U fuel) or three stream (for mixed Th-U-Pu fuel) reprocessing routes for recovery of Th, U & Pu from irradiated fuels;
- management of transuranic waste and handling and conditioning high level liquid wastes;
- development of non-aqueous reprocessing techniques.

Recognising that the utilisation of thorium requires an initial conversion of fertile Th-232 into fissile U-233 (the so-called breeding phase), there are two conceivable strategies to manage the spent fuel:

- an **open fuel cycle**, whereby spent fuel is disposed of, without or with separation;
- a **closed fuel cycle** effected by reprocessing the spent fuel, separating elements and re-fabricating new fuel to be returned to the reactor.

The open fuel cycle is arguably the most proliferation-resistant strategy to deal with nuclear fuel (both fresh and spent), and avoids the complications associated with partitioning and re-fabrication of highly radiotoxic actinide fuels. The thorium-fuel-cycle spent fuel is particularly radiotoxic due to the presence of U-232 (a strong gamma emitter), thus hindering the handling of waste fuel but also creating a natural proliferation-barrier.

For thorium-fuelled ADSRs, an open fuel cycle could be realised either by seeding the fuel with waste plutonium to create an active fuel rod prior to its insertion into the reactor; alternatively a pure thorium fuel rod may be irradiated for 6 to 12 months to breed the fissile material and make the rod active.

Appendix VII:  
 Technical challenges of the thorium-fuelled ADSR concept *continued*

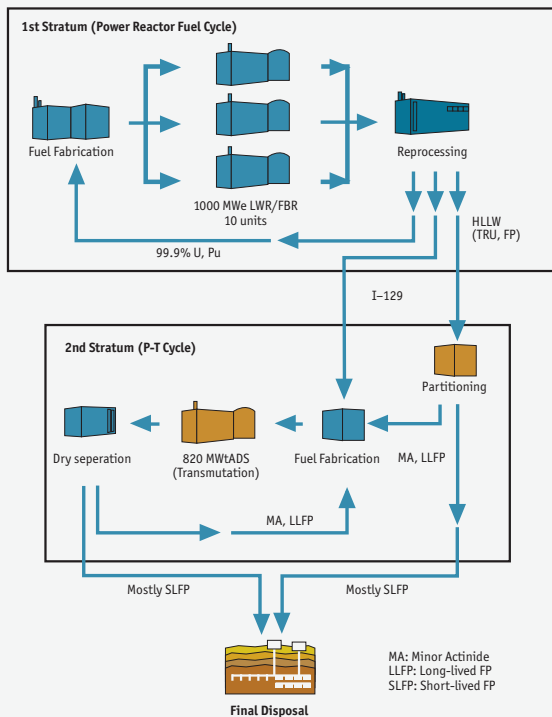


Figure 22. Schematic view of a possible closed fuel cycle scenario, with ADSR eliminating MA waste from conventional LWRs (Mukaiyama, 2002).

The closed fuel cycle is the most fuel-efficient and arguably sustainable strategy for large-scaled use of nuclear power, and offers markedly reduced waste streams. The closed fuel cycle is based on reprocessing spent fuel and using the recovered actinides as part of re-fabricated fresh fuel. However, there are significant challenges to be met, including the need for partitioning facilities, handling of highly radiotoxic substances, and the political acceptability of its proliferation risks. Reprocessing of irradiated Thorium-based fuels and separating out the bred U-233 are necessary in a closed fuel cycle and the subsequent reprocessing requires remote handling (such as that available at NNL). Several national research programmes have developed credible Th-U fuel strategies. In particular, India is currently testing a three stage closed-cycle strategy combining PHWRs, LMFRs and AHWRs (design presently being reviewed by the IAEA).

It should be noted that in a closed fuel cycle repositories would still be required although the waste stream to repositories would be greatly reduced. There would however be fewer restrictions on safety and secular confinement. In such a scenario, most of the radiotoxic waste stream would be composed of short-lived fission products (SLFPs), which due to their half-life require confinement for a limited time (up to 100 years).

Finally, ADSRs have been advocated as a potential technological alternative to geological disposal of waste from conventional nuclear reactors after high-level waste separation, for example in (NEA, 1999) or (Herrera-Martínez, 2004). Figure 22 presents a schematic view of a multi-tier closed fuel cycle strategy, incorporating ADSR to eliminate plutonium and MA.

## Appendix VIII: An historical UK perspective

The UK was one of the first countries to develop civil nuclear power, opening the first commercial-scale grid-connected power plant in 1956. The four-unit Calder Hall power station served two purposes: the first was to produce plutonium and other isotopes necessary for the UK nuclear weapons programme, whilst the second was to demonstrate the useful production of clean electricity free from the industrial-relations difficulties and air-pollution problems of coal-based power generation.

During the Second World War the UK had been a key contributor to the US-led Manhattan Project to develop the atom bomb. However, the 1946 US Atomic Energy Act forbade US collaboration with foreign powers, so from then the British were isolated for over ten years.

The UK made an early decision to focus on plutonium-based weapons production and this requirement motivated the development of graphite-moderated, natural-uranium-fuelled reactors such as Calder Hall. By 1964 the UK needed to plan for a second generation of nuclear power plants following the largely successful Magnox programme; various prototype technologies were possible such as the Steam Generating Heavy Water Reactor at Winfrith in Dorset, or the Windscale Advanced Gas-Cooled Reactor (AGR) prototype.

During the early 1960s France chose to migrate from gas-cooled reactors to pressurised light-water reactors: the UK stayed with graphite and gas, arguably making one of the worst technology policy decisions in UK history. The AGR programme suffered numerous setbacks, only some of which were technical. It was not until the late 1990s that the UK completed its first world-class light water reactor, based upon a US Westinghouse SNUPPS plant design: Sizewell B in Suffolk.

Since Labour came to power in 1997 it is notable that nuclear energy is back on the agenda, and that in the same period the former UK research and fuel cycle company BNFL has been systematically dismantled. From the ashes of BNFL we have the National Nuclear Laboratory who, together with an increasing number of UK universities, is pressing for future reactor build.

In the context of the present report, it is interesting to note that the HELIOS experiment, commissioned in Harwell in 1979, is a specific example of UK's leadership in the field of ADSR technology. In this experiment, an electron beam from Harwell's linear accelerator was coupled with a subcritical assembly, conforming one of the earliest examples of accelerator-driven subcritical devices (Lynn, 1980).

Similarly, the UK has experience of deployment of thorium fuel: Thorium fuel elements with a 10:1 Th/Highly Enriched Uranium ratio were irradiated in the 20 MWth Dragon helium-cooled High Temperature Gas Reactor at Winfrith, UK, for 741 full power days between 1964 and 1973. The Th/U fuel was used to 'breed and feed', so that the U-233 created from fertile Th-232 replaced the burnt U-235 at the same rate, and fuel could be left in the reactor for about six years.

Finally it is worth stating that of all the declared nuclear weapon states the UK arguably has the most unblemished record in proliferation prevention, an achievement the UK can be proud of. The development of thorium-fuelled ADSR would help to continue this tradition.





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## Glossary

**ADS** – Accelerator-Driven System

**ADSR** – Accelerator Driven Sub-critical Reactor

**ADTR** – Accelerator Driven Thorium Reactor

**AESIR** – Accelerator Energy Systems with In-built Reliability: the ADSR accelerator project

**AHWR** – Advanced Heavy Water Reactor (Indian Design)

**AISI** – American Iron and Steel Institute

**ALI** – Annual Limits of Intake

**ANL** – Argonne National Laboratory (US)

**ARC** – Adiabatic Resonance Crossing

**ATW** – Accelerator Transmutation of Waste

**BARC** – Bhabha Atomic Research Centre (India)

**BNCT** – Boron-Neutron Capture Therapy

**BOC** – Beginning-Of-Cycle

**BOL** – Beginning-Of-Life

**BWR** – Boiling Water Reactor

**CANDU** – Canadian Deuterium-Uranium reactor

**CEA** – Commissariat à l’Energie Atomique (France)

**CERN** – Conseil Européen pour la Recherche Nucléaire (Int. Org., Switzerland)

**CIEMAT** – Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (Spain)

**CONFORM** – COnstruction of a Non-scaling FFAG for Oncology, Research and Medicine (the UK ns-FFAG development programme funded by RCUK)

**DOE** – Department Of Energy (US)

**EA** – Energy Amplifier (synonymous with ADSR)

**EADF** – Energy Amplifier Demonstration Facility

**EMMA** – Electron Model of Many Applications, the world’s first ns-FFAG accelerator

**ENDF** – Evaluated Nuclear Data File

**ENEA** – Ente per le Nuove Tecnologie, l’Energia e l’Ambiente (Italy)

**EOC** – End-Of-Cycle

**EOL** – End-Of-Life

**ESS** – The European Spallation Source project

**ETS** – European Trading Scheme

**EURATOM** – European Atomic Energy Community

**EUROTRANS** – European Research Programme for the Transmutation of HLW in an ADS

**FBR** – Fast Breeder/Burner Reactor

**FEAT** – First Energy Amplifier Test

**FERFICON** – Fertile-to-Fissile Conversion Program

**FFAG** – Fixed Field Alternating Gradient

**FFEA** – FFAG Research for Energy Amplifiers, the second stage of the ADSR accelerator

**GFR** – Gas-cooled Fast Reactor

**GHG** – Green-house Gas

**GW<sub>e</sub>** – Giga-watt electric (1E9 electric watts)

**GW<sub>th</sub>** – Giga-watt thermal (1E9 thermal watts)

**HEU** – High-Enriched Uranium (>20% fissile content)

**HLW** – High-Level Waste

**HM** – Heavy Metal (measure of actinide mass in nuclear fuel)

**HTGR** – High Temperature Gas Reactor

**IAEA** – International Atomic Energy Agency

**IEA** – International Energy Agency

**INL** – Idaho National Laboratory (US)

**IPPE** – Institute of Physics and Power Engineering (Russia)

**ISIS** – The UK’s national spallation neutron source at STFC’s Rutherford Appleton Laboratory

**JAERI** – Japan Atomic Energy Research Institute (Japan)

**JINR** – Joint Institute for Nuclear Research (Russia)

**KWh** – Kilo-watts hour (energy, 3.6E6 joules)



**LBE** – Lead-Bismuth Eutectic  
**LEU** – Low-Enriched Uranium (<20% fissile content)  
**LFR** – Lead Fast Reactor  
**LINAC** – Linear Accelerator  
**LLFP** – Long-Lived Fission Product  
**LMFBR** – Liquid Metal Fast Breeder Reactor  
**LOCA** – Loss-Of-Coolant Accident  
**LOKI** – Low key injector, the first stage of the ADSR accelerator system  
**LWR** – Light Water Reactor

**MA** – Minor Actinide  
**MAG** – Ministers’ Advisors Group  
**MEGAPIE** – MEGAWatt Pilot Experiment  
**MeV** – Mega-electron-volt (energy, 1.6E-13)  
**MOX** – Mixed Oxide Fuel, (U-Pu)O<sub>2</sub>  
**MSR** – Molten Salt Reactor  
**MTA** – Materials Testing Accelerator  
**MUSE** – MUltiplication Source Externe experiment  
**MW<sub>e</sub>** – Mega-watt electric (1E6 electricity watts)  
**MW<sub>th</sub>** – Mega-watt thermal(1E6 thermal watts)  
**MWh** – Mega-watts hour (energy, 3.6E9 joules)

**N\_TOF** – Neutron Time-of-Flight experiment  
**NEA** – Nuclear Energy Agency  
**NS-FFAG** – Non-Scaling Fixed Field Alternating Gradient

**OECD** – Organisation for Economic Co-operation and Development  
**OMEGA** – Options Making Extra Gains for Actinides and Fission Fragments  
**OPEC** – Organisation of Petroleum Exporting Countries  
**ORNL** – Oak Ridge National Laboratory (US)

**P&T** – Partitioning and Transmutation  
**PHWR** – Pressurized Heavy Water Reactor  
**PSI** – Paul Scherrer Institute (Switzerland)  
**PUREX** – Plutonium Uranium Recovery by Extraction  
**PWR** – Pressurized Water Reactor

**R&D** – Research and Development

**SFR** – Sodium Fast Reactor  
**SLFP** – Short-Lived Fission Product  
**STCF** – Science and Technology Facilities Council (UK)

**TARC** – Transmutation by Adiabatic Resonance Crossing  
**TBP** – Tri-n-Butyl Phosphate  
**THOR** – The final (1GeV, 10mA) stage of the ADSR accelerator  
**THOREX** – Thorium Recovery by Extraction  
**TRASCO** – TRAsmutazione SCOrie project  
**TRADE** – TRIGA Accelerator-Driven Experiment  
**TRIGA** – Training, Research, Isotopes, General Atomics reactor  
**TRU** – Transuranic element  
**TWG** – Technical Working Group on ADSs  
**TWh** – Tera-watts hour (energy, 3.6E15 joules)

**UNFCCC** – United Nations Framework Convention on Climate Change  
**UOX** – Uranium Oxide fuel

**XADS** – eXperimental Accelerator-Driven Sub-critical reactor

## Frequently Asked Questions

A draft of the ThorEA report “Towards an Alternative Nuclear Future” was submitted by STFC to independent international expert accelerator scientists from whom referees comments were solicited. ThorEA would like to thank the referees for their thorough evaluation and for their positive and supportive comments in which they recognised the significance of alternative energy production based upon the ADSR principle, suggesting for example that:

- *“now is the right time for the UK to make a well-considered entry into ADSR accelerator technology R&D”*
- *“early investment at this tipping point has a good probability of a high long-term return”*
- *“The ThorEA proposal is a good starting point from which to discuss a reasonable portfolio of risk for the UK Accelerator R&D programme”*
- *“..an accelerator based ADSR system is a great idea. There are no show stoppers but there is also no free lunch.”*

The referees also raised specific questions and criticisms of the ThorEA project. These questions and criticisms, and ThorEAs responses are paraphrased in the questions and answers below:

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### Q1. Why is now the right time to invest in ADSR accelerator technology?

**A1.** Because there is broad and growing activity in ADSR Accelerator R&D around the globe. For example, the Belgian government has just announced their support for the Myrrha ADS reactor to start construction in 2015 and begin operation in 2023, with an initial investment M€384 of a total budget of around €1 billion. This growing interest is driven by the steady progress being made in 3 simple and well defined metrics that can be used to measure the success of step-by-step accelerator R&D:

1. **Average beam power** (now moving from 1.3 MW towards 5 MW, in the range of interest)
2. **High reliability** (short of requirements, but amenable to focused engineering, e.g. Myrrha)
3. **Capital cost** (currently the ESS 5MW accelerator is costed at ~M€400)

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### Q2. The 5 MW European Spallation Source currently plans to spend ~€1 billion over 10 years in 14 nations, and much less than €300m in the first 5 years. Although the UK has a potent nucleus of skills and facilities, could the UK by itself really expect to proceed at the initial spending rate suggested by ThorEA in the proposal of £300m in a 5 year “demonstrator” phase, before commissioning a prototype power station in 2025?

**A2.** ESS actually plans a 2 year R&D phase followed by a 6-7 year construction phase. The R&D phase, and indeed the cost, is not solely related to the accelerator and spallation target but also to the advanced neutron instrumentation suite and conventional facilities (each of which will absorb a third of the total costs). Similar large scale projects have included SNS in the United States and Diamond in the UK, both of which were delivered as fully operational facilities in seven years – the ThorEA project is more modest, wishing only to deliver an accelerator demonstrator within five years. In this respect the ThorEA proposal is much closer in cost and timing to the MYRRA project.

More generally, timescales are very much a matter of political will and socioeconomic necessity. A particular, if rather extreme, example is the speed of development of operational power stations from Fermi’s original Chicago Pile demonstrator.

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### Q3. Four accelerator technologies, each with advantages and disadvantages, contend for use in a 10 MW proton driver: 1) Cyclotrons, 2) Rapid Cycling Synchrotrons, 3) ns-FFAGs, and 4) Superconducting linacs. The UK has played a leading role in developing ns-FFAG technology, but it is controversial whether “... ns-FFAG holds the greatest potential ...” Will it not take more than 5 years for an ns-FFAG to play a critical part in a 10 MW demonstration driver, and is it advisable for the UK to put all its eggs in the ns-FFAG basket?

**A3.** Whilst the NS-FFAG concept has yet to be proven to provide the currents required, considerable theoretical and practical progress has been made, even in the last 12 months. Nevertheless, the ThorEA report repeatedly discusses how the project is very carefully planned not to put all the accelerator eggs into a single (ns-FFAG) basket. Instead a full evaluation of existing and emerging accelerator technologies will be performed within the first two years of the project before a final decision on the next stage accelerator driver development is made.

**Q4.** *Early investment in accelerator technology at this tipping point in ADSR development has a good probability of a high long-term return. Few technological advances would be as globally transformative as robust ADSR power generation, and transmutation. ADSR accelerator R&D would also pay other dividends – foreseeable and unforeseeable – even if robust ADSR power generation can not be achieved. Now is the right time for the UK to make a well-considered entry into ADSR accelerator R&D. The ThorEA proposal is a good starting point from which to discuss a reasonable portfolio of risk for the UK Accelerator R&D programme, but should the UK could choose to compete or collaborate with other countries, inside or outside the EU?*

**A4.** The competition vs collaboration argument is an interesting one: In principle there are perhaps two strategic choices:

1. A European project with EU political constraints and pace
2. A UK National project helping to rebuild national capacity with public money (as part of a UK return to industrial policy)

The prize for successfully competing with other countries in ADSR technology is substantial. At present estimates ~£30 billion plus will be spent on nuclear power in UK over next ten years. This will have macro-level effects on UK economy. Developing an ADSR capability for UK industry will have comparable effects.

Conversely there are aspects of ADSR R&D for which collaboration could be desirable, possible and fruitful. However, until the ThorEA initiative, the UK had little to take to the international ADSR table. The ThorEA project could place the UK at the very centre of global ADSR collaborations.

**Q5.** *ThorEA suggests that a 10 MW accelerator will require approximately 20 MW<sub>e</sub> to sustain its operation.” Is this realistic?*

**A5.** The estimate of 20 MW wall-plug power comes from the typical accelerating structure efficiency, which is where most of the power will go. A more robust estimate is needed, and will indeed be determined as part of the R&D programme. However, this is not a critical issue for the development of ADSR technology. Even a doubling of the estimated power demand to 40MW will not change the overall feasibility of the proposed ADSR scheme.

**Q6.** *The ThorEA report states that “... an extensive and coherent research and development (R&D) programme could secure all underpinning technology necessary to facilitate construction of the world’s first thorium-fuelled ADSR power station in the UK by the target date of 2025.” Is this date realistic?*

**A6.** The time scale for this, as for any highly technical project, is clearly dependent upon both technological development and political will. The suggested five year development programme for the basic ADSR technology is fully consistent with the development and delivery of, for example, scaling FFAG technology in Japan; the development of SNS and J-PARC; the construction 25 years ago of the world leading ISIS facility; our own ns-FFAG CONFORM project; and the projected schedule for delivering the 5MW accelerator stage of ESS. It is also commensurate with the suggested time scale of the MYRRHA project, which does not have the critical advantage of the global lead in innovative (ns-FFAG) technology provided by our CONFORM project. Additionally, it should be noted that the time scale 2025/2030 is not overly critical to the proposed R&D programme. The intention is to demonstrate thorium fuelled ADSR technology as a timely alternative to plutonium fuelled GEN IV systems, which are scheduled to come on line in 2030.

**Q7.** *ThorEA suggest “The principal objective of the five year AESIR (Accelerator Energy Systems with Inbuilt Reliability) R&D programme is to design, build and demonstrate a robust and reliable prototype accelerator system which will be suitable for mass production and commercialisation as an ADSR proton driver.” Can this be done in 5 years: the current state-of-the-art is the 5 MW ESS, which will take 10 years to design, build, and commission?*

**A7.** Unfortunately this is a mistaken comparison with ESS: the ESS driver itself will **not** take 10 years to design build and commission. The ESS, as fully working 5MW spallation source delivering neutrons, will take as little as nine years to complete. This suggests that coupling the development of the accelerator/target assembly design with the parallel design and development of an ADSR core will indeed be possible on a 15 year timescale. Again, we emphasise that the time scale of the ThorEA project is entirely comparable with estimates for the MYRRHA project.



Frequently Asked Questions *continued*

**Q8.** *ThorEA has suggested an ADSR core with a criticality factor of 0.985, but that optimal ADSR core design calculations may favour higher core criticalities and hence lower beam currents, relaxing somewhat the design parameters of the proton accelerator. Why not go to higher criticality factors, and perhaps greatly simplify the accelerator design?*

**A8.** ThorEA's initial choice of criticality coefficient is based upon how far below  $k=1$  it is feasible to go yet still be able exploit currently realisable accelerator technologies. A total proton beam power of 10MW is close to the current state of the art and therefore is an entirely appropriate starting point to maximise the flexibility in the criticality whilst increasing safety margins. It should also be noted that the report indicates that it may be desirable to deliver the total driver power using several accelerators simultaneously. This will also facilitate a simplification of the design of each individual accelerator, albeit at the expense of complexity in beam delivery. This latter point has already been addressed by IPR lodged by STFC and members of ThorEA.

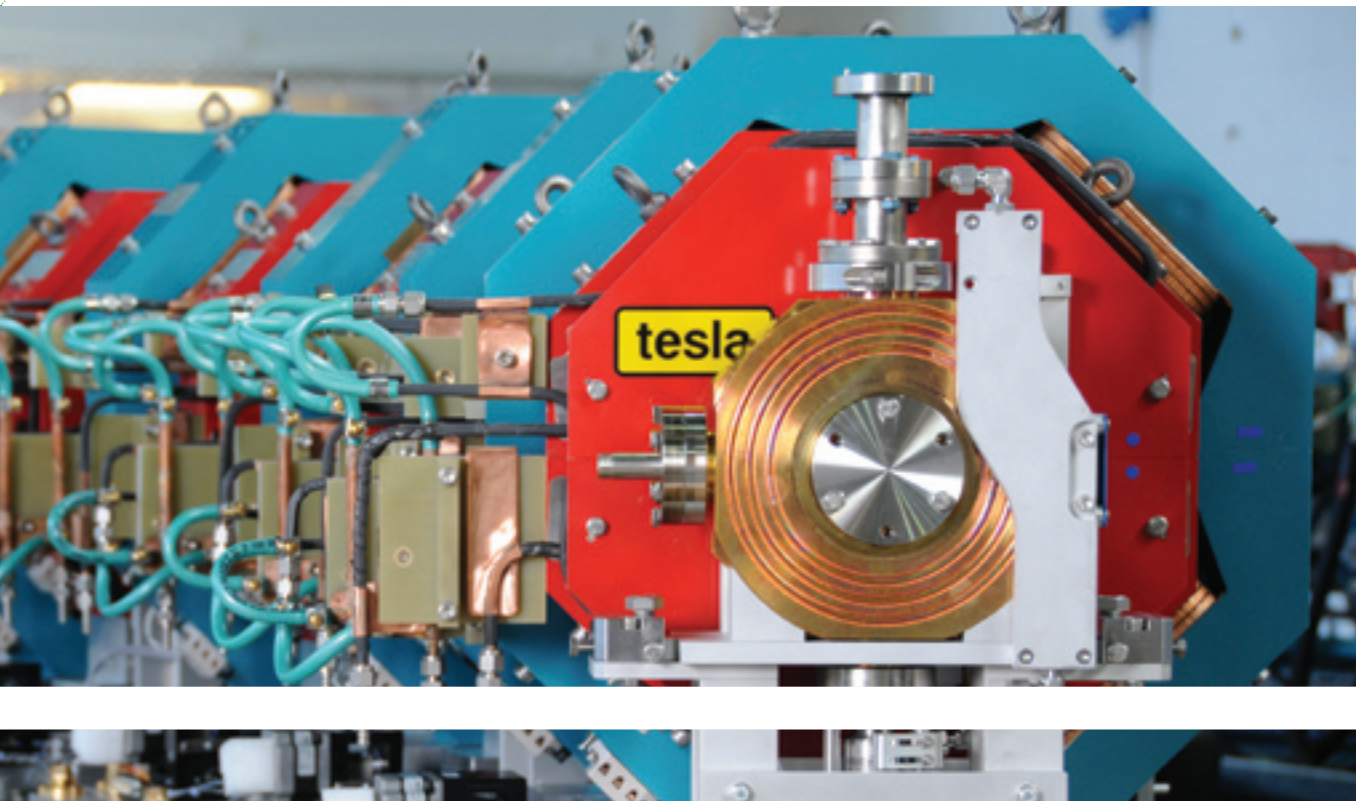
**Q9.** *ThorEA suggests higher currents are, broadly speaking, easier to achieve than higher energies. Doesn't this conflict with the opinion of the ESS, which is updating its parameters from the 2003 design to decrease the current and raise the energy by a factor of about 2.5, going to 2.5 GeV? Lower currents can enable higher reliability.*

**A9.** For a given accelerator power there is always a trade-off between current and energy, depending upon the particular accelerator technology employed. For some systems, at mA currents, it may well prove to be easier to double the beam power by doubling the beam energy. However, the statements about ESS are erroneous. Whilst the concept of the ESS driver energy increasing from 1.3 to  $>2\text{GeV}$  has been discussed (as it must) any decision on beam delivery parameters will be based not upon arguments of a trade-off between current and energy, but entirely upon the neutronic performance of the ESS neutron spectrometers themselves. Indeed our own calculations on the ESS target, performed for and funded by the EU-FP7 ESS Preparatory Phase Project, show that increasing the proton energy substantially increases the neutron density distribution within the target, with a potentially deleterious effect on neutron delivery to the moderators and subsequently the beam lines. Professor Colin Carlile, the Director of the ESS project has confirmed to ThorEA that no decisions have yet been made to take the ESS driver to energies above the 2003 value of 1.3GeV.

**Q10.** *FFAG R&D is still at an early stage, and FFAGs indeed deserve further support and exploration, but this direction is high risk, high gain. Is there not a significant probability that FFAGs will not be "more reliable, cheaper and more compact"?*

**A10.** There is a significant risk that FFAGs may not be appropriate for ADSR systems integration – but that is why a major R&D programme is proposed by ThorEA, and why other more conventional technologies will be evaluated alongside the ns-FFAG option. We also intend to discover whether FFAG will be more reliable, cheaper and more compact, noting that there have already been significant advances in FFAG technology over the last 12 months, particular when compared to the rather slow rate of development of competitor technologies.

Whilst it is clear that all ADSR technologies present major challenges, it is also widely accepted that thorium fuelled ADSR systems could afford a significant and timely solution to some of our energy needs. Therefore if existing accelerator systems were capable of delivering ADSR technology there is no doubt that they would already be doing so. It is in this context that we believe major investment at this stage of development could have major technological and socioeconomic impact for the UK.



**Q11.** *ThorEA focus upon FFAG technology. If we remove the synchrotron concept from the list of other potential ADSR accelerator technologies because of its pulsed nature, then the only two remaining are SCRF linacs and cyclotrons (or their combination). An SCRF linac concept has already received wide international attention. It was the basis for Rubbia's original proposal may be the most feasible concept to date. In this respect is the optimism regarding the feasibility of the ns-FFAG concept with regard to the ADSR applications really warranted?*

**A11.** This comparison with alternative accelerator types is relevant but the conclusions can be challenged. As of today, the linac is the simplest solution, but because of cost and size it may not be the best for ADSRs and hence other options must be investigated. Superconducting RF technology is also an attractive solution that could be appropriate for any ADSR accelerator driver, and may or may not turn out to be inappropriate for FFAG accelerators. That is why the evaluation of accelerator driver technology lies at the very core of the proposed R&D programme, and is the principal challenge of the ThorEA study. We therefore feel it is unreasonable at this stage to expect a detailed answer to the questions raised. Indeed if those answers existed then an ADSR would undoubtedly already have been built. The ThorEA report, rather than focusing upon FFAG technology, emphasizes the optioneering and feasibility aspects of the proposed programme within which all relevant accelerator technologies will be evaluated, not against FFAG technology but alongside it.

**Q12.** *Will not a crucial factor in the ADSR design be the minimization of beam losses to reduce component radio-activation and enable hands-on maintenance?*

**A12.** There is no doubt that for all types of accelerators, special care has to be taken to control beam loss and try to restrict it to certain, planned, places. In the case of linacs, a lot of beam loss can occur when the beam is first bent, which tends to be at high energy, where it can be particularly damaging. This is a problem that is present in all accelerator driven facilities and installations and is one that will have to be addressed as part of the proposed R&D programme. There is no indication as yet that it will be either better or worse for an ADSR driver.

**Q13.** *The spend profile jumps from 0 to £40m in the first year, and fluctuates from £53m to £90m and back to £60m in years 3, 4 and 5. Surely these features are unrealistic?*

**A13.** ThorEA believes that the proposed spend profile is realistic. The £40m step function in year one is not unmanageable. The assembly of LOKI requires significant up-front investment in existing accelerator technology. It is also important to point out that it intended that in the report we suggest that it will be advantageous to locate the project at the Daresbury Laboratory, where technical and managerial accelerator expertise, and the appropriate physical infrastructures capable of coping with a project of this magnitude already exist.



## ThorEA Biographies

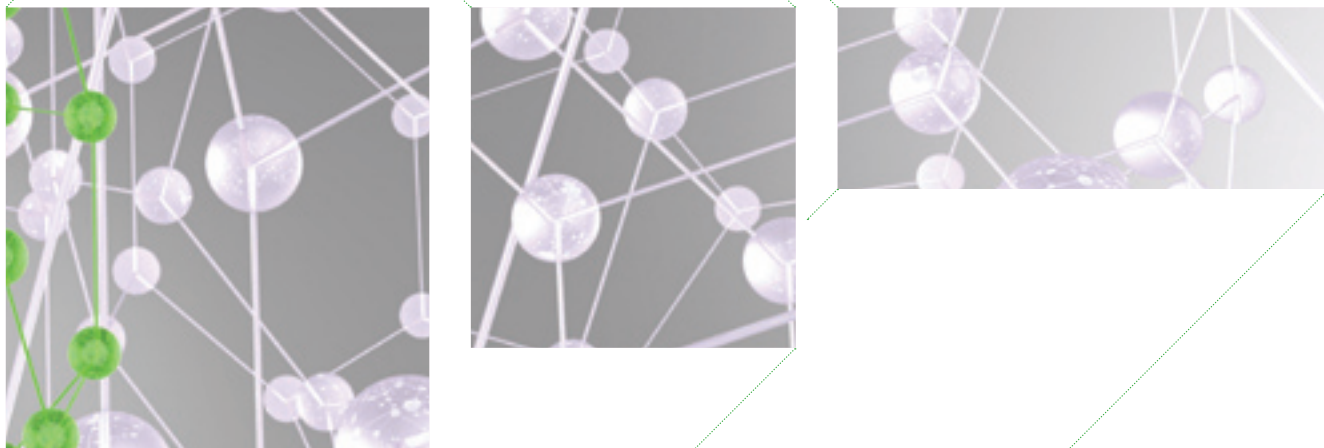
**Roger Barlow** is a Professor of Physics at the University of Manchester, and Head of the Particle Physics Group there, one of the largest research groups in the UK. He has over 30 years experience in the use of particle accelerators, in particular on the TASSO, JADE, OPAL, BaBar and CALICE experiments. He helped to found the Cockcroft Institute for Accelerator Science and Technology, and is Principal Investigator on the CONFORM project which is presently constructing the world's first non-scaling FFAG accelerator, and is Chair of the ThorEA organisation. He is a Fellow of the Royal Statistical Society and of the Higher Education Academy.

**Bob Cywinski** is a University Research Professor and Dean of Applied Sciences at the University of Huddersfield, with 35 years experience in the application of neutron and muon beams in condensed matter science. He was a member of the team that built and commissioned the ISIS spallation neutron source at RAL in Oxfordshire, and for over fifteen years has been central to the European Spallation Source project. He is currently a partner in the EU funded FP7 ESS Preparatory Phase Project. He has Chaired the European Neutron Scattering Association (ENSA), and has recently been re-elected as President of the International Society for  $\mu$ SR Spectroscopy in Europe (ISMS-E) and Vice President of the global ISMMS. He has had advisory roles at JINR-Dubna, TRIUMF (Canada) and ILL (France), J-Parc (Japan) and is Vice-Chairman of ThorEA and Programme Manager of the CONFORM Applications package.

**Leonardo Vila Nova Goncalves** is a postdoctoral research associate in the Department of Engineering at Cambridge University. His present activities concern the identification and simulations of core and fuel designs options for an ADSR driven by one or multiple ns-FFAG accelerators with the purpose of assessing the potential of this innovative accelerator technology and the strengths and weaknesses of ADSR-thorium energy systems when compared to viable alternatives on suitable timescales. Prior to his activities at Cambridge, he carried out his PhD research in the field of nuclear waste transmutation in ADS at the ENSM of St. Etienne in France and at CERN in Switzerland, where he had already worked as a fellow associate from 1999 to 2004, performing several thermo-hydraulic studies for the LHC detectors.

**Adonai Herrera-Martínez** received his MBA degree from INSEAD in July 2009. Previously, he worked as a consultant in Capacity Building for Energy Systems for a year at the UNDP, in HQ and West Africa. His worked included policy advising to governments in the region on costs and benefits of different energy for poverty reduction programmes. Until 2007, Adonai was working at CERN, managing the design of a 5 MW neutron spallation source within the EURISOL-DS project. In 2004, he obtained his PhD in Nuclear Engineering from the University of Cambridge, in the topic of Transmutation of Nuclear Waste in Accelerator-Driven Systems. From 2001 to 2004, PhD his research was carried out at the Emerging Energy technologies group at CERN, led by Prof. Carlo Rubbia. In 2000, he obtained his MEng from the Universitat Politècnica de València (Spain). Adonai's interests focus on strategic and technical solutions to develop sustainable energy systems and on energy policy advising, in particular for emerging and developing countries.

**Giles Hodgson** is an independent Business and Policy Advisor. He has a BSc(Hons) Management Sciences degree, an MPhil in Technology Policy from Cambridge University and is CEng qualified. His management consultancy background, combined with his policy advice experience (to the Conservative party) gives him insights into both the commercial and political worlds. His current work is focused on energy policy, low carbon generation alternatives and consumption reduction.



**William J. Nuttall** is a University Senior Lecturer in Technology Policy at the University of Cambridge. In 1987 he won a Fulbright Post-Graduate Student Award to the Massachusetts Institute of Technology to study for a PhD in physics awarded in 1993. Returning to the UK he took two post doctoral research positions in large-facility physics using x-ray and neutron scattering to study phase transitions in diverse systems including actinide magnets. In 1997 Dr Nuttall moved to the London headquarters of the Institute of Physics where he later became Manager, Policy. At the IOP he worked on a wide range of physics-based policy issues including energy. In early 2002 he moved to Cambridge University to be founding Course Director for a new Cambridge-MIT Institute (CMI) sponsored master's degree in Technology Policy. He holds a shared post between Judge Business School, where he is based, and Cambridge University Engineering Department. He is the author of the book *Nuclear Renaissance* (Taylor & Francis 2005), co-editor of the book *Future Electricity Technologies and Systems* (CUP 2006), co-editor of a special issue of the journal *Progress in Nuclear Energy* concerning long-term management options for separated civil plutonium (2007). Dr Nuttall has a leading role in the ESRC Electricity Policy Research Group. He has assisted the UK Parliamentary Office of Science and Technology and the International Energy Agency. He has given oral evidence on nuclear power to the UK House of Commons Trade and Industry Select Committee.

**Hywel Owen** is a Lecturer in Physics at the University of Manchester, with 15 years experience in the design, construction, and operation of particle accelerators. He was a co-designer of the DIAMOND storage ring – the largest accelerator facility in the UK, and successfully operating since 2006 – and has been closely involved in the accelerator design of every light source facility planned or built in the UK (SRS, 4GLS, ALICE, and the New Light Source). He presently sits on the committees of the Particle Accelerators and Beams Group and Chartered Physicist Review Panel of the Institute of Physics, and has been chief editor of the European Particle Accelerator Conference.

**Geoff Parks** is a University Senior Lecturer in Nuclear Engineering in the Department of Engineering at Cambridge University. He received his BA in Engineering from the University of Cambridge in 1984 and his PhD in Nuclear Engineering in 1989. He was subsequently elected to a Research Fellowship at Jesus College, Cambridge, and then became a Senior Research Associate at Cambridge University Engineering Department, funded by Nuclear Electric plc. He became a University Lecturer at the start of 1996. He was promoted to Senior Lecturer in January 2004. Dr Parks heads the Computational Design Group in the Cambridge Engineering Design Centre, which researches into the application of advanced optimisation methods to difficult real-world problems in a wide variety of application areas including aerodynamic, nuclear and structural engineering, in the development and application of multi-objective optimisation methods, and in the effective exploitation and integration of optimisation methods within the Engineering Design process. Dr Parks has long-standing interests in nuclear reactor operation and control with particular expertise in in-core fuel management, and helped develop the code used by British Energy to design reload cores for Sizewell B. He has more recently developed interests in the use of accelerator driven systems for waste transmutation and power generation and in gas turbine based power generation cycles.

**Steven Steer** is a fundamental nuclear physicist; he earned his PhD researching at the University of Surrey in coordination with international programs at world-leading accelerator facilities for the study of heavy-nuclei. He served 2 years as a member of the Institute of Physics nuclear physics group committee. He is currently a research associate at the University of Cambridge Engineering Department and a member of the Electricity Policy Research Group, where he is evaluating ADSR technology with consideration of both technology and economics.

