



A Review of the UK's Nuclear R&D Capability

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A Review of the UK's Nuclear R&D Capability

A report prepared by the Dalton Nuclear Institute, National Nuclear Laboratory and Battelle, commissioned by the Technology Strategy Board in partnership with Materials UK and Regional Development Agencies

Technology Strategy Board
Driving Innovation

A Review of the UK's Nuclear R&D Capability

A H Sherry¹, P J A Howarth², P Kearns³ and N Waterman⁴

Executive summary

With a market valued at around £600 billion for new nuclear build and £250 billion for decommissioning, waste treatment and disposal, the predicted resurgence in the nuclear market over the next 20 years could lead to significant opportunities for UK businesses both nationally and globally in the area of nuclear engineering and its associated technologies.

The UK has a strong historic track record in nuclear engineering, having been one of very few countries that has closed the complete fuel cycle. It has developed thermal and fast reactors, reprocessing technology, fuel manufacture, and enrichment expertise. However, it is recognised that much of this capability (with the exception of the defence sector) has been in decline over the past two decades as the UK focus has shifted away from nuclear to other power generation sources. With the advent of a global nuclear renaissance there should be significant opportunities for UK organisations to take advantage of this new market, particularly if a coordinated approach, which recognises the UK's core skills, is taken to develop the necessary supply chain and skill-base.

This report has been commissioned by the Technology Strategy Board in association with a number of the UK's Regional Development Agencies and Materials UK, and assesses the UK's current R&D capacity and the opportunities for UK organisations to develop and deploy innovative technologies to support the civil nuclear industry. The review has specifically addressed;

- the UK's R&D potential to develop and exploit the technology
- the potential for UK business to make an impact in the appropriate timeframe
- the national and global market opportunity for exploitation
- the potential role for public sector intervention that adds value above and beyond that of private investment

The study commissioned has been bounded to identify those opportunities associated with technology development yielding a potential commercial return over the next 5-10 years (although the report also takes account of longer term payback opportunities, where there are clear perceived benefits to UK business). It has also focused on organisations beyond the main industry players and 1st and 2nd tier suppliers to include SMEs. The intention has been to understand what role the sponsors could play in supporting organisations in developing and deploying technology and innovative products. Therefore, by definition, the technology exploitation must be closer to market than blue-sky science (such as that funded by the Research Councils), but not so close that any public-sector investment cannot be justified and could be regarded as anti-competitive. This implies investment around Technology Readiness Levels (TRL) 3-6 in the technology innovation chain.

The review has been compiled in consultation with many of the major organisations involved in the nuclear supply chain in the UK. In addition, the review has been given an international perspective to help understand the UK's actual and perceived position amongst the countries at the forefront of nuclear engineering R&D, such as the USA, France, Japan and India.

What is clear, if the UK is to capture a significant share of the nuclear energy market it must invest in those areas of nuclear engineering where there is existing capability and experience, and it is perceived by the rest of the world to be strong. It must collaborate with other nations where it can provide world class contributions to advanced reactor systems and nuclear fusion power systems (ITER and DEMO), and also decide that it will not repeat the errors of the 1960s and 1970s by researching every conceivable system for producing power from nuclear fission and nuclear fusion. It should stay with the mainstream efforts of other countries and organisations with the view of collaborating where appropriate to leverage the more recent experience of others.

Even though the next generation of reactors (Gen III) to be constructed will be designed by organisations from overseas (such as Westinghouse and Areva) the UK's supply chain still has a strong role to play. Opportunities exist mainly in support of the licensing of the new reactor technology being conducted by the NII/HSE, advanced modelling to improve operational efficiency, reliability and safety, Non-Destructive Evaluation (NDE) of components and structures during build, operation and maintenance, improved understanding of materials degradation mechanisms to ensure practical lifetimes in excess of 60 years, manufacture of components and sub assemblies, assessment of alternative components in the event of any supply restrictions, the development of advanced construction techniques to improve programme delivery and cost, and production and recycling of advanced fuels. The UK has long-established R&D strengths in each of these areas.

In addition to support for Gen III deployment, opportunities exist to support continued operation of

existing reactors (Gen II), advanced thermal systems (Gen III+) and more advanced reactors scheduled for 2020 and beyond (Gen IV).

There is further opportunity for R&D and subsequent innovative nuclear engineering associated with Gen III+ and Gen IV reactors including non-electricity generating opportunities such as high temperature process heat and desalination. Although these systems are not likely to be deployed commercially until after 2030, there are a number of on-going projects around the world to build Demonstrators / Prototypes / Test Reactors and these will create new business opportunities, e.g. the Pebble Bed Modular Reactor (PBMR) in South Africa, the High Temperature Reactor – Prototype Modular (HTR-PM) in China and Fast Breeder Reactors (FBRs) in several countries. The UK currently has minimal involvement with these projects although it does have the skills and experience to contribute in several areas of relevant technologies. Greater investment in support of R&D on advanced reactor systems is necessary if the UK is to have any continuing credibility as a major player.

Construction of new reactors is only part of nuclear energy deployment; supporting infrastructure is required associated with the nuclear fuel cycle. This includes conversion of resources into fuel at the front-end prior to loading into the reactor, followed by spent fuel management and handling once fuel is discharged. There is also the potential for significant development of some of these fuel recycle options in order to support the more advanced Gen IV systems.

An additional aspect of the UK's nuclear industry is associated with security, safeguards and non-proliferation. Given the UK's historic capability, it is well placed and indeed already active in supporting international initiatives such as the IAEA, GNEP, Global Threat Reduction, Nuclear Safety in FSU countries etc.

Whilst this study does not consider defence-related nuclear development there are nonetheless some capabilities from this sector that

could be utilised in the civil nuclear market. For example, the Light Water Reactor nuclear naval propulsion capability within Rolls-Royce has direct relevance to civil reactor build and operational support. The non-proliferation, materials detection, tracking and safeguarding work at AWE is also relevant to the development of advanced civil nuclear fuel cycles that are proliferation resistant. BAE Systems have developed modular construction techniques and virtual reality modelling to support construction, in addition to being actively engaged in reactor plant integration and commissioning.

Spent fuel handling technology has been considered in this report given its relevance to advanced fuel cycles, however assessment has not been included of market opportunities or technology development associated with the decommissioning, legacy waste management or geological disposal markets. These opportunities have been excluded from the study, however technology development within the industry that could be transferred from these markets to the civil nuclear energy market has been considered.

The domestic and overseas responses to the review indicate the wider global nuclear industry believes that the UK has outstanding R&D capabilities in the following areas:

- Advanced modelling and analysis of reactor cores of all types used commercially at present and also including those planned for the new build Generation III systems and some advanced reactor systems in particular gas-cooled reactor systems.
- Thermal hydraulics and major accident modelling
- Fuel design, manufacture and performance modelling.
- Fuel enrichment and re-cycling
- NDE and Structural Integrity of materials and structures
- Advanced construction methods
- Materials Degradation (metals, concrete and plastics)
- Decontamination and decommissioning
- Waste treatment and management
- Fuel cycle assessment

Some of these areas of special expertise have already demonstrated the potential for technology spin-out and spin-in, in particular NDE for other large process plant industries and advanced modelling for areas as diverse as coastal erosion and flow modelling of pollutants in an urban environment.

Investment in advanced reactor or fuel cycle technology associated with Gen III+ or Gen IV systems does not fit the defined exploitation requirements of this review, given the long development timescales and the fact that commercialisation is not likely for a couple of decades. However, investment in such advanced systems might be justifiable if it results in new products and services that could be utilised on existing reactor systems or business opportunities that are likely to exist within the next 5-10 years. Examples that have been included here include:

- Fuel manufacture and development – improving burn-up and performance of fuel in existing reactors
- Control, detection and monitoring systems – techniques to support lifetime assessment of existing reactor systems
- Materials analysis, assessment and characterisation techniques – understanding and predicting plant related issues on current systems
- Assessment of advanced fuel cycles – support to global threat reduction programmes associated with safeguards and non-proliferation
- Knowledge management activities that can help transfer the UK's vast experience base to the new wave of engineers that will support the global nuclear renaissance.

The wide consultation which has taken place over the period March – June 2009 with with key national and international players has been distilled into this report.

In summary, it is considered that the TSB and the RDAs can assist UK industry, including SMEs, to access the opportunities that the nuclear renaissance offers by:

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- Investing in appropriately scoped R&D programmes and infrastructure projects
- Leading knowledge transfer and capture activities both within the nuclear sector and establishing links to other business areas
- Communicating the new business opportunities in nuclear engineering. (This is already happening through a series of well-attended supply chain workshops.)
- Encouraging and assisting UK companies to become accredited to supply the nuclear engineering industry
- Facilitating closer contact with UK universities engaged on nuclear engineering R&D and in particular encouraging two-way secondments and knowledge transfer partnerships
- Promoting international engagement and collaboration

Specific opportunities that have been identified as satisfying the above criteria for “public-sector intervention” arise within general categories of Technology, Infrastructure and Knowledge, and include the engagement with the Euratom Framework programmes. The opportunities identified during the course of the review include the following:

- Non-destructive Testing and Examination (NDT/NDE)
- Condition monitoring and preventative maintenance
- Materials degradation, structural integrity and lifetime
- Digital command and control systems
- Advanced Manufacturing Research Centre(s) for Nuclear components and systems and fuels
- Modularisation
- Advanced fuel manufacturing
- Fuel recycling
- Fuel cycle assessment
- Knowledge capture, storage and transfer
- Virtual reality to assist manufacture and maintenance of new build plant
- Advanced modelling of systems, structures and components

Against these technology areas there are considered to be real commercial opportunities over the next 5-10 years that have specific market sizes ranging from >£1M to £100M with commensurate investment requirements ranging from <£1M to >£10M.

There are also UK based companies that could take these opportunities to market and spin-in and spin-out opportunities as well.

The assessment conducted here has shown there are many opportunities for UK organisations to exploit. However, in order for the UK to maintain its nuclear industry heritage and status as well as benefit from the global nuclear renaissance, public sector investment in R&D and technology development will be essential and can be justified.

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Summary Table of Technical Opportunities (further details provided in Section 6)

Key Investment Needs	Technical Opportunity	Size of market per new reactor	Likely UK share (probability)	Cost to market	UK Company (example only)	Spin-out opportunity (H/M/L)	Priority (H/M/L)	Comments	
Technology-based	A	NDE/NDT to reduce inspection times and accelerate new build programme	£10M's for construction, £100M's through life	High for UK, Medium for Global	< £10M	Industrial support to RCNDE,TWI, 20 to 30 key SMEs	High - nuclear and non-nuclear	High	Saving in manufacturing & construction costs, improving quality and reproducibility. Fingerprint welds at SOL
	B	Condition monitoring & preventative maintenance to increase safe life and reduce downtime	> £10M for construction, £100M's through life	High for UK, Medium for Global	< £10M	SMEs (and universities e.g. Cardiff, Manchester)	Many - nuclear and non-nuclear	High	Add-on to normal control & instrumentation. Need to demonstrate near-term value. Examples of gas turbine on-line monitoring, life extension, and Formula 1.
	C	Materials degradation, structural integrity and lifetime prediction including water chemistry and doping to reduce corrosion and advanced materials	> £10M. But note consequential impact.	High in UK, Low for Global	< £10M	Tiers 1 & 2, e.g. Atkins, Amec, RR, Babcock Marine, Serco, EDF/BE, ...	High e.g. creep, creep-fatigue, long-term corrosion issues. Other nuclear e.g. legacy waste management	High	Irradiation, corrosion, EAC, erosion, creep, etc. Impact of water chemistry on plant operation and reduction of degradation. Westinghouse use EPRI standards. Including local and global chemistry. Consider establishment of UK node for Materials Ageing Institute. Major benefit to utilities.
	D	Digital command & control systems to improve the performance, reliability and safety of complex systems	> £10M	Medium in UK, Medium for Global	> £10M	Rolls-Royce, BAE systems	High	High	Each new reactor will require a new digital command and control system.
Infrastructure-based	E	Advanced Manufacturing Research Centre(s) for Nuclear to address high value manufacturing and technical challenges by the supply chain.	> £100M	Medium in UK, Medium for Global	< £1M (less than £1M per project, but potentially 10 or so projects)	Existing AMRCs - university/industry (e.g. Sheffield Forgemasters, Metal Improvement) links.	High	High	Higher probability for smaller components rather than large components. Niche areas for SMEs in areas including HIPing, welding & joining, surface technology, new materials.
	F	Modularisation to encourage local build and assembly and engage the UK supply chain	> £100M	High for UK, Low for Global	< £10M	BAE Systems, RR, Doosan-Babcock flow through to SMEs	Low	Medium	Modularisation approaches to AP1000 using approaches used in ships, submarines, etc. Assembly on-site, building local industry. Reduce construction time, costs & improve quality. Standardisation in design is a goal, though different requirements in UK and overseas.
	Ga	Advanced fuel manufacturing processes including more efficient processes & improved fuel performance	Approx. £450M over 60 year lifetime	High for UK, Medium for Global	< £10M UK capacity already in place, but requires capital and R&D investment to compete for new build business.	Westinghouse, NNL, Rolls-Royce, Urenco	High- Strong possibility of combining civil and naval interests, but subject to MOD.	High	Build up manufacturing capacity in UK. Higher predictability, better QA, but sticking with existing design. Development of improvements to manufacturing processes. Including better inspection of each stage of the process.
	Gb	Fuel recycling including MOX fuel manufacture	Fuel recycling would need to be offered at a cost of >£10M per reactor per year.	High for UK, High for Global	> £1000M	Sellafield Ltd, Areva, Energy Solutions - SMEs, NNL and universities as technology suppliers	Low	Low	Political hurdles may limit additional recycling in UK and participation of UK companies in overseas recycling.
Knowledge-based	H	Fuel cycle assessment to reduce proliferation concern and waste volumes	Initially < £10M over 5 years, potentially to grow to > £10M per year if assessments are converted into improvements in industrial practice	High for UK, High for Global	< £10M	NNL, Manchester University, Sellafield Ltd	Low to Medium	High	Includes reprocessing, aqueous product volume reduction, Co-extraction reducing proliferation concern, separation of minor actinides, waste matrices & fuel fabrication.
	I	Knowledge capture, storage & transfer, roadmapping, knowledge transfer network	> £1M per new reactor year of operation	Medium in UK, Medium for Global	> £10M	LSC, NNL, Data Capture Solutions, etc.	High	High	Online, interactive and flexible, drawing on the latest information & communication technologies, ICT, (Google, gaming technologies, etc), networking people, with online access 24/7, and real-time updates.
	J	Virtual reality (3D visualisation & simulation tool) to assist manufacture and maintenance of new build plant	> £1M. But note consequential benefit	High for UK, Medium for Global	> £10M	Tier 1 interest but much involvement of SMEs including software organisations	High and Spin-in high	Medium	Combining software packages. Interactive approach to design & construction of new plant. Training for operation & maintenance engineers on existing and new plant leading to commercial advantage.
K	Advanced modelling to enable more efficient operation and higher levels of safety and plant availability	> £10M per new reactor year of operation	High for UK, Medium to high for Global	> £10M	Manchester, Imperial, Strathclyde Universities	High	High	Full multi-dimensional model of reactor core. Coupling of physics codes, CFD & structural codes. Pay-off for operating plant to predict where & when there may be a problem, e.g. flow distribution into reactor.	

*Information, Communication & Technology (ICT)

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Acronyms

AECL	Atomic Energy Canada Limited	MMM	Materials Management Matrix
AGR	Advanced Gas-Cooled Reactor	MOD	Ministry of Defence
AMRCs	Advanced Manufacturing Research Centres	MOX	Mixed Oxide
AWE	Atomic Weapons Establishment		
		NDA	Nuclear Decommissioning Authority
BNFL	British Nuclear Fuels Ltd	NDE	Non Destructive Evaluation
		NDT/NDE	Non-destructive Testing and Examination
C&I	Control and Instrumentation	NGNP	Next Generation Nuclear Plant
CFD	Computational Fluid Dynamics	NII	Nuclear Installations Inspectorate
CORWM	Committee on Radioactive Waste Management	NNL	National Nuclear Laboratory
CRD	Collaborative Research and Development Programmes	OECD	Organisation for Economic Co-operation and Development
		PBMR	Pebble Bed Modular Reactor
DEMO	Demonstration Power Plant	PWR	Pressurised Water Reactor
DoE	Department of Energy		
		QA	Quality Assurance
EAC	Environmentally Assisted Cracking		
EDF/BE	Electricité de France/ British Energy	R&D	Research and Development
EPR	European Pressurised Reactor	RCNDE	Research Centre in Non Destructive
EPRI	Electric Power Research Institute	Evaluation	
EU	European Union	RDAs	Regional Development Agencies
EURATOM	The European Atomic Energy Community	RR	Rolls-Royce
FBRs	Fast Breeder Reactors	SMEs	Small and Medium Enterprises
FR	Fast Reactor	SOL	Start of Life
FSU	Former Soviet Union		
		THORP	The Thermal Oxide Reprocessing Plant
GIF	Generation IV International Forum	TRISO fuel	Tristructural-isotropic fuel
GNEP	The Global Nuclear Energy Partnership	TRL	Technology Readiness Level
		TSB	Technology Strategy Board
HTR	High Temperature Reactor	TN	Technology Network
HIPing	Hot Isostatic Pressing	TWI	The Welding Institute Ltd
HSE	Health and Safety Executive		
		VHTR	Very High Temperature Reactor
IAEA	International Atomic Energy Agency		
ICT	Information Communication Technology		
IRIS	International Reactor Innovative and Secure		
ITER	International Thermonuclear Experimental Reactor		
JAEA	Japan Atomic Energy Authority		
KAERI	Korea Atomic Energy Research Institute		
KTN	Knowledge Transfer Network		
KTP	Knowledge Transfer Partnership		
LOCA	Loss of Coolant Accident		
LLWR	Low Level Waste Repository (UK)		
LWR	Light Water Reactor		

In May 2008, the Technology Strategy Board published its strategy to support innovation in the UK energy sector¹ which acknowledged the role that nuclear power could make in contributing to the security of electricity supply and in meeting climate change targets.

1.0 Introduction

The Technology Strategy Board (TSB) recognised the possibility that there could be significant opportunities for UK businesses in areas of research and development (R&D) presented by the global resurgence of new nuclear build and from spill-over technologies. In the light of this, the TSB, in combination with a number of Regional Development Agencies (RDAs) and MaterialsUK, has requested a review of the current status of the UK's nuclear R&D capability and its status as a technology provider and user. This review advises the sponsors of the potential business opportunities and makes the case for intervention for innovation in particular areas of nuclear engineering.

1.1 Remit from Technology Strategy Board

The TSB has set criteria for this review in the form of 4 questions:

- Is there a UK capacity to develop and exploit the technology and become a leading global player?
- Does the technology have potential for impact in the right timeframe?
- Is there a UK and global market opportunity for exploitation?
- Is there a clear role for public sector intervention and support that adds value above and beyond that of private investment?

1.2 Description of the Process and Participants

A consortium of the University of Manchester's Dalton Nuclear Institute, Battelle Memorial Institute and the UK's National Nuclear Laboratory (NNL) has undertaken the review through the mechanism of informal interviews with major players and stakeholders in the UK nuclear industry and nuclear industries in other countries. This was the basis for obtaining current first hand information about the UK's nuclear R&D capability, potential technology impact, market opportunities and appropriate role of intervention.

A significant body of detailed analysis has been assembled and this is described in a series of appendices to support the main report:

Appendix 1	Overview of the UK nuclear sector
Appendix 2	GEN III+ Medium Term Thermal Systems
Appendix 3	Current UK Nuclear R&D
Appendix 4	R&D for Future Systems
Appendix 5	Feedback from UK Stakeholders
Appendix 6	Feedback from International Stakeholders
Appendix 7	Materials Nuclear R&D Capacity, Opportunities and Spill-over Benefits

To complement the informal interviews, a stakeholder workshop was held to consider the analysis and views presented in a draft report. The resulting feedback has been incorporated into the final report.

The review has targeted reactor and fuel cycle technology but has not included legacy waste management and geological disposal or military applications of nuclear engineering. The aim is to identify R&D opportunities linked to technology deployment primarily within the next 5-10 years although R&D impacting in longer timeframes has also been considered where appropriate.

¹ Technology Strategy Board, "Energy Generation and Supply – Key Application Area 2008-2011"; T08/005, 2008.

The UK has had a self-sufficient programme of nuclear power since the 1950's that included the ability to design and build reactors, to manufacture and enrich fuel and to manage the irradiated fuel after discharge from the reactor.

2.0 Overview of the UK Nuclear Sector

The UK is one of only a few countries that has developed a fully closed fuel cycle with the ability to reprocess spent fuel and subsequently fuel prototype fast reactor systems. A more complete account is given in Appendix 1. The UK's extensive nuclear programme also includes naval propulsion, nuclear fusion research and development of deterrent technologies. As noted earlier these markets, as well legacy waste management and geological disposal, are not considered here but where there is technology overlap this is taken into account.

Whilst reactor deployment (Gen III) systems represent a major proportion of market opportunities there are additional opportunities associated with support to existing (Gen II) reactors in the form of lifetime extension as well as technology development associated with fuel cycle and infrastructure support.

For new nuclear build, there is potentially a significant number of UK organisations and universities that could be involved. Whilst the total list is too large to cover, an indication is given using in Figure 1, which shows the Nuclear Industry Association map of the UK civil industry and number of employees by parliamentary constituency in 2008. The diagram is illustrative and there are a number of other organisations and universities that can support new nuclear build that may not be represented on this map. A recent review of the nuclear capability within UK universities has been published by Dr John Roberts and indicates that indicates over 200 academics with nuclear research and teaching interests in over 30 universities across the UK².

Research by the Nuclear Industries Association (NIA) concludes that companies in the UK nuclear industry have the capability to provide approximately 70% of the scope of new nuclear power plant projects (see Figure 2). This could be increased to approximately 80% with investment in preparation as shown.

The location of potential new nuclear plants is shown in Figure 3, which indicates a broad geographical spread and thus benefits across the UK.

There is also a growing market associated with global threat reduction, safeguards and non-proliferation. The UK plays a full and active role in international activities in this area and there are numerous technology development opportunities. Recently the Cabinet Office announced the establishment of a new national Centre of Excellence for Nuclear³ that will address the issues associated with expansion of nuclear power to support climate change but also global threat reduction through non-proliferation of nuclear material.

2.1 Continued Operations and lifetime extension

Ensuring the UK's operational plants (both reactors and fuel cycle facilities) can be safely and efficiently operated through to the end of their life is an important goal for the UK. The UK generates 15% of its electricity from nuclear, the principal reactors being mainly Gen II AGR stations and the Sizewell 'B' PWR. The older Gen I Magnox reactors, except for Oldbury and Wylfa, have now reached end-of-life. The primary aim with respect to the AGRs is to manage the plant safely until their declared closure dates or, where possible, to obtain lifetime extensions to between 2015 and 2020. The PWR at Sizewell is currently planned to operate until 2035.



© Image copyright of Doumreay Site Restoration Ltd and NDA.

² Available at www.nuclearliaison.com/directory

³ "The Road to 2010 – Addressing the nuclear question in the twenty first century", Cabinet Office Report, July 2009

2.0 Overview of the UK Nuclear Sector

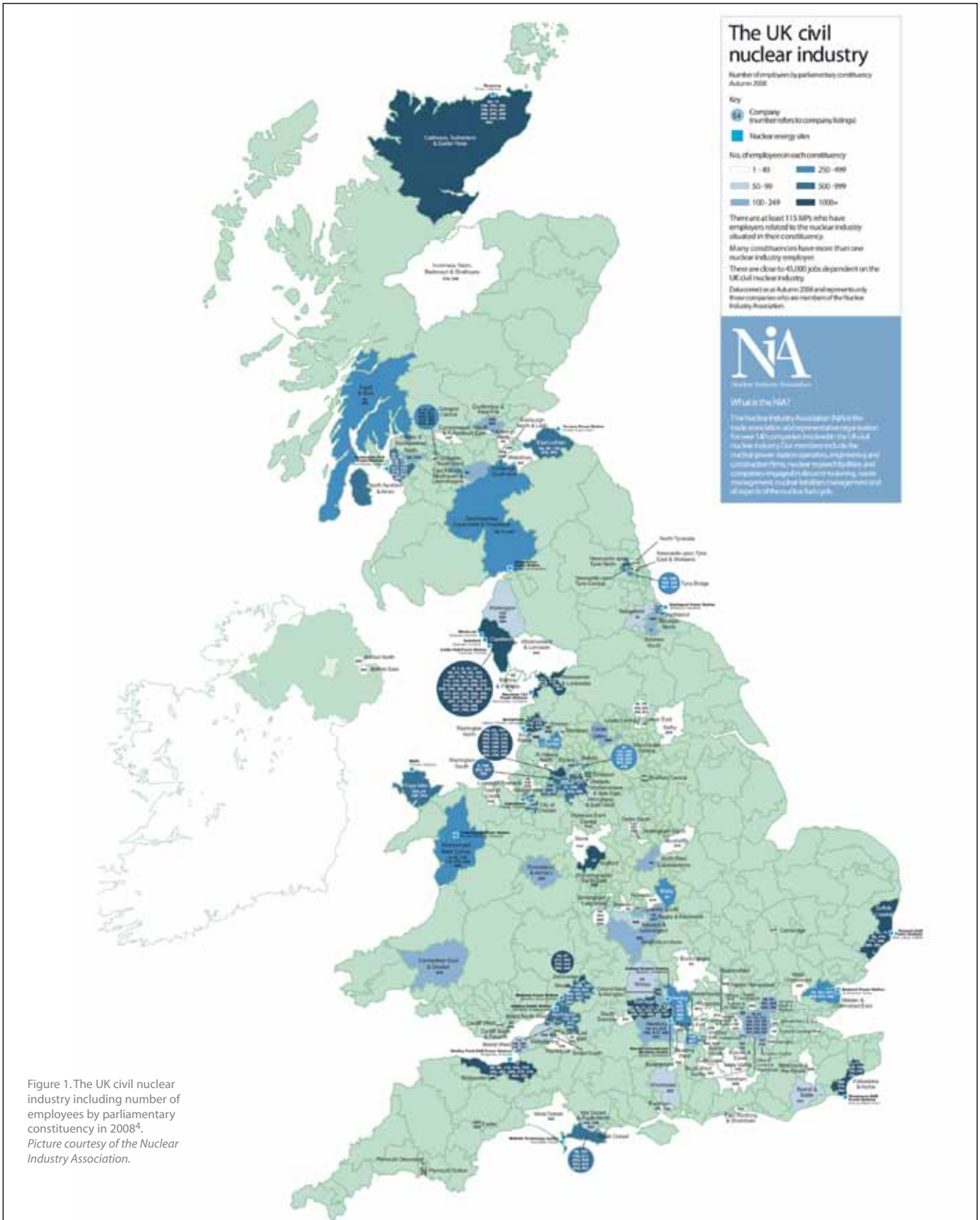


Figure 1. The UK civil nuclear industry including number of employees by parliamentary constituency in 2008⁴.
Picture courtesy of the Nuclear Industry Association.

⁴ Note, the above diagram is illustrative and there are a number of other organisations and universities that can support new nuclear build that may not be represented on this map.

2.2 Generation III near-term thermal systems

The near term opportunity for the UK is the planned deployment of third generation systems, notably Westinghouse's AP1000⁶ system and Areva's EPR system. Both of these are the culmination of developments over the past two decades and offer evolutionary improvements on earlier LWR systems. These include innovative passive safety features, molten core catcher, improved performance characteristics, improved systems layout, modular construction techniques and enhanced safety control systems. By building upon previous experience the new designs will offer improved overall safety and performance. UK experience in PWR deployment for both civil and defence applications can be used to improve component fabrication and joining, manage safety case development and mitigate materials degradation for new plant. Furthermore, there are opportunities for the UK in optimising the operation of the Gen III systems, without having to become a reactor vendor, and this experience will produce capabilities that have the potential to be marketed overseas. (A summary of the international context for new reactor build is given in Appendix 1). The timeline for the deployment of Generation III systems is shown in Figure 4.

2.3 Medium term thermal systems

The UK has no plans for reactor systems beyond the proposed tranche of Gen III reactors but other countries are actively pursuing developments which may offer opportunities to UK businesses and which may provide an option for UK deployment at some future time. These reactor systems (commonly called Gen III+) are high-temperature gas-cooled reactors and novel integral light-water reactors. They are under development and are expected to be deployed around 2030, though prototype reactors are already under construction (e.g. in China) with further prototypes expected over the next 5 to 10 years. (Appendix 2 provides further details.)

High Temperature gas-cooled reactors such as the Pebble Bed Modular Reactor (PBMR) offer improved levels of safety through inherent design features. They are smaller in size and modular such that they can be deployed on less well established grids or in geographical areas where there is not the infrastructure for large plants. The world leaders in the field of high temperature reactor design are South Africa and China; both countries have plans for near term deployment, beginning with a demonstration reactor before 2020. In the USA, the Next Generation Nuclear Plant project is aiming for commissioning of a high temperature reactor, capable of supplying process heat, by 2021. Elsewhere research and development on high temperature reactors is being carried out in Russia, France, and S Korea. UK participation in the R&D could take advantage of collaborative research by these and other countries through the High Temperature Reactor Technology Network (HTR-TN) – a 21 partner network of the EU and the 10 member network of the Generation IV International Forum (GIF). UK experience, particularly in relation to structural graphite and high temperature weld performance, with respect to AGR reactors provides a significant opportunity for technology transfer in the short-term for prototype reactors, and in the medium term for the commercial design, fabrication and deployment of Gen III+ reactors.

Increased concern about CO₂ emissions and the move away from dependence on fossil fuels is focusing attention upon the role that high temperature reactors can play in industries that use high temperature process heat / steam and in a hydrogen economy, because they produce heat at around 700 to 900°C and are suited to thermochemical cycles or high temperature electrolysis that can be used to generate hydrogen using water only.

A separate class of Light Water Reactors (LWRs), the integral light water reactor systems, also have improved safety characteristics by incorporating the steam generators within the reactor pressure vessel. An entire class of potentially severe accidents associated with LWRs, known as the large-break loss of coolant accidents (LOCAs), can be eliminated by adopting such a design feature. IRIS (International Reactor Innovative and Secure) is a conceptual integral light water reactor plant that is currently being developed by an international consortium led by Westinghouse. The reactor will be of small modular size with an electrical output of approximately 350MWe. Likely markets for IRIS are mainly countries with small-scale electricity grids that perhaps do not have the infrastructure to support a fleet of large light water reactors. Designs for similar but smaller reactor are also being advanced by Areva, JAEA, KAERI and in the USA (for example, NuScale and B&W's m-Power concept).

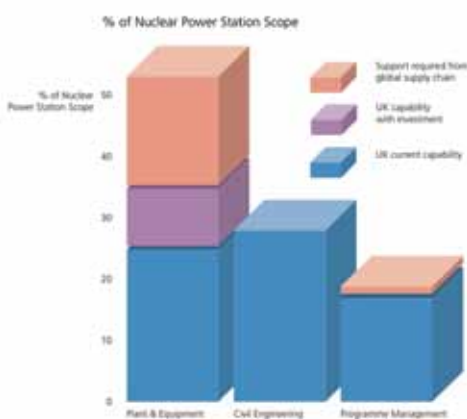


Figure 2. NIA analysis of UK capability to support new nuclear power plant build⁵.

- 5 "The UK capability to deliver a new nuclear build programme 2008 Update", Nuclear Industry Association Report, 2008
- 6 Note Westinghouse's AP1000 system is often categorised as a Gen III+ system due to its passive safe features. However more recently, and throughout this report, it is referred to as Gen III because it will be built on a similar timescale to other reactor systems.

2.0 Overview of the UK Nuclear Sector

2.4 Advanced thermal and fast reactor systems

Typically, these advanced reactor systems (commonly called Gen IV) are aimed for deployment after 2030 and there is not yet any commitment from the UK to such systems. They comprise both evolutions of Gen III+ designs, notably the Very High Temperature Reactor, and a series of designs based on fast reactor technology.

The reactor systems are characterised by:

- Significant improvements compared with existing systems in terms of economics, safety, environmental performance, and proliferation resistance.
- Offering a complete nuclear system (fuel, fuel cycle, and waste management facilities), not just a reactor.
- Being capable of commercial deployment after 2030.

Fast reactors can be configured either to breed or to burn fissile material (primarily plutonium) and thus meet concerns about scarcity of uranium stocks or, in contrast, the need to destroy surplus fissile material or burn long life transuranics that contribute significantly to the heat load of high level radioactive waste products. There are various prototype units operating or planned around the world but the timing of commercial deployment has not been decided.

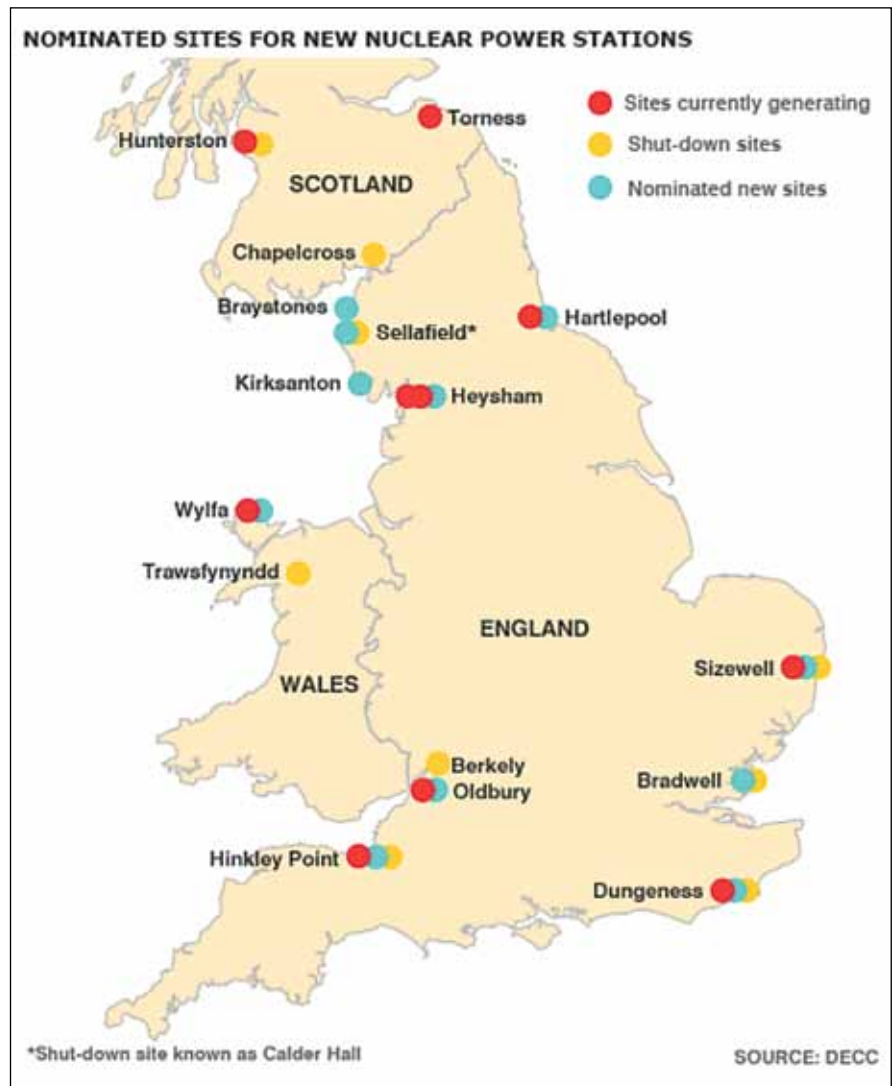


Figure 3 Nominated sites for new nuclear build

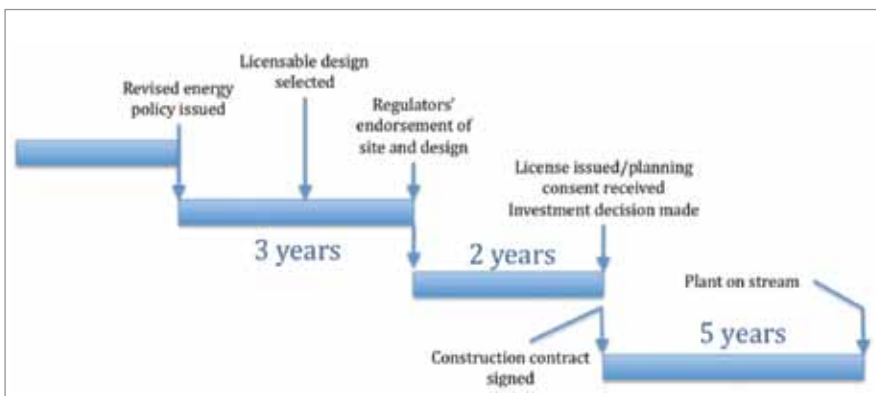


Figure 4 Timeline for Generation III deployment.

7 Details of the concepts and technology can be found on the websites for the GEN IV International Forum and the EU's Sustainable Nuclear Energy Technology Platform www.gen-4.org/Technology/roadmap.htm and www.snetp.eu

The development of such advanced nuclear reactor systems is extremely expensive and beyond the inclination of a single country to do alone without overseas support and investment. As a result many nations have recognised the benefit in collaborating by pooling resources in order to gain leverage on their own investment. Some of the main international programmes have been initiated by the US Department of Energy (DoE), European Union (EU) and International Atomic Energy Agency (IAEA).

Historically the UK was active in development of a sodium-cooled fast reactor system and this has produced a legacy of knowledge that could be exploited in international programmes. In addition, the technology developed for AGRs does provide a number of technical strengths that would enable the UK to contribute to programmes on gas-cooled thermal and fast reactors⁷.

2.5 Fuel Cycle technology

The need to recycle fissile materials within a fast reactor system necessitates the development of reprocessing technology as the first requirement is for recovery of fissile material from thermal fuels in order to be able to start up a fast reactor system. This, in turn, leads to the requirement to reprocess the fast reactor fuels and to be able to manufacture new fuel from the recovered fissile material. The current generation of technologies (such as used in THORP) are capable of providing fissile material recovery but there is growing international interest in fuel recycling that is more proliferation resistant, produces lower waste volumes and has minimal effluents. Some countries also see advantages in developing technology that separates long-lived and/or heat-generating radio-nuclides as a means of using proposed geological disposal facilities more efficiently.

2.6 Safeguards, non-proliferation and threat reduction

There is a growing recognition of the need for international activity to address safeguards, non-proliferation and threat reduction. This presents a market opportunity for UK organisations given that a number of the technologies deployed in this market are those already applied across the UK nuclear industry. Key technologies include: materials detection, assay and analysis, nuclear data evaluation, radiochemistry etc. There is a close relationship with fuel cycle technology, as reduction in proliferation of nuclear material partly implies the development of advanced fuel cycle technology such as co-extraction of uranium and plutonium.



A scientist wearing a white lab coat and safety glasses is operating a complex control panel in a laboratory. The panel features various gauges, digital displays, and buttons. The background shows industrial equipment and a clean, well-lit environment.

The near, medium and far term nuclear technologies all require supporting R&D activities to ensure operations are carried out safely, timely and to cost.

3.0 Research & Development Requirements

In addition to science and engineering R&D activities, a wide range of disciplines are required such as social, risk perception, human factors, safety analysis, socio-economics etc. The consortium has held informal interviews with major players and stakeholders in the UK and other countries to obtain current understanding of all the R&D requirements.

3.1 Continued Operations R&D

Issues relate to the support to existing (Generation I and II) reactor systems such as the Magnox and Advanced Gas-Cooled Reactors and the single Pressurised Water Reactor at Sizewell B. The licensees operating these systems have developed technology strategies that identify what is required to support the reactor systems through to the end-of-life. R&D and innovation development for these systems is mainly associated with either ensuring safe operation, lifetime extension where possible or cost reduction of operations, such as through predicting operability and plant condition monitoring.

The Nuclear Installations Inspectorate, charged with regulating UK nuclear operators, defines an index of safety issues, based on ensuring safe operation, which is referred to as the Nuclear Research Index. The Research Index categories are given below and indicate the main R&D activities performed:

- Plant Life Management - Steel Components
- Plant Life Management - Civil Engineering
- Chemical Processes
- Fuel and Core
- Radio-Nuclides
- Nuclear Physics
- Plant Modelling
- External Events
- Control and Instrumentation
- Human Factors
- Probabilistic Safety Analysis
- Radiological Protection
- Waste and Decommissioning
- Nuclear Systems and Equipment
- Graphite

In addition to reactor stations, many of the Research Index categories are also applicable to infrastructure supporting the rest of the nuclear fuel cycle.

3.2 Gen III R&D

The views from UK stakeholders are that for near-term deployment of Gen III reactors, a major technical development programme is not necessary as designs are already being deployed. There will, however, be a requirement to ensure licensees and utilities fully understand the safety related performance of advanced reactor systems. The main focus for R&D will be improved modelling of reactor cores, impact of fabrication and joining technologies on component performance, better understanding and prediction of materials degradation (including metals, plastics and concrete), including environmental degradation (all forms), fatigue, fracture toughness and irradiation damage of fuel and reactor materials. Within the UK, the first Gen III systems are expected to be deployed around 2017. However it is possible that R&D conducted now could support the licensing, deployment and construction of such systems; a programme of activity that will be ramping up significantly from now onwards.

Additional areas of R&D to assist with licensing were considered to be:

- Use of digital C&I systems for protection & control
- Incredibility of failure of items (e.g. pressure vessel)
- Probabilistic risk assessment – reconciliation of approach
- Acceptable engineering codes, standards and computer codes
- Severe accident management
- Radiation and contamination zoning – compatibility with overseas designs
- Reactor shutdown provision (control rods versus boronation system)
- Advanced Passive Safety features
- Security

3.0 Research & Development Requirements

It is noted that EPRI are developing a Materials Management Matrix (MMM) for potential new LWR build in the USA based on experience of operating LWR to date. The approach seeks to use expert elicitation to identify the risk and consequence of key materials degradation mechanisms for reactor components based on operating experience to date from the existing (and ageing) LWR systems. It is recognised that within the UK the vast majority of LWR experience resides in the naval propulsion programme. This experience could provide a valuable input to the new build agenda along the lines of the EPRI MMM approach.

A key aspect of technical programmes will be to ensure that the existing skill base in the industry is retained and key facilities are strengthened so that the supply chain can be re-invigorated. The view of the major players and stakeholders is that maintenance of critical capabilities is needed in the following areas:

- Core Design and Fuel Performance
- Systems Engineering
- Advanced component fabrication and joining
- Materials Performance
- Water Chemistry
- Criticality, Shielding and Radiation Protection
- Thermal Hydraulics and Transient Analysis
- Safety Performance Assessment

Previously, BNFL funded R&D on advanced reactor systems as a means to maintain skills in important areas. There is now an argument for similar investment in international reactor R&D to continue the maintenance of important skills.



It will also be necessary to perform research associated with societal issues. No appropriate roadmap currently exists although the Research Councils have funded a programme on Sustainable Nuclear Power that addresses many of these societal and policy issues. Research activities will need to include:

- Socio-economic studies
- Financing
- Siting information
- Project delivery
- Stakeholder perception
- Energy security
- Environmental impact etc.

There were repeated views that management of irradiated fuel will be an important issue. While storage of irradiated fuel can be undertaken safely for many decades, it will be necessary for the UK to have a strategy for eventual disposal or recycling of the fuel from the Gen III systems. R&D is required to underpin the strategy, to explore technical options and to maintain capability in management of irradiated fuel.

A fleet of Gen III reactors will also provide an opportunity to recycle some of the UK's separated plutonium stocks as MOX fuel. This will produce value from fissile material which might otherwise be considered as a waste.

Interviews with nuclear industry stakeholders in other countries indicate similar needs to support each country's programmes on LWR and advanced LWRs, particularly managing the reliability of the plant, materials behaviour throughout the plant's extended lifetime, improving fuel performance and enhancing plant performance and workforce productivity. However, there is greater emphasis placed on the need to develop reactor systems beyond the near term. A common view is that R&D for future reactor systems will provide the means to maintain cross-cutting capabilities in education and training, knowledge management and safeguards/security.

3.3 R&D for Medium Term Thermal Systems

Generation III+ are anticipated to be deployed around 2030 although prototype systems will be available in the next 5 to 10 years. Thus positioning for opportunities and demonstrating competence is commencing now.

The R&D requirements for Gen III+ systems have been widely published and a summary is provided in Appendix 4. As an example, the requirements for HTR reactors are:

- Fuels Technology - capability to manufacture and test coated particle fuel.
- Materials Technology - assess and qualify graphite and high temperature materials
- System Design - finalise key design parameters, such as reactor power, outlet temperature, plant configuration
- Test Facilities - such as a high-temperature fluid flow test facility
- Hydrogen Process Development - water-splitting process development

Views from the UK nuclear industry are that while there is no UK programme on medium term thermal systems, the UK does have relevant capabilities in a number of key areas that it could contribute to international programmes. The principal areas were judged to be:

- Performance of materials at high temperatures in AGR systems
- Irradiation behaviour of graphite
- Knowledge of production and behaviour of high temperature welds
- Gas coolant chemistry
- Capability in manufacture of TRISO coated particles

Views from international stakeholders reinforce the UK views and emphasise the value of participation in international R&D, which is a low risk approach to gaining intelligence into future opportunities and for gauging where UK investment is best targeted.

3.4 R&D for Advanced Thermal and Fast Reactor Systems

The R&D requirements of advanced thermal and fast reactor systems (Gen IV) have also been widely publicised and are also summarised in Appendix 4. The systems require long term and extensive R&D on both the reactors and the fuel cycle(s). Commercial deployment is not expected before 2030 although prototypes are planned to be constructed by 2020 (particularly the sodium cooled system in France). Therefore positioning and involvement in market development is required over the next few years. An important point is that these systems will require demonstration reactors to be built and operated well ahead of commercial deployment. There are indications from the EU that demonstration plant may be operating by 2020.

Views from the US nuclear industry, where advanced reactor concepts are being actively explored, indicate that the key R&D issues are as follows:

- Develop recycling technologies that are economically competitive, increase proliferation resistance and minimise the impact on waste disposal
- Develop new fuels
- Understand heat transport for new applications
- Enhance modelling and simulation capabilities
- Develop improved materials

3.5 R&D for Fuel Cycle Technologies

At present, Magnox fuel is reprocessed as a means to stabilise the waste form, while AGR fuel is destined for either interim storage or reprocessing and fuel from Sizewell B is currently in interim storage. R&D is required to support the continued operation of the infrastructure associated with spent fuel management on the grounds of safety assessment, plant performance predictability, operating cost reduction etc. There is also a continuing requirement to assess the overall strategy for spent fuel management and this requires

on-going research in developments associated with either open or closed fuel cycle options. R&D payback on fuel cycle technologies is possible from now supporting existing systems right through to 2040 and beyond for the advanced Gen IV systems.

Historically in the UK, there has been research conducted on advanced aqueous reprocessing. Technology development has been associated with chemical flow sheet and process engineering to improve separation between waste species and reusable species such as plutonium. Research has focussed on reducing waste volumes and costs as well as simplification of the process.

Recycle technology is fundamental to the deployment of fast reactor systems and hence fundamental to the goals of Generation IV. There are also strong synergies with technologies that may be of interest to the legacy waste management programme in the UK.

Reprocessing technology has the potential to be enhanced from that deployed in THORP and this may match a growing need for technology to treat irradiated fuels. Given the concerns over proliferation risks with separating plutonium from irradiated fuels, enhancement to produce inherently proliferation-resistant reprocessing could be an emerging technology. To some extent this has been happening through NNL working with Energy Solutions to offer proliferation-resistant reprocessing concepts to the US DOE's GNEP programme. It is likely that a number of countries will explore options for recycling/reprocessing by means of technology demonstrators before making commitments to industrial scale processing. The UK's capability in fuel recycling means it would be well placed to exploit opportunities in development, design and operation that such demonstrators might offer.

Typical research areas include:

- Aqueous reprocessing – simplifications, alternative head end reprocessing

- Reduction in effluents and waste volumes
- Single cycle flow sheet
- Co-extraction to avoid proliferation concern
- Separation and treatment of minor actinides
- Waste matrices
- Refabrication of fuel

There have been some R&D activities on molten salt (non-aqueous) recycle, and in particular the engineering base that would be required to deploy a molten salt recycle system. This technology is regarded as a strong candidate for next generation reprocessing plants, but there are no significant plans worldwide to develop it as such.

The US Global Nuclear Energy Partnership initiative includes significant research and development aimed at fuel cycle and spent fuel management technologies. Although this programme's future is politically very uncertain underlying research in the US which is part of the Advanced Fuel Cycle Initiative is likely to continue.

3.6 R&D for Safeguards, Non-proliferation and Global Threat Reduction

As noted above there is a close link with fuel cycle technology given the importance of development of proliferation resistant fuel cycles. In addition there is research on detection, assay and characterisation of nuclear material. Typical research under this area would include:

- Fuel cycle assessment
- Advanced separation technologies for proliferation resistant fuel cycles
- Radiometric instrumentation development
- Radiochemical clean-up

Involvement in this market and the opportunities for commercial return can be realised from now onwards. The UK Government has already strongly indicated its desire to be at the forefront of this market given the recent announcement of the National Centre of Excellence for Nuclear.

Interviews with the major players and stakeholders in both the UK and overseas have helped develop a picture and perceptions of the strengths and weaknesses of UK R&D in the nuclear sector.



4.0 UK R&D Strengths and Weaknesses

Opinions were sought on which nuclear capabilities can be obtained from spin in from non-nuclear R&D and which have potential to be spun out to non-nuclear industry. Stakeholder views have been collated in Appendix 5 (UK stakeholders) and Appendix 6 (international stakeholders).

4.1 UK stakeholder views on R&D Capabilities Relevant to New Nuclear Build Programme

The UK R&D capabilities in nuclear fission power generation vary widely and while they have been much decreased over the past decades, the UK continues to have significant strengths in some important areas. The UK stakeholders' views are summarised in Table 1.

4.2 International Stakeholder Views

Views gathered from international stakeholders recognised the historic strengths of UK nuclear R&D but perceived that there has been a substantial decline over 20 years or so. A common view is that the UK ranks no higher than 5th or 6th in the world in terms of its nuclear R&D capabilities overall. Areas where the UK is perceived to be strong align with the current industrial focus of clean-up and decommissioning and reprocessing. Table 2 summarises the International stakeholder views in a similar fashion to those presented for the UK.

4.3 Summary of Nuclear Industry, UK and international views

The perceptions of R&D strengths and weaknesses, and a view of the potential development, are summarised in the matrix in Figure 5. Various strengths and weaknesses are positioned according to their strength (high, medium, low) and their potential for marketability or wealth generation. The green arrows indicate those technologies where the UK R&D capabilities are growing and the red arrows where they are perceived to be declining.

R&D Capabilities perceived as strong	<ul style="list-style-type: none"> Reactor physics Gas-cooled reactor experience Computational fluid dynamics/thermal hydraulics Accident simulation, e.g. Loss of coolant accident Reactor core modelling Radiation damage (physical examination & modelling) Graphite technology Fuel design and manufacture Fuel cycle assessment Enrichment Reprocessing Waste treatment
Spin-in/Spin-out Technologies where UK perceived as strong	<ul style="list-style-type: none"> Decontamination and Decommissioning Non Destructive Evaluation Structural Integrity Assessment Materials Degradation Mechanisms including welds, and non-metallic materials including concrete. (Mechanisms include corrosion, fatigue, creep, thermal cycling.) Digital command and control systems Thermal Hydraulics/Computational Fluid Dynamics Structural Integrity Corrosion
R&D Capabilities perceived as weak	<ul style="list-style-type: none"> Operational Experience of Gen III reactor systems Optimisation of modern Generation III reactor systems Specific aspects of advanced reactor systems including Fast Reactor (FR), High Temperature Reactor (HTR) and Very High Temperature Reactor (VHTR) including Pebble Bed Modular Reactor (PBMR), Thorium Cycle Systems

Table 1
UK stakeholder views on UK R&D capabilities in nuclear

R&D Capabilities perceived as strong	<ul style="list-style-type: none"> Sodium-cooled reactor experience Post-irradiation examination of fuel & reactor components Fuel performance modelling Storage of irradiated fuel Management of irradiated fuel including reprocessing Irradiation behaviour of graphite Facilities for experimental work on radioactive materials Physical protection of nuclear infra-structure
Spin-in/Spin-out Technologies where UK perceived as strong	<ul style="list-style-type: none"> Systems for remote handling High temperature materials High temperature chemical processes Digital instrumentation and control Probabilistic risk assessment Human factors engineering
R&D Capabilities perceived as weak	<ul style="list-style-type: none"> Limited R&D programmes in advanced reactors and fuel cycles Limited academic base experienced in nuclear Limited R&D infrastructure

Table 2
International stakeholder views on UK R&D capability, additional to those gathered from UK stakeholders

8 Note, the UK is perceived to have strength in certain aspects of advanced reactor systems from its historic experience. However this capability is eroding due to lack of present activity

This review has shown that there is growing interest across the world in expanding nuclear capacity and in developing future reactor systems.



5.0 Summary of UK R&D Opportunities

The world market for nuclear engineering over the next 20 years is huge – around 300 new reactors to be built at a cost of £2billion each and 250 to be decommissioned at around £1billion each, i.e. £850 billion⁹. The UK has maintained a number of key technical capabilities that now have the potential to be exploited domestically and in overseas markets. At this time, public sector investment has a role to play because some of the technology development is immature and is beyond the time horizon for commercial investment from industry. Appropriately targeted, the investment can enable technology development that will

lead to the UK having a world-leading position in commercial exploitable technology. The spin-in and spin-out technology between the nuclear and other industries has potential in a number of key areas. The case study in the side box illustrates benefits that might result from appropriate stimulation of R&D to encourage spin-in and spin-out of technology.

In the following section, a short summary of the different market aspects is given, and Table 3 (page 26) summarises a number of specific market opportunities in a quantitative manner.



Case Study:

Innovative NDE Technique Offers Spin-In Opportunity for the Nuclear Industry.

The nuclear industry's need for rapid inspection of large structures can be met by a significant advance which has resulted from research into long wavelength ultrasonic technology at Imperial College. As part of the UK Research Centre in Non-Destructive Evaluation (RCNDE), they have used the properties of guided waves to propagate through a structure to provide a means to detect faults over distances much greater than conventional techniques from a single transducer position in one test, resulting in large savings of inspection time.

A system, originally developed for the detection of corrosion under insulation in chemical plant pipework is now being marketed by Guided Ultrasonics Ltd, a spin out company set up by members of the original research group.

Other new techniques and instruments which have progressed to TRL 4-5 with RCNDE funding, but would be greatly helped by TSB funding to TRL 7.

For more details see:
www.rcnde.ac.uk
www.guided-ultrasonics.com

⁹ M. Saunders, (AMEC President of Power and Process Nuclear), "AMEC Power and Process: Nuclear", Presentation at Market Seminar 11 December 2008, page 5.
 D. Kennedy, "New nuclear power generation in the UK: Cost benefit analysis" *Energy Policy*, Vol 35, pp. 3701-3716, 2007

5.0 Summary of UK R&D Opportunities

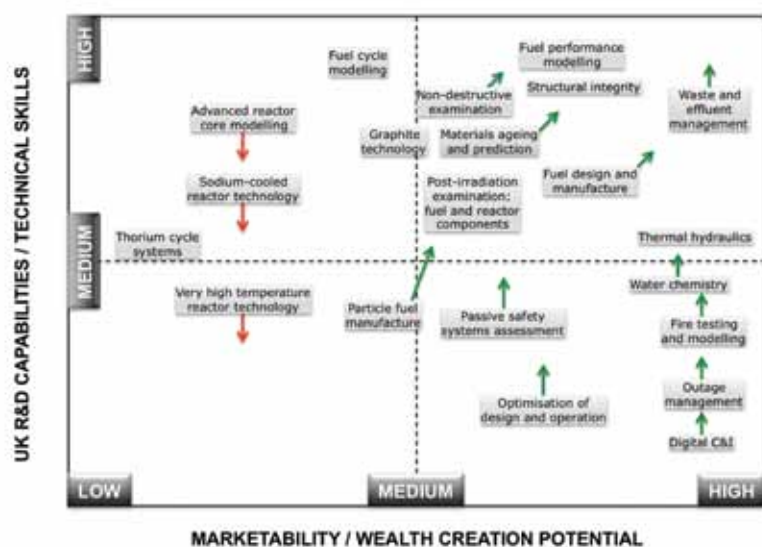


Figure 5 Potential of UK R&D Capabilities for Commercial Exploitation

R&D programmes, such as fuel manufacture, component fabrication and joining (including weld simulation), modular construction, waste and effluent treatment, inspection and monitoring, prediction and assessment of materials degradation and safety case development.

The fuel supply for the new build system(s) need not be tied to the reactor vendor after the initial core and first few fuel loads, and consequently R&D into improving fuel manufacture and fuel performance is a more open field and one in which existing UK capabilities can be deployed. This also leads to an opportunity for R&D into recycle of Pu as MOX fuel and there is an opportunity to convert theoretical studies on Pu disposition via MOX fuel into a proven, under-pinned option. A necessary component would be to develop a full understanding of MOX fuel performance in the reactors.

A new build programme of Gen III reactors in the UK is likely to require firmer plans for the management of irradiated fuel, since prolonged storage of the irradiated fuel at reactor ponds is only an interim solution. The eventual treatment options, whether disposal or recycling, will need further detailed study.

Overall, a re-energised R&D programme that successfully supports the domestic deployment of Gen III technology should provide a base from which the UK R&D supply chain can offer a greater range of services to countries that are either renewing their nuclear programme or launching one from scratch. Successful participation in licensing, build and operation of the Gen III reactors should position UK companies to exploit their learning in other countries which are contemplating new build, e.g. Sweden, Belgium, and the Netherlands. The UK's current strengths in fuel cycle analysis and management of irradiated fuel are potentially exploitable with countries that are launching Gen III systems and have a need to develop a strategy to manage the irradiated fuel in the near and medium term.

5.1 Opportunities associated with current reactor systems, fuel cycle and infrastructure

The majority of the current programme focuses on materials performance issues such as structural integrity of graphite, steels and civil components under conditions of high temperature and irradiation and also understanding materials phenomenon such as stress corrosion cracking, creep, embrittlement, void swelling and other irradiation-assisted processes. Work on probabilistic risk assessment, severe accident analysis, release mechanisms and non-destructive testing also form major parts of the research programme.

The research challenges for existing generation include:

- Degradation of specific materials and components, such as the graphite core and AGR boiler components.
- Obsolescence of plant/equipment making like-for-like replacement difficult.

Management of irradiated fuel presents significant challenges in terms of ensuring longevity from the current facilities and optimising the system wherever possible. There is also a continuing requirement to assess the overall strategy for spent fuel management and this requires on-going research in developments associated with either open or closed fuel cycle options.

Table 3 provides examples of potential opportunities, including the use of NDE, condition monitoring and preventative maintenance. Materials degradation research is also significant given the ability to develop new methodologies for reducing primary circuit corrosion or giving assurance over structural integrity.

Knowledge capture is clearly a key aspect for lifetime extension and assessment of the current operational performance of existing plant. Similarly virtual reality tools will help with plant maintenance.

5.2 Opportunities in the UK's deployment of Gen III systems

It is recognised that the UK nuclear industry will not become a vendor of Gen III systems but there are opportunities to exploit R&D capabilities by supporting and improving operational performance. There will continue to be a need to underpin the safety case, particularly to ensure the operating lives of 60 years are achieved, and R&D into optimisation of operations to reduce outage times and to reduce waste and effluent will be important. The reactor vendors are likely to have R&D programmes to address some or all of these issues but it need not be a fore-gone conclusion that they will carryout the R&D entirely in-house. With a strengthened R&D capability the UK supply chain will have the opportunity to undertake some of the

It can be seen from Table 3 that examples of market opportunities relate to ongoing work associated with materials degradation. Even though these will be new plants, operational conditions will vary and continual assessment of materials performance, corrosion, cracking etc. will be essential to reduce maintenance and maximise plant lifetime. Improvement throughout the plant life of digital command and control systems will also provide an opportunity for UK organisations. From reactor vendor and component suppliers there is also interest in manufacturing techniques. It is very likely that the UK supply chain will be involved in new build and the supply of components. Here R&D on welding, joining, surface finishing etc. could give some UK organisations a niche market opportunity, thus allowing them to win business to support new build projects overseas.

5.3 Opportunities to support medium term thermal reactor systems

There are opportunities worth pursuing in the medium term thermal reactor systems, such as IRIS and PBMR, because of their earlier timeframe for deployment compared to the fast reactor systems. There is also more scope for R&D than with the Gen III systems and these include niche areas that play well into the UK's strengths, e.g. fuel strategy, graphite behaviour with irradiation and subsequent waste management and materials support.

Increasing the breadth of the UK's R&D capability in key areas such as these will enable industry to exploit commercial opportunities outside of the UK for medium term reactor systems.

5.3.1 Small integral light water reactors

The timescale for deployment of a first of a kind system is around 2015 and a proven system will require development work relevant to the UK's capability. This includes development of a range of fuel management schemes, assessment of fuel performance conditions, crud transport and integrity and qualification of the reactor pressure vessel.

With appropriate investment to strengthen the R&D base, the UK would be well placed to exploit its R&D capability in:

- Fuel Performance and Fuel Cycle Assessment
- Materials and Corrosion Performance
- Thermal Hydraulics / Transient Analysis
- Safety Performance Assessment

5.3.2 HTR

South Africa and China are making significant progress with the HTR and deployment of full scale demonstrators is expected by 2020. Opportunities are expected to arise in the fields of materials and fuel manufacture, such as ensuring the satisfactory performance of the coated particle fuel, amongst others.

The UK's long experience and capability in the technology and licensing of gas-cooled graphite moderated reactor systems and its ability to contribute to the experimental programmes on fuels and materials provide a platform from which to address those opportunities. Support in HTR technology can cover the following areas:

- Materials performance: structural steel and welds, fuel and graphite
- HTR fuel development and coatings
- Reactor physics analysis
- Fuel cycle studies
- Waste management activities
- Thermal hydraulics and CFD
- Hydrogen economy links and thermochemical cycles
- Socio-economic studies of nuclear energy

5.4 Opportunities in demonstrators for advanced thermal, fast reactor systems and associated fuel cycle technology

The opportunities with these systems lie with the need to build and deploy demonstration systems, which is expected to be around 2020, much sooner than the post-2030 date for full commercial deployment. The European Union's plans for

demonstration systems indicate a timescale that needs action sooner rather than later and well ahead of any proposed commercial deployment.

Stakeholders clearly see the benefits in terms of:

- Being in a position to capture contract opportunities to design and build the demonstrators/ prototypes
- Skills upgrading for their nuclear engineers
- Long term positioning to be involved with commercial fast reactor systems

The best opportunities, based on UK R&D nuclear engineering strengths are:

- Gas Cooled Fast Reactors
- Sodium Cooled Fast Reactors
- High Temperature/Very High Temperature Reactors
- Industrialisation of technology for processing and recycle of irradiated fuel
- Evolution of industrially-proven reprocessing technology

R&D opportunities include:

- Advanced aqueous and non aqueous reprocessing, e.g. separation technologies
- Recycle of irradiated fuel that is more proliferation resistant and more economical
- Research into Pu management via fast reactors including experimental tests
- Waste management research
- Fuel Cycle studies and assessment

As noted in previous sections much of the technology developed here can also be applied to the safeguards, non-proliferation and global threat reduction work. Here opportunities exist for organisations that have capabilities in modelling and assessment of fuel cycle technologies (production of model packages), and the development of novel instrumentation and detection techniques, which is an active field within the SME supply chain.

Specific opportunities that have been identified as satisfying the criteria for “public-sector intervention” arise within general categories of Technology, Infrastructure and Knowledge, and include the engagement with the Euratom Framework programmes.

6.0 Summary and Assessment of Technology, Infrastructure, and Knowledge-based Opportunities

The opportunities identified during the course of the review include the following (see Table 3 for further detail).

6.1 Technology-based opportunities

6.1.1 Non-destructive Testing and Examination (NDT/NDE)

Advanced NDE technologies could significantly improve the quality and reliability of inspection of safety critical items in nuclear power plants during both construction and operation. Some techniques offer very attractive time savings in the inspection/analysis processes which in turn lead to time savings in construction and during plant outages. Other techniques offer possibilities for on-line monitoring of critical areas that can assist operators to avoid operation in damaging regimes and to determine when maintenance operations should be carried out. The savings in time for inspection and reduction in plant down time would be very substantial.

Technologies that are currently being developed and applied in a preliminary manner are briefly described below. It is proposed that development programmes are initiated under the TSB initiative to improve and validate these techniques, leading to Regulator approval and acceptance by plant owners and operators.

- **Ultrasonic Phased Arrays:** this technique is similar to the advanced ultrasonic methods used in medical diagnostics. By electronically controlling ultrasonic beam frequencies, angles and focus, many inspections can be carried out in a single scan of a phased array probe. This saves time and gives a much more searching examination.
- Much work has been done on this and there are several examples of successful applications. The technique would benefit from further development to reach its full capability.
- **High Temperature Ultrasonic Inspections:** During power station outages, much time is required to allow components to cool down to enable inspection. Much of this could be avoided if ultrasonic inspections could be carried out at higher temperatures.
- Development work to date enables inspections at around 100°C to be undertaken fairly routinely and, with special equipment, short periods at 220°C can be achieved, but major benefits could be realised if 500°C or greater could be achieved. Indications are that this is possible, but more development is necessary.
- **Long Range Ultrasonics:** The ability to remotely monitor critical components and welds ultrasonically offers great benefits in plant operation and predictive maintenance. In this technology, special probes using different types of ultrasonic waves are attached to particular areas of pipework, for example, which enables welds some distance away to be scanned ultrasonically. Preliminary work appears promising, but much more needs to be done to demonstrate the reliability and practicality of the techniques. The advantages are obviously avoiding the need to get to welds/components that are otherwise difficult to access.

6.1.2 Condition monitoring and preventative maintenance

Condition Monitoring is a preventative maintenance procedure involving the sensing and analysis, over time, of certain parameters that indicate the condition of critical elements of plant and machinery in order to give warning of incipient failure.

Parameters that are monitored include vibration, temperature, wear debris, corrosion and the growth of defects. Hence condition monitoring is closely allied to NDE/NDT and Materials Ageing. Condition monitoring is widely employed in the petrochemical, power engineering and aerospace industries where alternative maintenance strategies of breakdown or routine maintenance are unacceptable on safety and cost grounds. The sensors to detect the required information may be built into the item being monitored or incorporated into portable diagnostic equipment.

6.0 Summary and Assessment of Technology, Infrastructure, and Knowledge-based Opportunities

6.1.3 Materials degradation, structural integrity and lifetime assessment

Whilst materials for nuclear components are carefully selected for their properties and to minimise in-service degradation, the operating conditions present in a nuclear power plant are such that degradation will inevitably occur over time. Typically, degradation can be categorised into three broad types, all of which may be present to a greater or lesser extent in an operating plant:

- **Materials degradation** includes the changes that occur at a microstructural level in components during service. Examples in nuclear power plant include the thermal ageing of austenitic components that operate in the high temperature boilers of AGRs and the irradiation-induced changes that occur in ferritic pressure steels and welds located close to the reactor core.
- **Mechanical degradation** includes the initiation and growth of cracks that occur in components under the action of an externally applied or internal residual stress, such as is present in non stress-relieved welds. Examples include fatigue cracks under cyclic loading or reheat cracks that occur in the vicinity of non stress-relieved welds operating in the temperature range 500 to 550°C.
- **Electrochemical degradation** includes the development of environmentally assisted cracking in components under the combined action of the local environment and a static or cyclic stress. Examples include primary water stress corrosion cracking and corrosion-fatigue, both of which may occur in austenitic components within the primary circuit.

Whilst NDE methods provide information regarding the presence and development of crack-like flaws, structural integrity methodologies provide a means for judging the severity of such flaws and the

consequence for component integrity. The results from such assessments provide the plant operator with valuable information that may be used to inform decisions regarding component operation, repair, and (or) replacement. The results also form part of the development of Safety Cases to support the continued operation of nuclear plant components.

Within the UK nuclear industry, defect assessments are carried out according to the Failure Assessment Diagram (FAD) approach described in the British Energy methodology R6¹⁰. The method is based on the assessment of the component containing the defect with respect to failure and plastic collapse. By understanding the development of materials properties throughout a component's lifetime as well as the crack growth rate (e.g. by fatigue) the R6 approach can be used as a framework for providing a lifetime assessment for engineering components in nuclear plant.

6.1.4 Digital command and control systems

The new generation of advanced reactor systems will utilise digital command and control systems. These systems are an integral and essential part of the reactor and used for plant control for normal operation as well as safety monitoring, protection and control during any possible transient event or off-normal condition. Compared to the previous generation of reactors, much of the control and monitoring is now done through software based systems rather than actual readings from instrumentation appearing in the control room. The change is similar to that in aircraft where "fly-by-wire" systems mean the controls in the cockpit no longer physically move the rudder, ailerons, flaps but instead do so through electronic control.

Due to the rapid changes that are taking place in digital computer and graphic display technologies employed in modern human systems interfaces, design certification of advanced reactors such as AP1000 or EPR has focused on systems available

at the time of design. There will have been some updating during the process but there will always be a lag compared with the most modern systems.

This presents an opportunity to ensure modern command and control systems are included where possible. Improvements in technologies such as instrumentation, detection systems, electronics, signal processing, data acquisition, software and human interface technologies will all prove beneficial for improving and building upon the standard design. Such technology development will not have necessarily come from the nuclear industry but could have been developed in industries such as oil, chemical, gas, aerospace, space, defence etc. In addition, while the systems developed for the nuclear industry might not as a whole be applicable to other industries, specific components could be (such as the human interface display systems). Potentially, this area could prove highly beneficial with spin-in and spin-out opportunities as well as the means for smaller companies that have developed novel components to gain an entry into the nuclear market.

6.2 Infrastructure-based opportunities

6.2.1 Advanced Manufacturing Research Centre(s) for Nuclear

The Advanced Materials Research Centre at Sheffield has proved highly successful in supporting the aerospace industry as a public/private partnership aimed at innovative approaches to manufacturing components. The Centre brings together a number of industrial partners interested in collaborative generic research. Techniques researched include alternatives to the current expensive and wasteful milling of components such as rapid prototyping from metallic powder, wire wrapping and welding, reverse engineering of components etc. In addition to the Sheffield Centre, other centres which organisations such as Rolls Royce are heavily involved with include the Advanced

¹⁰ R6 Revision 4, "Assessment of the integrity of structures containing defects", British Energy Generation Ltd, 2006

Forming Research Centre at Glasgow which researches forming and forging, the Manufacturing Technology Centre at Ansty which researches automation, fixing, joining and operational performance and the Commonwealth Centre for Advanced Manufacturing in Virginia, US which specialises in surface engineering and manufacturing systems.

None of these centres currently specialises in nuclear systems and therefore the proposal for an Advanced Manufacturing Research Centre for Nuclear as made by the Secretary of State for Business, Innovation and Skills on 15th July 2009 is a welcome step forward. Rolls-Royce is the lead Industrial partner involved in the formation of this centre and this will provide underpinning technology to the new UK based Nuclear factory announced by Rolls-Royce on 28th July 2009. This factory will be designed to manufacture, assemble and test components for new civil nuclear power stations. These include pressure vessels, heat exchangers and other large and complex reactor parts, manufactured to exacting nuclear standards.

This centre will be able to specialise in component manufacture, operational performance, systems integration etc. associated with the construction of nuclear power plants. There are significant links, benefits and opportunities associated with such a centre in terms of spin-in and spin-out with respect to similar industries such as aerospace. The centres are also established with a business model that ensures supply chain organisations and small to medium enterprises are actively involved and can benefit from the research, ultimately resulting in them being able to supply the industry in the future.

There is also a case for an Advanced Manufacturing Research Centre for nuclear fuels. This AMRC would combine the expertise of UK based industry and academic excellence and undertake research on performance enhancement of nuclear fuel assemblies, advanced manufacturing techniques, and novel fuel concepts.

6.2.2 Modularisation

Construction of reactor systems has changed significantly over the years through learning from previous projects. Rather than stick-building plants with all components assembled on site during the construction phase, the reactor system is broken down into major components such as the pressure vessel, steam generator, containment vessel etc. These are assembled off-site at a dedicated facility and then shipped to site when required during the construction phase. This approach is not new and was used on many of the Generation 1 systems such as Magnox, however modern reactors have an even greater number of modules – thousands of modules now make up designs such as the AP1000 and ACR-Candu design. Many of these modules are pre-assembled off-site in portable sized packages. The use of CAD design has proved to be an essential tool here to enable many components to be broken down into modules. BAE Systems have extensively used a modular approach for construction of the nuclear naval submarines at Barrow and the construction time has been significantly reduced through assembly of modules in workshops rather than attempting to work within the confined space of the boat itself. Modularisation has also been used in this instance for small modules such as sections of piping where a “slice” is taken through a system that may contain pipework for many different uses, thus forming a module that can be inserted during construction.

The links between original design, CAD manipulation, component manufacture (CNC milling for example), modular construction and system assembly are complex but also present significant opportunity for learning and improvement. There are also spin-in and spin-out opportunities from other industries such as oil, chemical, gas, automotive, aerospace, defence etc. For example the Advanced Manufacturing Research Centre (AMRC) at Sheffield University that works closely with the aerospace industry has developed some novel techniques associated with CAD, CNC milling, rapid prototyping,

virtual reality etc. Exploring the development of such innovative techniques and the link with the nuclear industry could prove very fruitful as far as new commercial opportunities are concerned.

6.2.3 Advanced Fuel Manufacturing

There is likely to be an opportunity to exploit the UK's capability in fuel manufacturing to provide fuel for the UK's tranche of Gen III reactors. Success in the UK market could be a precursor to overseas sales. The prospects to capture sales in either market will be improved through technology developments that reduce the costs of fuel manufacturing and also offer higher performance fuels (e.g. reduced frequency of failures or greater power production from increased irradiation).

Improved fuel manufacturing processes will require a multi-disciplinary approach to optimise a complex sequence of processes. There will be opportunities to apply learning from elsewhere in the nuclear industry in terms of minimisation of wastes and effluents, improvements in process monitoring and improved test procedures. There are also opportunities to bring learning from other industries to optimise the whole system, particularly the precise mechanical handling operations.

The development of improved fuels is an area where UK R&D has been latent but existing capabilities in materials and chemistry provide a substantial knowledge base to launch fresh R&D. Analysis of fuel performance to enable higher irradiations to be obtained is an important capability that the UK can deploy in this area. In addition, the UK has well-developed facilities, particularly for examination of irradiated test fuels, which can be a cornerstone in a fuel's development programme.

There is a parallel opportunity in the manufacture of MOX fuel, which could be a route to recycle some of the UK's separated plutonium. The current Sellafield MOX plant has yet to prove capable of yielding sufficient throughput, but the UK has the

6.0 Summary and Assessment of Technology, Infrastructure, and Knowledge-based Opportunities

technical capability to design and install an alternative plant and thus exploit this opportunity. There is also an opportunity for technical solutions to address proliferation concerns with MOX fabrication and these, once addressed, should provide access to a wider market in MOX fuels across the world.

6.2.4 Fuel Recycling

A global renaissance in nuclear power brings to the fore the issue of optimising the use of uranium resources and management of irradiated fuel. Increasingly, national governments will be seeking to develop long term strategies that minimise their reliance on the finite resource of uranium and the environmental challenge of disposal of irradiated fuel. The strategies will involve long timescales and significant financial investments, so there will be a recognition that it is better to explore the technical options sooner rather than later.

Development of strategic plans provides an opportunity for the UK's R&D capability in fuel cycle technology, including reprocessing, to enable governments and utilities to explore options that will be capable of industrial implementation. There will be a need to develop strategies that address issues concerning waste and effluents from reprocessing and also to develop technically robust answers to concerns about proliferation. There will be options that involve the development of cost-competitive, proliferation-resistant fuel cycles. The UK will be well placed to exploit knowledge it has gained from its industrial reprocessing activities and its R&D capability to examine new approaches.

There will be opportunities to benchmark international standards in non-proliferation and the UK would be well placed to advise emerging nations on compliance with international expectations in non-proliferation.

6.2.5 Fuel cycle assessment

There are also opportunities in the field of fuel cycle assessment, which are strongly linked to strategic approaches for fuel recycling. Governments, utilities and regulators are expected to seek increased understanding of broader fuel cycle issues and challenges such as sustainability and comparison of fuel cycle options. Opportunities exist for organisations to offer modelling and assessment of fuel cycles to determine mass flows, radiotoxicities, heat loads, throughputs, economics etc. of complex, dynamic fuel cycle options. Options will include offering assessment tools (i.e. models) and providing reference sources of data to enable assessments to be made on a consistent and accurate basis.

6.3 Knowledge-based opportunities

6.3.1 Knowledge capture, storage & transfer

In most OECD countries, nuclear technology has been at a standstill or declining for several decades. This has resulted in a stable workforce supporting the existing nuclear industry, e.g. commercial operating reactors, national laboratories, reactor vendors, etc. This workforce is now reaching or approaching retirement with the potential that the nuclear industry will lose a great wealth of experience and detailed knowledge that was acquired over these decades. At the same time, information technology has changed dramatically since the early days of nuclear power; personal computers, internet access, three-dimensional modelling, interactive graphics, search engines, etc., have altered the way modern engineers relate with their work and with their colleagues. In particular, new graduates/new employees are comfortable and accustomed to interacting 24/7 via the internet to gain the knowledge they need rather than reading manuals and talking one-on-one with the knowledge experts of their company.

So as to not lose the knowledge of those retiring and to facilitate the efficient acquisition of this

knowledge by the new generation of engineers, modern information technology techniques that are available today must be harnessed. The techniques being explored include interactive discussions with 'Avatars' of knowledge experts; embedded video, presentations, and graphics; knowledge trees that show the relationships to other related experts on a given subject or associated subjects; and embedded links to reference material that are essential to perform tasks, e.g., ASME Code, regulatory requirements, sample calculations, etc.

By using techniques like these, new engineers will be working in an environment similar to that in which they conduct their daily lives. They will have easy access to information as and when they need it. They can casually explore a subject or delve more deeply into it. The opportunity will still exist for face-to-face contact with company experts, but this can be for clarification or problem solving rather than for basic knowledge transfer.

6.3.2 Virtual reality to assist manufacture and maintenance of new build plant

Powerful software exists for project planning, scheduling of resources, time and cost forecasting. In addition, powerful 3-D visualisation techniques exist using 360° laser scanning that can then be digitised to create computer simulations of actual installed plants.

Techniques are emerging for combining these types of simulations to produce virtual reality models of plants, equipment, maintenance records, construction and/or maintenance processes. These can be used to optimise scheduling and manning of construction or maintenance operations. For example, it will be possible to establish clashes on accessibility of numbers of personnel to confined areas or evaluate the usability of a proposed design, without having to manufacture mock-ups.

The techniques have obvious applications to training personnel for operations in confined or radioactive areas where safety and speed of implementation are paramount.

Software techniques as used in computer games and visualisations could offer great advantages in the development of this technique.

Some work has already been performed on combining these different types of simulations, but more work could bring about major advances that would be used in the forthcoming nuclear new build programme, the current clean up programmes and in training for maintenance of existing generating stations.

The R&D project would be to assess the capability of existing simulations and to work with specialised software houses to integrate appropriate packages, thus producing the required overall plant construction and maintenance simulations.

6.3.3 Advanced modelling and Analysis

Many of the analyses associated with fuel or reactors revolve around a detailed and comprehensive understanding of how the fuel is loaded into the core, how to maximise energy output from that fuel, how many tonnes of fuel are loaded per year, how the fuel and core will perform (in energy output and safety response). With the continuing advances in computing power there is a world-wide trend towards the development of new methods in reactor modelling that dispense with the approximations that have until now been needed. Examples include:

- Development of coupled core neutronics/thermal-hydraulic codes.
- Coupling of neutronics and fuel performance codes.
- Direct modelling of plant transients, with 3-D core neutronics models coupled to detailed plant component models, with feedback from control and protection systems.

- Direct calculation of 3-D core inventories.
- Direct calculation of multiple transient scenarios in place of bounding calculations.
- Elimination of core neutronics approximations such as the use of neutron transport theory (deterministic or Monte Carlo) in place of diffusion theory; use of multi-group or continuous energy models in place of few-group models; replacement of single-assembly spectral models with multiple-assembly models and direct calculation of microscopic cross-sections in three-dimensions.

One opportunity is to provide direct models to supply reference solutions, which align with the needs of numerous customers – utilities, vendors, regulators and research organisations. Comparison of the results of the approximate models and the direct models can be used to quantify the errors introduced by the approximate models and thereby provide a sound basis for the uncertainty allowances that need to be applied. The inability to perform direct calculations in the past may have predicated larger uncertainty margins than was necessary. Reducing uncertainty margins is beneficial to the utility through increased operational flexibility and possibly increased generating output. Alternatively, the direct models may be used to completely replace the approximate models, in which case the modelling uncertainty allowance can be eliminated completely.

A second opportunity lies in work to reduce uncertainty margins by means of improved modelling. This approach can benefit from much world-wide R&D on advanced reactor modelling methods and it will offer utilities the possibility of restoring the operating margins when seeking to target higher burn-ups.

6.4 Summary

Within these technology areas there are considered to be real commercial opportunities over the next 5 years that have market sizes ranging from >£1M to £100M with commensurate investment requirements ranging from <£1M to >£10M.

There are also UK based companies that could take these opportunities to market, together with spin-in and spin-out opportunities. However the nuclear engineering capabilities are not widely known in overseas markets and there is a need for a promotional campaign to present effectively the UK's strengths.

It is noted that opportunities exist for international participation (e.g. through Euratom) to address the issues and challenges associated with nuclear R&D and to contribute to consolidation of the European Research Area in nuclear power. Euratom Nuclear Energy research addresses the continued safe operation of reactor systems taking into account new challenges such as life-time extension, and the assessment of potential safety and waste-management aspects for future reactor systems. There is Tier 1 company interest in Euratom programmes, however involvement of SMEs is only possible with support.

The assessment conducted here has shown there are many opportunities for UK organisations to exploit. However, in order for the UK to maintain its nuclear industry heritage and status as well as benefit from the global nuclear renaissance, public sector investment in R&D and technology development will be essential and can be justified.

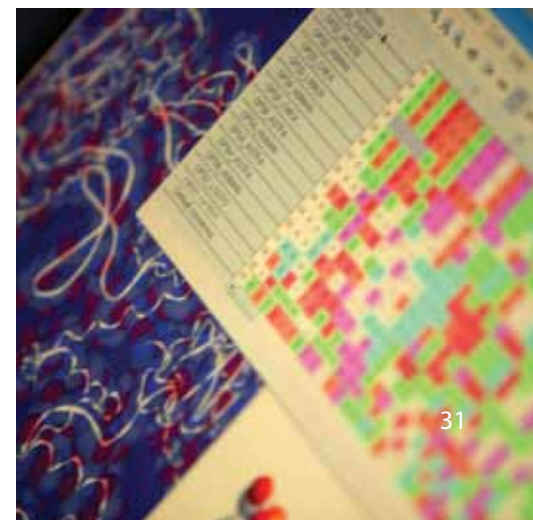
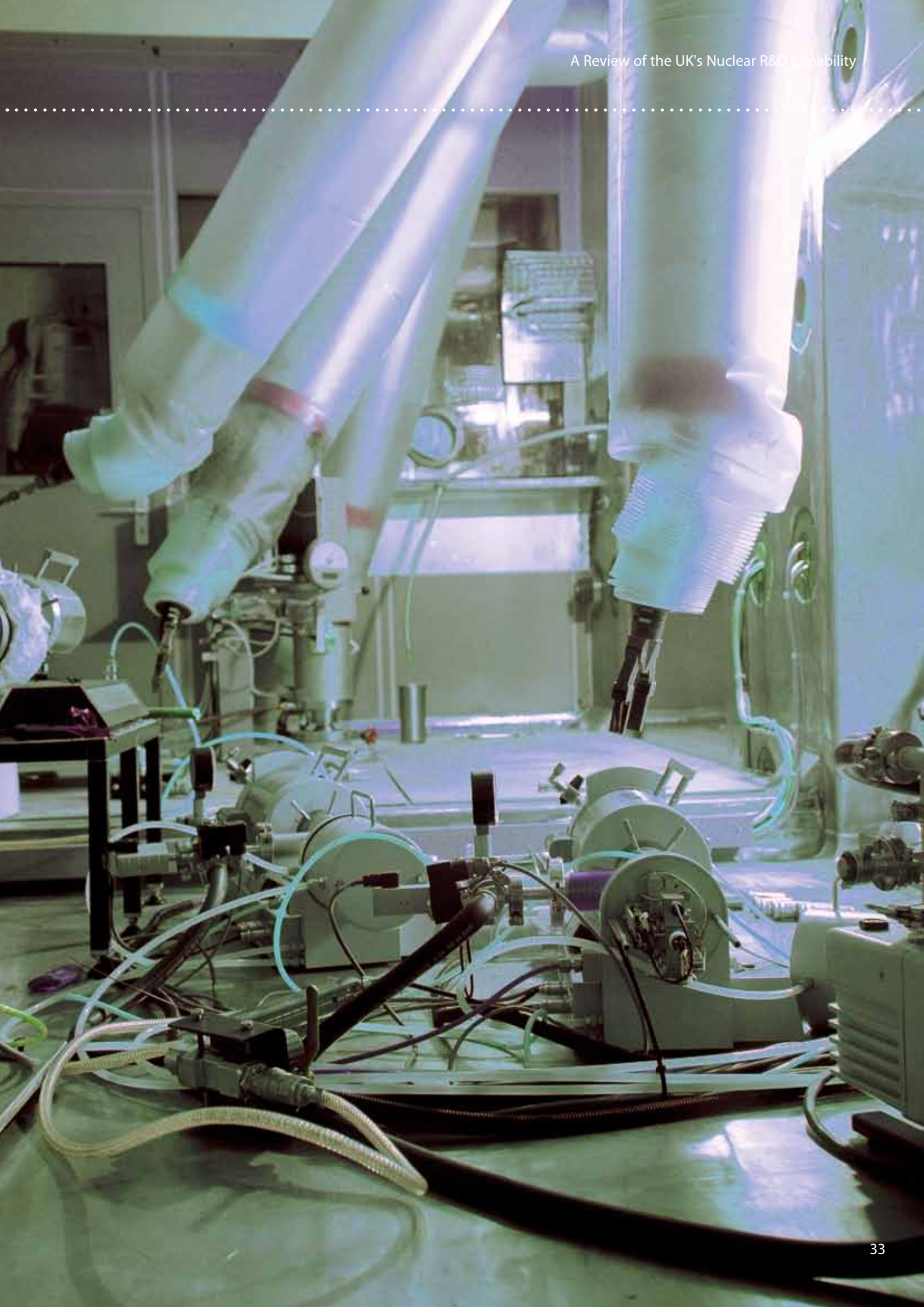


Table 3 Summary Table of Technical Opportunities

Key Investment Needs	Technical Opportunity	Size of market per new reactor	Likely UK share (probability)	Cost to market	UK Company (example only)	Spin-out opportunity (H/M/L)	Priority (H/M/L)	Comments	
Technology-based	A	NDE/NDT to reduce inspection times and accelerate new build programme	£10M's for construction, £100M's through life	High for UK, Medium for Global	< £10M	Industrial support to RCNDE,TWI, 20 to 30 key SMEs	High - nuclear and non-nuclear	High	Saving in manufacturing & construction costs, improving quality and reproducibility. Fingerprint welds at SOL
	B	Condition monitoring & preventative maintenance to increase safe life and reduce downtime	> £10M for construction, £100M's through life	High for UK, Medium for Global	< £10M	SMEs (and universities e.g. Cardiff, Manchester)	Many - nuclear and non-nuclear	High	Add-on to normal control & instrumentation. Need to demonstrate near-term value. Examples of gas turbine on-line monitoring, life extension, and Formula 1.
	C	Materials degradation, structural integrity and lifetime prediction including water chemistry and doping to reduce corrosion and advanced materials	> £10M. But note consequential impact.	High in UK, Low for Global	< £10M	Tiers 1 & 2, e.g. Atkins, Amec, RR, Babcock Marine, Serco, EDF/BE, ...	High e.g. creep, creep-fatigue, long-term corrosion issues. Other nuclear e.g. legacy waste management	High	Irradiation, corrosion, EAC, erosion, creep, etc. Impact of water chemistry on plant operation and reduction of degradation. Westinghouse use EPRI standards. Including local and global chemistry. Consider establishment of UK node for Materials Ageing Institute. Major benefit to utilities.
	D	Digital command & control systems to improve the performance, reliability and safety of complex systems	> £10M	Medium in UK, Medium for Global	> £10M	Rolls-Royce, BAE systems	High	High	Each new reactor will require a new digital comand and control system.
Infrastructure-based	E	Advanced Manufacturing Research Centre(s) for Nuclear to address high value manufacturing and technical challenges by the supply chain.	> £100M	Medium in UK, Medium for Global	< £1M (less than £1M per project, but potentially 10 or so projects)	Existing AMRCs - university/industry (e.g. Sheffield Forgemasters, Metal Improvement) links.	High	High	Higher probability for smaller components rather than large components. Niche areas for SMEs in areas including HiPip, welding & joining, surface technology, new materials.
	F	Modularisation to encourage local build and assembly and engage the UK supply chain	> £100M	High for UK, Low for Global	< £10M	BAE Systems, RR, Doosan-Babcock flow through to SMEs	Low	Medium	Modularisation approaches to AP1000 using approaches used in ships, submarines, etc. Assembly on-site, building local industry. Reduce construction time, costs & improve quality. Standardisation in design is a goal, though different requirements in UK and overseas.
	Ga	Advanced fuel manufacturing processes including more efficient processes & improved fuel performance	Approx. £450M over 60 year lifetime	High for UK, Medium for Global	< £10M UK capacity already in place, but requires capital and R&D investment to compete for new build business.	Westinghouse, NNL, Rolls-Royce, Urenco	High- Strong possibility of combining civil and naval interests, but subject to MOD.	High	Build up manufacturing capacity in UK. Higher predictability, better QA, but stickng with existing design. Development of improvements to manufacturing processes. Including better inspection of each stage of the process.
	Gb	Fuel recycling including MOX fuel manufacture	Fuel recycling would need to be offered at a cost of >£10M per reactor per year.	High for UK, High for Global	> £1000M	Sellafield Ltd, Areva, Energy Solutions - SMEs, NNL and universities as technology suppliers	Low	Low	Political hurdles may limit additional recycling in UK and participation of UK companies in overseas recycling.
H	Fuel cycle assessment to reduce proliferation concern and waste volumes	Initially < £10M over 5 years, potentially to grow to > £10M per year if assessments are converted into improvements in industrial practice	High for UK, High for Global	< £10M	NNL, Manchester University, Sellafield Ltd	Low to Medium	High	Includes reprocessing, aqueous product volume reduction, Co-extraction reducing proliferation concern, separation of minor actinides, waste matrices & fuel fabrication.	
Knowledge-based	I	Knowledge capture, storage & transfer, roadmapping, knowledge transfer network	> £1M per new reactor year of operation	Medium in UK, Medium for Global	> £10M	LSC, NNL, Data Capture Solutions, etc.	High	High	Online, interactive and flexible, drawing on the latest information & communication technologies, ICT, (Google, gaming technologies, etc.), networking people, with online access 24/7, and real-time updates.
	J	Virtual reality (3D visualisation & simulation tool) to assist manufacture and maintenance of new build plant	> £1M. But note consequential benefit	High for UK, Medium for Global	> £10M	Tier 1 interest but much involvement of SMEs including software organisations	High and Spin-in high	Medium	Combining software packages. Interactive approach to design & construction of new plant. Training for operation & maintenance engineers on existing and new plant leading to commercial advantage.
	K	Advanced modelling to enable more efficient operation and higher levels of safety and plant availability	> £10M per new reactor year of operation	High for UK, Medium to high for Global	> £10M	Manchester, Imperial, Strathclyde Universities	High	High	Full multi-dimensional model of reactor core. Coupling of physics codes, CFD & structural codes. Pay-off for operating plant to predict where & when there may be a problem, e.g. flow distribution into reactor.

"Information, Communication & Technology (ICT)"



It is considered that the Technology Strategy Board and the RDAs can assist UK industry, including SMEs, to access the opportunities that the nuclear renaissance offers.



7.0 Conclusions

- Investing in appropriately scoped R&D programmes and infrastructure projects
- Leading knowledge transfer and capture activities both within the nuclear sector and establishing links to other business areas
- Communicating the new business opportunities in nuclear engineering. (This is already happening through a series of well-attended supply chain workshops.)
- Encouraging and assisting UK companies to become accredited to supply the nuclear engineering industry
- Facilitating closer contact with UK universities engaged on nuclear engineering R&D and in particular encouraging two-way secondments and knowledge transfer partnerships
- Promoting international engagement and collaboration

Specific opportunities that have been identified as satisfying the above criteria for “public-sector intervention” arise within general categories of Technology, Infrastructure and Knowledge, and include the engagement with the Euratom Framework programmes. The opportunities identified during the course of the review include the following:

- Non-destructive Testing and Examination (NDT/NDE)
- Condition monitoring and preventative maintenance
- Materials degradation, structural integrity and lifetime
- Digital command and control systems
- Advanced Manufacturing Research Centre(s) for Nuclear components and systems and fuels
- Modularisation
- Advanced fuel manufacturing
- Fuel recycling
- Fuel cycle assessment
- Knowledge capture, storage and transfer
- Virtual reality to assist manufacture and maintenance of new build plant
- Advanced modelling of systems, structures and components

Against these technology areas there are considered to be real commercial opportunities over the next 5-10 years that have specific market sizes ranging from >£1M to £100M with commensurate investment requirements ranging from <£1M to >£10M.

There are also UK based companies that could take these opportunities to market and spin-in and spin-out opportunities as well.

The assessment conducted here has shown there are many opportunities for UK organisations to exploit. However, in order for the UK to maintain its nuclear industry heritage and status as well as benefit from the global nuclear renaissance, public sector investment in R&D and technology development will be essential and can be justified.



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Appendices

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Appendix 2	Gen III+: Medium Term Thermal Systems
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Appendix 1: Overview of the UK Nuclear Sector

Historical perspective and international context

The UK has had a self-sufficient programme of nuclear power since the 1950s which included the ability to design and build reactors, to manufacture and enrich fuel and to manage the irradiated fuel after discharge from the reactor. It is one of only a few countries that has developed a fully closed fuel cycle with the ability to reprocess spent fuel and subsequently fuel prototype fast reactor systems. The UK's extensive nuclear programme has also included naval propulsion, nuclear fusion research and development of deterrent technologies. This overview focuses predominately on civil nuclear energy generation although relevant technology developments from other aspects of the UK's nuclear programme will be considered.

The original civil power generation programme, consisting of Magnox reactors, is drawing to a close with the remaining two stations, Oldbury and Wylfa, due to shutdown by 2014; these are regarded as Generation I technology systems. There is a substantial programme of reprocessing to manage the irradiated Magnox fuel which is planned to be completed by 2016.

During the 1960s and 1970s the UK continued to develop gas-cooled systems with the successor to the Magnox reactors being the Generation II Advanced Gas-cooled

Reactors (AGRs). These included the use of enriched, stainless steel clad fuel pins enabling higher fuel burn-up, higher reactor operating temperatures and thus improved efficiencies.

The AGR stations, operated by British Energy (now part of EDF) are currently scheduled to operate for the next 5 to 14 years, with the final station, Torness, closing in 2023. There is an expectation that life extension programmes will permit extended operation of some of the stations, but there is no certainty of any AGR operating beyond 2030. While they provide a substantial contribution to UK non-fossil fuel electricity generation, there are no plans for further build of AGRs. The system is unique to the UK and requires maintenance of all aspects of the capability to support the AGR system – maintenance of safety cases, manufacture of fuel, reprocessing of fuel, storage and eventual disposal of fuel.

The unique nature of the Magnox and AGRs reactors and fuel designs has not provided many opportunities for expansion into overseas markets and has limited the scope to utilise the international supply chain. There was early export success with two Magnox stations built in Italy and Japan but no overseas sales of the AGR system.

Whilst the UK has pursued gas-cooled reactor technology, the dominant technology deployed worldwide

during the 1980s was Generation II light water reactor systems, either pressurised water (PWR) or boiling water (BWR) systems. A decision was made in the UK to “switch horses” and the country's sole PWR, Sizewell B (a Westinghouse-licensed design) was constructed and started operation in 1995. Whilst this was a Westinghouse design, there were substantial design changes as a result of the approvals process in the UK. The reactor was manufactured by UK industry (including technical work on mechanical design, fuel performance, reactor physics and thermal-hydraulics), as was the fuel for the first four reloads of operation.

Current Situation

The current situation in the UK is a combination of deriving maximum value from the existing reactor systems (Magnox, AGR and PWR), preparing for a tranche of new build of advanced light water reactors (Gen III) and clean-up and decommissioning of the legacy of wastes and facilities. Each aspect is described briefly below:-

Support to existing operations

The UK generates 15% of its electricity from nuclear fission and there is a primary aim to manage the AGRs and remaining Magnox stations to the end of their lives or where possible obtain lifetime extension. Figure A1-1 shows the predicted decline in generation from existing reactors.

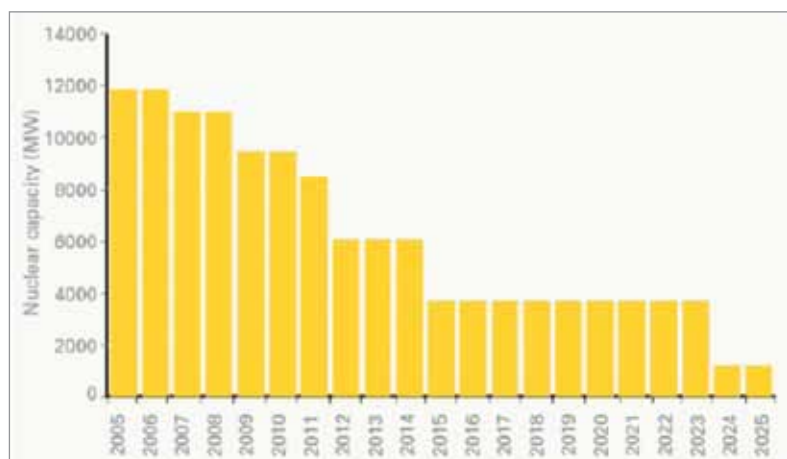


Figure A1-1 Expected decline in nuclear generating capacity in the UK - (from 'The Role of Nuclear Power in a Low Carbon UK Economy: Consultation Document', Dept of Trade & Industry (DTI) May 2007)

Ensuring continued and safe electricity generation from the installed systems has provided a valuable UK capability across a range of activities, including the capability to monitor and assess all safety aspects of the reactor system. Examples include monitoring of corrosion within the reactor and satisfactory performance of the graphite cores, both of which are essential to safe operation. Some aspects of reactor support need to be undertaken at the station, whilst other aspects, such as post-irradiation examination of fuel and graphite, need specialist facilities.

The published dates for decommissioning of the AGR reactors are as shown in Table A1-1, below. It is expected that technical studies will permit extension of some station lives, as is already the case for Hinkley, Hunterston and Dungeness, and that this is likely to be sought in blocks of 5 years. The unique design of the AGRs will mean that the technical studies will not benefit

from life extension work on water reactors around the world and this knowledge will have little value outside the UK.

The extensive world-wide experience on life extension for water reactors yields the prospect to extend Sizewell B operation out to 2045 or even 2055.

A necessary requirement of the Magnox and AGR systems is the means to produce fuel and to manage it after irradiation. The UK has a complete capability to produce reactor fuel: namely to process uranium ore, produce uranium hexafluoride, uranium metal, oxide powders and pellets. There is a capability to design and produce fuel pins and assemblies for AGRs and LWRs. The heart of these operations for the UK is at NDA's Springfields' site, now operated by Westinghouse, where the primary focus is the manufacture of AGR fuel but also production of uranium hexafluoride for enrichment and intermediate

products for water reactor fuels (powder, granules and pellets) to be sold to overseas utilities. There is no current LWR fuel manufacture but this remains an option if market prospects improve.

The enrichment of uranium for oxide fuels is undertaken by Urenco Ltd. at its Capenhurst facility, near Chester. The capability was part of BNFL and, with European partners, successfully developed gas centrifuge technology for enrichment. However, in the 1980s the decision was made to form a single company from the three European partners in order to enable it to compete successfully in the world enrichment market, which it continues to do.

Management of the irradiated fuel initially comprises storage in water-filled ponds, or a dry store at Wylfa. In the case of a significant proportion of the AGR fuel and all of the Sizewell fuel the current strategy is to continue the storage for many decades in water under carefully controlled conditions.

The remainder of the AGR fuel and all of the Magnox fuel is scheduled to be processed to recover uranium and plutonium as material for manufacture of fresh fuel. Reprocessing of irradiated fuel is undertaken at NDA's Sellafield site where separate plants treat the metal Magnox fuel and thermal oxide AGR fuels. Reprocessing of Magnox fuel is an essential part of management of Magnox fuel and is scheduled to be completed by 2016. Oxide fuel reprocessing (in THORP) is undertaken as a commercial operation to treat both AGR fuel and LWR fuel for Japanese and European utilities. Contractual arrangements exist for the return of the separated U and Pu and the fission product waste to the customer. A necessary part of reprocessing is the ability to immobilise radioactive wastes in cement or glass matrices, depending upon the radioactive content.

Table A1-1 Decommissioning Dates for AGR Reactors

Station	Generation Started	Decommissioning	After life extension?
Hinckley Pt B	1976	2016	Yes
Hunterston B	1976	2016	Yes
Dungeness B	1983	2018	Yes
Hartlepool	1983	2014	
Heysham 1	1983	2014	
Heysham 2	1988	2023	
Torness	1988	2023	
Sizewell B	1995	2035	

Appendix 1: Overview of the UK Nuclear Sector

The use of reprocessing to separate plutonium from irradiated fuel provides the UK with the opportunity to manufacture mixed oxide fuel (MOX), suitable for water reactors. This capability is currently carried out in NDA's Sellafield MOX Plant (SMP). This is aimed solely at international business, since no UK reactors are currently licensed for MOX fuel.

New Nuclear Build

With the UK government's decision to seek additional nuclear generating capacity, third generation systems are now being proposed for deployment, notably Westinghouse's AP1000 system and Areva's EPR system. Both of these are the culmination of developments over the past decade or so and offer evolutionary improvements on Generation II systems. For example a key part of the AP1000 system is its innovative passive safety features that rely on natural processes such as gravity and

convection. Likewise the EPR reactor offers evolutionary features such as molten core catcher and improved performance characteristics, systems layout and safety control systems. Both designs draw on experience gained to date to improve the overall safety and economics of the system. Other advanced water reactor designs are in the process of certification in various countries or under construction or in operation, as summarised in Table A1-2.

The UK has now nominated 11 sites and 3 consortia have announced plans to bid to build new reactors:-

- GDF Suez/ Iberdrola/Scottish and Southern Energy
- E.ON UK/RWE npower
- EDF

The timeline for the deployment of Generation III systems is shown in Figure A1-2

Deployment of next generation reactor systems (Generation III) may occur over the next decade and in which case the following issues will need to be addressed:

- Assessment of safety of advanced reactor systems from the perspective of licensability and operability
- Guaranteeing operational performance based on vendors specification
- Fuel cycle assessment in terms of core loading and spent fuel management.
- Energy policy assessment such as financing new nuclear build, planning and licensing
- Social and Societal issues such as risk perception, consultation, security

Table A1-2
Advanced Thermal Reactors being marketed (from www.nuclear-world.org/info/inf08.html)

Reactor	Country and developer	Size MWe	Status
Advanced Boiling Water Reactor (ABWR)	US-Japan (GE-Hitachi, Toshiba)	1300	Commercial operation
AP-600 AP-1000 (PWR)	USA (Westinghouse)	600 1100	AP-600: NRC certified 1999, AP-1000 NRC certification 2005, many units planned in China.
EPR US-EPR (PWR)	France-Germany (Areva NP)	1600	French design approval. Being built in Finland and France, planned for China. US version developed.
ESBWR	USA (GE- Hitachi)	1550	Advanced state of certification.
APWR US-APWR EU-APWR	Japan (utilities, Mitsubishi)	1530 1700 1700	Basic design in progress, planned for Tsuruga US design certification application 2008. Submitted for certification in 2008
APR-1400 (PWR)	South Korea (KHNP, derived from Westinghouse)	1450	First units expected to be operating c 2013.
SWR-1000 (BWR)	Germany (Areva NP)	1200	Under development, pre-certification in USA
VVER-1200 (PWR)	Russia (Gidropress)	1200	Replacement under construction for Leningrad and Novovoronezh plants
CANDU-6 CANDU-9	Canada (AECL)	750 925+	Potential new build in Ontario Licensing approval 1997
ACR	Canada (AECL)	700 1080	Undergoing certification in Canada

Designs of Gen III systems from Westinghouse Electric Company and AREVA NP are currently being reviewed by the HSE as part of Generic Design Assessment (GDA, or precicensing). These systems can be expected to have operating lives of 60 years and so there will be an ongoing need for reactor support activities, similar to those deployed for the AGRs and Sizewell B. Fuel supply will probably be sourced from the international market if it is U-235 enriched fuel.

This intended new nuclear build in the UK needs to be set in an overall resurgence of interest in nuclear power around the world where over 40 power reactors are currently being constructed in 11 countries notably China, South Korea, Japan and Russia. There are a number of licensed advanced water reactor designs, see Table A1-3, and new construction programmes likely to commence in USA, China, Russia, India as well as the UK. The recent report¹¹ on the UK supply chain indicates that “of the estimated US\$11.6 trillion investment in electricity generation to 2030, approximately US\$200 billion will be invested in new (and replacement) global nuclear capacity. However, a more optimistic estimate of the global, civil nuclear market has recently been made by Rolls-Royce, which estimates that by 2023 the global civil nuclear market, currently worth around £30 billion a year, will be worth approximately £50 billion a year, with £20 billion in new build, £13 billion in support to existing nuclear plant, and £17 billion in support for new reactors”

Legacy waste clean-up and decommissioning

This is one of the major aspects of the UK's nuclear programme with a significant challenge in cleaning up historic facilities, packaging wastes and remediating sites.

Most of the legacy material originates from the initial nuclear activities, research and prototype reactors and the early years of Magnox reprocessing. Decommissioning of

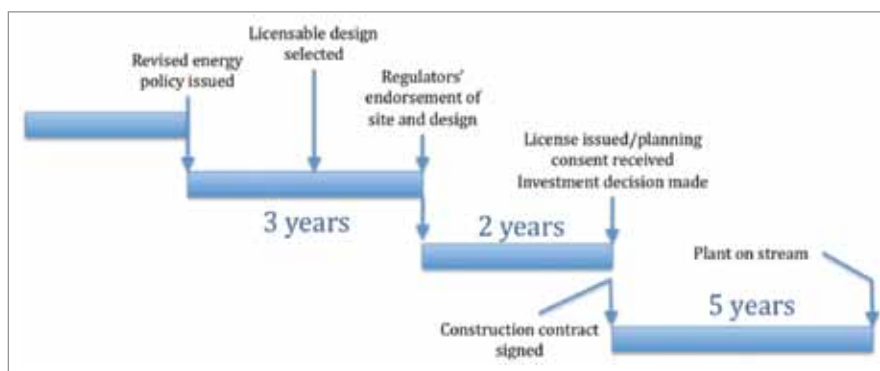


Figure A1-2 Timeline for Generation III deployment.

Magnox reactors and subsequently AGRs will occupy much of the current century and be accompanied in due course by decommissioning of chemical plant associated with fuel manufacture and reprocessing. The estimated cost of this programme is at least £70bn and is scheduled to last for over 100 years. The Nuclear Decommissioning Authority has the responsibility to drive forward this programme with private sector organisations competing to run site management contracts. There is a significant R&D programme associated with this activity as the NDA is keen to encourage innovation to reduce costs timescales and improve safety. The NDA's R&D programmes will provide one means to support the skills base, as well as developing innovative solutions to enable the clean-up programme to be delivered more quickly, safely and cheaply.

Waste Disposal

An essential part of any nuclear programme is the means to dispose of low and high activity radioactive waste and this is the responsibility of the NDA. Provision to dispose of low activity waste already exists at the NDA's LLWR site in Cumbria, while NDA's Radioactive Waste Management Directorate is charged with the design, siting and implementation of a geological repository for wastes with higher radioactive inventories, including

irradiated fuel and vitrified high level waste. In 2006 the Committee on Radioactive Waste Management (CORWM) concluded that deep geological disposal is the most appropriate way forward for managing the UK's inventory of intermediate and high level waste and spent nuclear fuel. Previously NIREX had been the body responsible for implementation of geological disposal in the UK, however NIREX has since become part of the Nuclear Decommissioning Authority.

Nuclear Propulsion

The UK's submarine-based nuclear deterrent has required the development of a self-contained capability in the design and build of submarine reactors and the manufacture of the associated fuel. While the reactor system is based upon PWR technology it is sufficiently different not to be interchangeable with civil power generation. However, there are common technology areas and significant overlap in technical skills. Strong synergies exist for example in materials research, structural integrity, reactor physics etc.

11 "The Supply Chain for a UK Nuclear New Build" by namec, September 2008

Appendix 1: Overview of the UK Nuclear Sector

2010	Korea, KHNP	Shin Kori 1	PWR	1000
2010	China, CGNPC	Lingao 3	PWR	1080
2010	Argentina, CNEA	Atucha 2	PHWR	692
2010	Russia, Energoatom	Severodvinsk	PWR x 2	70
2011	India, NPCIL	Kalpakkam	FBR	470
2011	China, Taipower	Lungmen 2	ABWR	1300
2011	Russia, Energoatom	Kalinin 4	PWR	950
2011	Korea, KHNP	Shin Kori 2	PWR	1000
2011	China, CNNC	Qinshan 6	PWR	650
2011	China, CGNPC	Lingao 4	PWR	1080
2011	Pakistan, PAEC	Chashma 2	PWR	300
2012	Finland, TVO	Olkiluoto 3	PWR	1600
2012	China, CNNC	Qinshan 7	PWR	650
2012	Korea, KHNP	Shin Wolsong 1	PWR	1000
2012	France, EDF	Flamanville 3	PWR	1630
2012	Russia, Energoatom	Beloyarsk 4	FBR	750
2012	Japan, Chugoku	Shimane 3	PWR	1375
2012	Russia, Energoatom	Novovoronezh 6	PWR	1070
2012	Slovakia, SE	Mochovce 3	PWR	440
2012	China, CGNPC	Hongyanhe 1	PWR	1080
2012	China, CGNPC	Ningde 1	PWR	1080
2013	China, CNNC	Sanmen 1	PWR	1100
2013	China, CGNPC	Ningde 2	PWR	1080
2013	Korea, KHNP	Shin Wolsong 2	PWR	1000
2013	Russia, Energoatom	Leningrad 5	PWR	1070
2013	Russia, Energoatom	Novovoronezh 7	PWR	1070
2013	Russia, Energoatom	Rostov/ Volgodonsk 3	PWR	1070
2013	Korea, KHNP	Shin Kori 3	PWR	1350
2013	China, CGNPC	Yangjiang 1	PWR	1080
2013	China, CGNPC	Taishan 1	PWR	1700
2013	China, CNNC	Fangjiahan 1	PWR	1000
2013	China, CNNC	Fuqing 1	PWR	1000
2013	Slovakia, SE	Mochovce 4	PWR	440
2014	China, CGNPC	Hongyanhe 2	PWR	1080
2014	China, CNNC	Sanmen 2	PWR	1100
2014	China, CPI	Haiyang 1	PWR	1100
2014	China, CGNPC	Ningde 3	PWR	1080
2014	China, CGNPC	Hongyanhe 3	PWR	1080
2014	China, CNNC	Fangjiahan 2	PWR	1000
2014	China, CNNC	Fuqing 2	PWR	1000
2014	China, China Huaneng	Shidaowan	HTR	200
2014	Korea, KHNP	Shin-Kori 4	PWR	1350
2014	Japan, Tepco	Fukushima I-7	ABWR	1350
2014	Japan, EPDC/J Power	Ohma	ABWR	1350
2014	Bulgaria, NEK	Belene 1	PWR	1000
2014	Russia, Energoatom	Leningrad 6	PWR	1200
2014	Russia, Energoatom	Rostov/ Volgodonsk 4	PWR	1200
2015	Japan, Tepco	Fukushima I-8	ABWR	1080
2015	China, CGNPC	Yangjiang 2	PWR	1080
2015	China, CGNPC	Taishan 2	PWR	1700
2015	China, CPI	Haiyang 2	PWR	1100
2015	Romania, SNN	Cernavoda 3	PHWR	655
2015	Korea, KHNP	Shin-Ulchin 1	PWR	1350
2015	Russia, Energoatom	Seversk 1	PWR	1200
2015	Russia, Energoatom	Baltic 1	PWR	1200
2015	Russia, Energoatom	Tver 1	PWR	1200
2015	Russia, Energoatom	Leningrad 7	PWR	1200
2015	Japan, Chugoku	Kaminoseki 1	ABWR	1373
2015	Japan, Tepco	Higashidori 1	ABWR	1080

Future Options

Once building of the Gen III fleet is established there will also be an opportunity for fuelling with MOX fuel, however this will require a Government decision to use UK Pu stocks and accept the additional liability of the irradiated MOX fuel.

There will be an opportunity to manufacture MOX fuel for the domestic Gen III system using plutonium from the UK's stockpile and to produce MOX fuel for customers who have had fuel reprocessed in THORP. Production of MOX fuel for other utilities using Pu not currently stored at Sellafield would raise a major political issue and is a less likely scenario. Current difficulties with the Sellafield MOX Plant either need to be overcome or a new MOX manufacturing plant would need to be built. Deciding upon the future of SMP is one of NDA's strategic goals for 2009.

Regardless of MOX fuel, the current position is that all irradiated fuel will be stored at the reactor until a Government decision on its fate is taken.

There could be an option for renewed reprocessing of oxide fuels during the following decade, once the major legacies at Sellafield have been reduced. Reprocessing could be focused on a combination of domestic fuels – AGR and PWR and overseas LWR. Concerns about nuclear proliferation resulting from separation of Pu might be allayed by returning Pu in the form of MOX fuel.

Table A1-3
Power reactors under construction, or almost so

Appendix 2: Gen III+ Medium Term Thermal Systems

High Temperature Reactors

High Temperature reactors (HTR) use nuclear fission to produce heat, similar to the over 440 nuclear reactors in operation globally, but with several important differences. Unlike the bulk of the world's operating light water reactors (LWRs), the HTR uses helium instead of water to cool the nuclear core and transfer heat for the energy conversion function of the reactor system. This helium "coolant" and the use of graphite as the neutron "moderator" and as part of a very resilient fuel, give the HTR its unique capability to operate at very high temperatures – much higher than all other reactor designs. HTRs operate at approximately 800° C, with even higher temperatures possible. This is in contrast to 300° C for existing LWRs. At these higher temperatures, HTRs can achieve higher efficiency and also perform "process heat" missions beyond the capabilities of existing reactor types. HTR plants are also smaller in capacity than conventional LWRs, which provides advantages for some electricity generation applications. Plant size has been a factor in the appeal of LWRs for baseload electricity generation, because of their "economy-of-scale" advantage in this marketplace. Newer HTR designs are nonetheless capable of supporting certain electricity generation needs. These smaller plants provide modular capacity additions with lower overall financial risk for smaller US utilities and they may be deployable in remote locations without established, robust high voltage transmission systems to support large central generating stations.

As eluded to above, one of the unique features of the HTR is its fuel. All HTRs use a small (~1mm diameter) fuel particle as its basis. These small fuel particles have a kernel of enriched uranium in the form of an oxide (or carbide), coated with a porous carbon layer to absorb fission gases, which is surrounded by a hard pyrolytic carbon layer, covered by a silicon carbide layer and finally covered by another pyrolytic carbon layer. These "TRISO" particles are extremely robust and can withstand temperatures well in excess of

licensing basis reactor accident temperatures. It is virtually impossible for a core melt accident. The robust coatings on each fuel kernel provide containment for the radioactive materials. The distributed containment structures incorporated in the HTR fuel replace the central, massive reinforced concrete structure on nuclear plants currently in service.

In the USA, the Next Generation Nuclear Plant (NGNP) Demonstration concept is emphasising the non-electricity generation applications of the HTR. In a typical configuration, electricity is generated by taking the process heat from the reactor through a secondary heat exchanger and transport system to drive a power conversion system while a hydrogen production facility also receives heat from the reactor through a secondary heat exchanger and transport system to produce hydrogen using either a thermo-chemical or a high temperature electrolysis process. The higher temperatures of the HTR open the door for industrial processing opportunities currently unattainable using the lower temperature of light water technology. HTR technology can meet the challenges of rising energy costs and CO₂ emissions from fossil fuels by providing process heat for industrial manufacturing.

Demonstration reactors plants are already being constructed or planned, such as HTTR in Japan, HTR-10 in China and the proposed Pebble Bed Modular Reactor (PBMR) in South Africa. The Next Generation Nuclear Plant in the USA is also based on HTR technology and will seek to demonstrate the application to hydrogen generation and process heat production as well as electricity generation.

Integral reactors

Among a range of designs for small reactors (see Table A2-1) integral light water reactor systems also have improved safety characteristics by incorporating the steam generators within the reactor pressure vessel. An entire class of potentially severe accidents associated with LWRs, known as the large-break loss of coolant accidents (LOCAs) can be eliminated by adopting such a design

feature. There are a range of designs being developed, many of which have evolved from nuclear propulsion systems. Designs vary in the size of unit proposed but the technical benefits are largely those quoted for Westinghouse's IRIS system.

IRIS (International Reactor Innovative and Secure) is a conceptual integral light water reactor plant that is currently being developed by an international consortium led by Westinghouse. IRIS is a modular 335 MWe pressurised water reactor with integral steam generators and primary coolant system all within the pressure vessel. It is nominally 335 MWe but can be less, e.g. 100 MWe. Fuel is initially similar to present LWRs with 5% enrichment and burn-up of 60,000 MWd/t with a fuelling interval of 3 to 3.5 years, but is designed ultimately for 10% enrichment and 80 GWd/t burn-up with an 8 year cycle, or equivalent MOX core. The core has low power density. IRIS could be deployed in the next decade, and US design certification is at the pre-application stage. Estonia has expressed interest in building a pair of them. Multiple modules are expected to cost US\$ 1000-1200 per kW for power generation, though some consortium partners are interested instead in desalination or district heating.

A similar unit is the NuScale multi-application small PWR which is apparently similar to IRIS but with natural circulation. It is about 150 MW thermal or 45 MWe, factory-built and with 3 metre diameter pressure vessel and convection cooling. The whole unit is installed below ground, and eight modules together might form a 360 MWe power station. An application for US design certification is expected in 2010, with pre-application meetings from mid 2008. The first unit is planned to be operating from 2015.

Babcock & Wilcox's mPower™ is also a modular, passively safe light water reactor. It is planned to generate between 125 & 750 MWe, with a five year refuelling cycle.

Appendix 2: Gen III+ Medium Term Thermal Systems

VK-300	300 MWe BWR	Atomenergoproekt, Russia
CAREM	27 MWe PWR	CNEA & INVAP, Argentina
KLT-40	35 MWe PWR	OKBM, Russia
MRX	30-100 MWe PWR	JAERI, Japan
IRIS-100	100 MWe PWR	Westinghouse-led, international
SMART	100 MWe PWR	KAERI, S. Korea
NP-300	100-300 MWe PWR	Technicatome (Areva), France
NuScale	40 MWe PWR	NuScale, USA
mPower™	125-750 MWe PWR	Babcock & Wilcox, USA

Figure A2-1
Small-medium light water reactors with development well advanced (from www.nuclear-world.org/info/inf33.html)

Appendix 3: Current UK Nuclear R&D

R&D Perspective

The current situation and the future options for nuclear power in the UK both require supporting R&D activities to ensure operations are carried out safely, timely and to cost. In addition to science and engineering R&D activities, a wide range of disciplines are required such as social, risk perception, human factors, safety analysis, socio-economics etc.

History

The UK has an impressive track record in nuclear R&D since the 1950s. Over the period 1954 – 1994, four reactor systems were developed, including building and operating prototype reactors (AGR, SGHWR, Dragon and sodium cooled fast reactor). The reactor systems were accompanied by R&D into fuel design and fuel treatment which led, in the case of the fast reactor, to demonstration of the complete fuel cycle. Specialised facilities were built and operated for handling and examination of irradiated fuel. R&D into reprocessing of thermal and fast reactor fuels utilised a range of glove box and shielded highly active facilities.

With successful industrialisation of the Magnox and AGR systems and without a pressing need for further nuclear stations the volume of nuclear R&D carried out in the UK has declined substantially since the 1970s when approximately £500m

per annum was invested. By 2000, direct publicly funded R&D was virtually zero. This came about partly due to the change in UK energy policy as a result of the discovery of North Sea gas, prompting a move away from nuclear energy, and partly as a result of the divestment of the Atomic Energy Authority with no national entity taking forward fundamental R&D. Back in the 1970/80s the UK saw nuclear as a means of providing energy security of supply and the country was developing the AGR reactors, supporting deployment of PWRs, developing the fast reactor and deeply involved in fuel processing operations (hence the historic levels of investment). With the discovery of North Sea Gas, loss of the AEA and move away from nuclear energy, by the 1990s, British Nuclear Fuels assumed the de facto role as national champion for backstopping fundamental R&D and maintained a corporate investment programme, roughly £10m per annum, directed at longer-term R&D and capability management.

Alongside reactor R&D, significant studies were conducted into the thermal fuel cycle, principally into improved enrichment technology and thermal oxide reprocessing. Both programmes were undertaken by BNFL and were aimed at international as well as domestic needs. Work on gas centrifuge technology has been successfully industrialised while R&D into laser

enrichment was discontinued once the potential returns were seen to be insufficient to justify the high development costs.

A large programme of R&D into reprocessing of thermal oxide fuels was undertaken in the 1970s and 80s to enable the design and build of THORP and this was funded by advanced payments from THORP's customers. The THORP R&D was accompanied by programmes to develop waste and effluent treatment technologies, partly to improve the Magnox reprocessing systems and also to ensure that wastes and effluents from THORP could be treated. This R&D enabled the UK to industrialise technology for vitrification of high level waste and for cement encapsulation of various intermediate level radioactive wastes.

The reactor operators (CEGB, Magnox Electric, British Energy) undertook smaller programmes to develop waste treatment and encapsulation technologies initially to treat wastes arising from operations and subsequently to treat stored wastes and wastes from decommissioning.

From the 1980s until 2005 BNFL played a role on behalf of the UK to maintain expertise and influence in the development of nuclear technology, including advanced reactor systems. The company used its corporate R&D fund to support development work in the UK and collaborative programmes overseas. It

ensured that experienced technologists participated in international forums on advanced reactor systems and were able to influence programmes to the UK's benefit. From 2005, with the formation of NDA BNFL no longer took this role of acting in the national interest. NDA now has the remit to ensure that R&D in legacy clean-up and decommissioning takes advantage of international collaboration but no organisation has a parallel role in reactor technology.

During the early years of this century the UK government via DTI & DBERR funded R&D to enable participation in the Gen IV forum. In 2006, the government decided to withdraw from active participation, on the basis of short-term funding constraints. Some R&D in Gen IV has continued as part of the EPSRC's KNOO programme (Keep the Nuclear Option Open), but has not formed part of the UK's contribution to the international Gen IV programme; there are some limited activities, mainly in universities as part of the KNOO programme even though the UK has essentially ceased participation in Gen IV. The short-term nature of decisions about KNOO and Gen IV underline the need for a national strategy on the longer term nuclear needs.

R&D for the UK's current reactor systems (Gen I & II)

Whilst R&D originally helped to develop new systems, plant designs and supporting technologies, much of today's R&D helps to underpin the industry's safe and effective operation. There is an ongoing need for R&D to maintain the safety cases for the reactors, to underpin management of the irradiated fuel and to manage the wastes and effluent.

The licensees operating the existing (Generation I and II) reactor systems, i.e. the Magnox and Advanced Gas-Cooled Reactors and the single Pressurised Water reactor at Sizewell B, have developed technology strategies that identify what is required to support the reactor systems through the end-of-life. R&D and innovation development for these systems is mainly associated

with either ensuring safe operation, lifetime extension where possible or cost reduction of operations such as through predicting operability and plant condition monitoring.

The majority of the current programmes focus on materials performance issues such as the structural integrity of graphite, steels and other components under conditions of high temperature and irradiation and also understanding materials phenomena such as stress corrosion cracking, creep, embrittlement, void swelling and other irradiation assisted processes. Work on probabilistic risk assessment, severe accident analysis, release mechanisms and non-destructive testing also form major parts of the research programme.

The research challenges for existing generation include:

- Ageing and degradation of specific materials and components, such as the graphite core and AGR boiler components.
- Obsolescence of plant/equipment making like-for-like replacement difficult.

On fuel cycle technology, currently Magnox fuel is reprocessed as a means to stabilise the waste form. AGR fuel is destined for either interim storage or reprocessing and fuel from Sizewell B is destined solely for interim storage. R&D is required to support the continued operation of the infrastructure associated with spent fuel management on the grounds of safety assessment, plant performance predictability, operating cost reduction etc. There is also a continuing requirement to assess the overall strategy for spent fuel management and this requires on-going research in developments associated with either open or closed fuel cycle options.

Historically in the UK, there has been research conducted on aqueous reprocessing in order to support the fuel current fuel cycle activities, ie Magnox reprocessing and also employed in the THORP reprocessing plant. Technology development has been associated with chemical flowsheet engineering improving

separation between waste species and reusable species such as plutonium. Research has focussed on reducing costs, waste volumes and improving environmental performance.

One of the additional aspects of the UK's nuclear programme that does receive significant attention is the work on contributing to international safeguards and non-proliferation. Whilst R&D activities specifically related to this field may be limited it is still necessary to have expertise and knowledge which often is generated through R&D. In addition this area does drive future R&D in terms of development of new detection techniques and proliferation resistant fuel cycles and reactors.

A related area of R&D is that on emergency preparation to understand, in the event of a release of radionuclides, the impact on flora, fauna and uptake into the food chain. Research also involves communication systems, infrastructure requirements and social aspects in terms of how individuals respond and decisions are made in the event of a nuclear emergency.

R&D for Legacy Waste management

The major issue for the legacy waste management and clean-up programme is to ensure safe, timely and cost-effective delivery of the work. Science, Technology and Innovation play a key role in helping to expedite the programme as quickly, safely and cost-effectively as possible. Research and Development will play a key role in topics such as:

- Waste characterisation, separation, encapsulation and packaging
- Assessment and remediation of contaminated land
- Determining the end state for sites, operations and plants
- Future use of plutonium and treatment of uranium stockpiles
- Radiation epidemiological studies
- Decommissioning and dismantling of plant
- Integrity of waste for interim storage
- Management of low-level waste disposal sites

Appendix 3: Current UK Nuclear R&D

Gen III R&D

For near-term deployment of Gen III reactors, a major technical development programme is not necessary as designs are ready for deployment. However, a key aspect is ensuring the existing skill base in the industry is retained and the supply chain can be re-invigorated. Research can play a key role in helping to maintain critical capabilities such as the following:

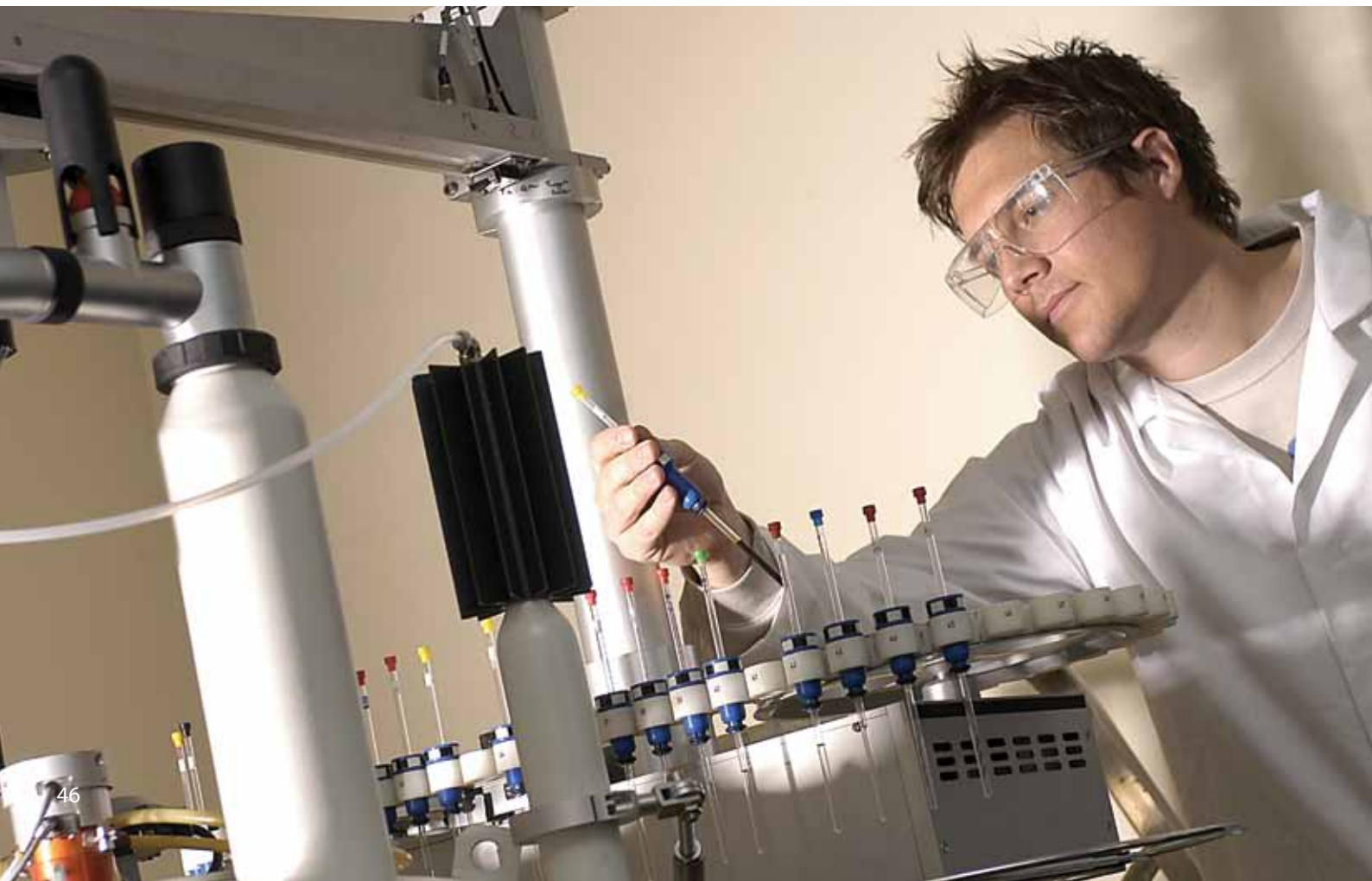
- Core Design and Fuel Performance
- Systems Engineering
- Materials Performance
- Water Chemistry
- Criticality, Shielding and Radiation Protection
- Thermal Hydraulics and Transient Analysis
- Safety Performance Assessment

While R&D to support new nuclear build will be limited it is likely there will be a small but finite requirement to ensure licensees and utilities fully understand safety related performance of the reactor systems. This is currently under consideration by the Nuclear Installations Inspectorate. Possible areas of interest for licensing a new system in the UK might include:

- Use of digital C&I systems for protection & control
- Incredibility of failure of items (e.g. pressure vessel)
- Probabilistic risk assessment – reconciliation of approach
- Acceptable engineering codes and standards
- Acceptable computer codes
- Severe accident management
- Radiation and contamination zoning – compatibility with overseas designs
- Reactor shutdown provision (control rods vs boronation system)
- Advanced Passive Safety features
- Security

It will also be necessary to perform research associated with societal issues and, while no roadmap currently exists, the Research Councils have funded a programme on Sustainable Nuclear Power which addresses many of these societal and policy issues. Research activities include:

- Socio-economic studies
- Financing
- Siting information
- Project delivery
- Stakeholder perception
- Environmental impact etc.



Appendix 4: R&D for Future Systems

The R&D requirements for advanced reactor systems are well publicised, so for the purposes of this report a summary only is provided.

High temperature reactors (Gen III+ systems)

The world leaders in the field of high temperature reactor design are South Africa and China; both countries have plans for near term deployment, beginning with a demonstration reactor before 2020. Elsewhere research and development on high temperature reactors is being carried out in USA, Russia, France, and S Korea. There are mechanisms for collaborative research by these and other countries through the High Temperature Reactor Technology Network (HTR-TN) – a 21 partner network of the EU, and the 10 member network of the Generation IV International Forum (GIF).

Key R&D areas for development of HTR reactors which will be needed by other countries include those shown in the Table A4-1.

An illustrative technology development roadmap for High Temperature Reactors is shown in Figure A4-1.

Fuels Technology	Capability to manufacture and test coated particle fuel. Work must continue to demonstrate repeatable fabrication of highly reliable coatings and kernels on a commercial scale and to prepare for qualification testing in accordance with nuclear standards
Materials Technology	Preliminary work on preliminary creep, creep-fatigue, and environmental effects. Testing of high-temperature materials for intermediate heat exchanger applications. Much work remains to assess and qualify materials options for the reactor pressure vessel, hot ducting, hydrogen process heat exchangers and control rod guide tubes, and to qualify ceramic and metallic components. Licensing guidance is required for all these materials issues
System Design	Designing the integrated nuclear heat supply system, power conversion system, and hydrogen production facility requires finalising key design parameters, such as reactor power, outlet temperature, plant configuration, etc. Improved computer methods are required to supplement existing neutronic, thermal hydraulic, and safety codes applicable to HTR technology. Improved methods and associated experiments are needed to validate the computational tools
Test Facilities	Designing, constructing and operating the necessary test facilities (or modifying existing facilities) such as a high-temperature fluid flow test facility will advance the development and demonstration of HTR systems, key process equipment, and hydrogen production concepts
Hydrogen Process Development	Water-splitting process development must be advanced through demonstration of the integrated nuclear heat supply system, power conversion, and hydrogen production facility

Table A4-1
Key R&D areas for development of HTR reactors

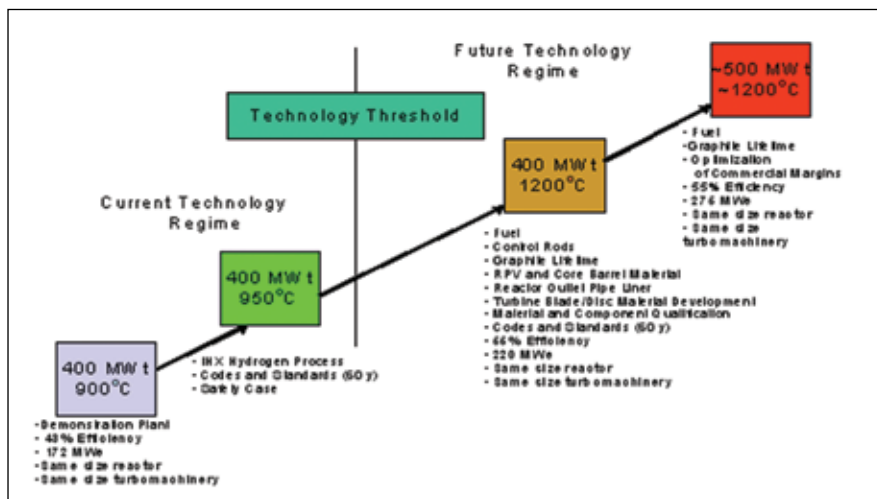


Figure A4-1
Roadmap for High Temperature Reactor Development

Appendix 4: R&D for Future Systems

Hydrogen and process heat applications

Hydrogen is expected to play a key role in the commitment by many nations to reduce CO₂ emissions and move away from dependence on fossil fuels. High Temperature Gas Cooled reactors (HTR) which produce heat at around 700 to 900°C are particularly suited to the hydrogen economy. This is because thermochemical cycles can be used to generate hydrogen using only water as the feed but still require temperatures of the order of 900°C.

Technology issues that need to be addressed specifically on the nuclear related aspects are as follows:

- Integration with nuclear heat source
 - Thermal coupling method, associated technologies (e.g. Heat exchanger materials)
 - Operational considerations (e.g. pressure balancing requirements)
- Integrated Process Demonstration
 - Pilot loop applying prototype materials at proposed operating conditions
- Regulatory Considerations
- Economics

R&D for Advanced Thermal and Fast Reactor Systems (Gen IV)

The VHTR (Very High Temperature Reactor)

While this is an evolution of the HTR, the drive to higher temperatures and larger cores requires further R&D. Technology gaps include novel fuels and materials that:

- Support increased core-outlet temperatures (850-1000°C)
- Permit the maximum fuel temperature following accidents to reach 1800°C without damage
- Permit maximum fuel burnup of 150-200 GWd/tHM
- Avoid excessive core power peaking and temperature gradients
- Fuel R&D
 - Qualification of TRISO fuel
 - ZrC coatings for T>1000°C
 - Burnable Absorbers, sic-sic and C-C composites
- Materials
 - Reactor Pressure Vessel materials studies
- Balance of plant R&D
- Safety R&D
- Fuel Cycle R&D
 - HTR Graphite Minwaste
 - Fuel Recycle

Fast reactors

Fast reactor designs must address issues related to economics, safety, system performance and reliability, and safeguards and security.

Technology development is needed in:

- Coolant control (chemical, thermal and hydraulic)
- Core structural materials
- Instrumentation and control
- Seismic isolation
- Fuel handling
- Reactor vessel and structures
- Maintenance and inspection technology
- Balance of plant

For the two systems of greatest relevance to the UK, the R&D requirements can be summarised as follows:

Gas-Cooled Fast Reactor

Technology gaps include novel fuels and materials:

- Fuel form and material
- Decay heat removal
- Fuel cycle technology
- Structural materials for high temperatures and fast neutrons
- Fuels Research
 - Matrix type
 - Cladding
 - Burn-up
 - In core performance
 - Remote manufacture
- Materials
 - Structural components
 - Irradiation testing and examination
- Fuel Cycle
 - Processing options

Sodium-cooled Fast Reactor

Technology gaps are present in the following areas:

- Fuels Research
 - Matrix type
 - Cladding
 - Burn-up
 - In core performance
 - Remote manufacture
- Materials
 - Structural components
 - Irradiation testing and examination
- Fuel Cycle
 - Processing options
- Fuels
 - Manufacture
 - In-core performance
- Materials
- Fuel Recycle options
- Safety Assessment
- Decommissioning / design experience

Fuel Cycle Technology to support fast reactor deployment

Recycle technology is fundamental to the deployment of fast reactor systems, and hence fundamental to the goals of Generation IV. There are also strong synergies with technologies which may be of interest to the legacy waste management programme in the UK.

R&D is needed in two broad areas:

- a) LWR spent fuel separation and refabrication into fast reactor fuel
- b) Fast reactor spent fuel separation and refabrication into fast reactor fuel.

The overall aim is to develop reprocessing and fuel treatment technologies that are cleaner, more efficient, less waste-intensive and more proliferation resistant.

One focus of R&D needs to be on the development of aqueous technologies:

- Simplifying the flowsheet with fewer unit operations
- Alternative reagents and separation processes to reduce wastes and effluent
- Increasing proliferation-resistance by avoiding separation of pure fissile material
- Separation of heat-generating or long-lived radionuclides
- Recycle of minor actinides
- High integrity waste matrices

A second focus of R&D will be on pyrochemical (molten salt) technologies, which have the potential for more compact plant, fewer unit operations and greater proliferation resistance:

- Minimising fissile material losses
- Improved cleaning of the molten salt
- Increased efficiency of electrochemical deposition.
- Materials with increased corrosion resistance

A third focus of R&D will be on technologies to refabricate the fuel for re-irradiation in the fast reactor system. Fuels containing the entire mix of transuranics must be qualified. Fuel testing and qualification will require the use of a fast test reactor.



Appendix 5: Feedback from UK Stakeholders

Questionnaire relating to New Build: Technical Challenges

1	<p>What do you see as the key technical challenges with the new nuclear build programme? Discuss Gen III and Gen IV+?</p> <ul style="list-style-type: none"> • There is a little or no call for R&D in support of the new nuclear build programme. The PWRs will be built to a well proven design with minor, evolutionary changes. • Main challenge is to extend lifetime to 60 years and maintain efficiency and safety • Main focus for Gen III R&D is improved modelling of reactor core, better understanding and prediction of materials (including metals, plastics and concrete) ageing, i.e. corrosion (all forms), fatigue, fracture toughness, irradiation damage of fuel and reactor materials. Improvements here will bring further improvements in reactor safety and reliability. <p>Gen III+ and Gen IV are perceived to be very long time scale R&D (commercial deployment unlikely before 2040). The main opportunities for R&D are in Gen III+ and Gen IV systems, as follows:</p> <ul style="list-style-type: none"> • Numerous issues specific to graphite including stress ratios for combined states, ageing, non destructive investigation, irradiation testing, inspection techniques and creep modelling. • Identification of long term environmental conditions and material properties of concrete components, particularly at high temperatures. • Numerous issues relating to welding and joining technologies. • These include: <ul style="list-style-type: none"> - constitutive models for high temperature operation under creep and creep/fatigue - methods to predict weld degradation - re-heat cracking aspects - quantification of crack driving forces and fracture toughness - environmentally assisted corrosion fatigue and stress corrosion cracking - qualified methods and inspections of heavy section welding required for new large containment vessels - long term ageing effects - evaluation of residual stresses - treatment of dissimilar metal welds particularly in fracture mechanics evaluations • Materials information needs to be generated so as to be able to address: <ul style="list-style-type: none"> - long term ageing data for new reactor pressure vessel materials - strategies for mitigation of ageing effects - strength and ductility data at high temperature (maybe up to 900oC) - quantification of the effects of supercritical water systems on stress corrosion cracking - material selection for better high temperature performance - alloy selection for heat exchangers • Other structural integrity/materials issues include: <ul style="list-style-type: none"> - User variability for application of structural simulation software to highly nonlinear events - coupled analyses rather than sequential for in-service transients, earthquake, air and ground shock and impact - micro-scale modelling methods describing microstructure in FeCr alloys under thermal ageing and irradiation, to correlate micro structural changes to changes in mechanical properties - strain based acceptance criteria for energy limited accident events
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Questionnaire relating to New Build: Technical Challenges

2	<p>Is the UK R&D base capable of responding to these challenges? Discuss strengths and weaknesses of UK Universities, UK supply chain and their own R&D activity.</p> <ul style="list-style-type: none"> • Strong UK R&D base in the area of structural integrity and materials, consisting of industrial companies, R&D supply chain organisations and the universities. In addition, there is participation in relevant European programmes and links to programmes world-wide. • Strong UK R&D base in fire testing and fire modelling. • Concern about lack of level of UK qualified and experienced resource in the reactor chemistry and civil engineering areas. • Potential lack of funding and uncertainty about whether UK academic expertise can adequately be focused on real issues. • In the area of fuel modelling, there is a view that practical experience in other countries (e.g. France, Sweden and Finland) is more helpful than university R&D in addressing any economic, technological or sociological issues. • In the area of control and instrumentation, there is a view that the supply chain organisations are aware of NII concerns and focus their research on addressing them. However, overseas suppliers are potentially more focused on their home country regulators and may be less prepared to meet NII requirements. • In the field of non destructive examination (NDE), there is a view that the UK R&D base is only partly capable of responding to the challenges. This is because it is considered that universities are not geared to deliver industrial solutions and that the supply chain is getting depleted due to loss of funding and retirement of key staff. • UK has strengths in R&D on Future Reactor Systems: This has little or no relevance to PWRs. The experience would be relevant to some Gas Cooled Fast Reactors, Sodium Cooled Fast reactors, High Temperature / Very High temperature reactors but experience needs to be captured or utilised now on Government funded international programmes. • UK universities need to re-establish their strengths in depth in high temperature metallurgy and ceramics. • UK R&D base has been run down from the high point when CEGB and Harwell Labs were world leading. Some UK Universities still have world class skills (see Item 6 below). UK expertise in operation of PWRs is limited. • Ability to close the fuel cycle is a strength not found in many other countries but facilities perceived to be unreliable and operating well below full capacity. • Based on the current performance in reprocessing, manufacture of MOX fuel and decommissioning redundant facilities, there is an alternative view though that the UK R&D base may not be capable of responding to the challenges. • This also applies to Fast Breeder Reactor technology where UK was perceived to be very strong but again the experience is likely to be lost unless deployed on demonstrators or test reactor programmes. • UK nuclear supply chain not well known apart from the major industrial players. Special expertise believed to exist in digital command and control systems.
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Appendix 5: Feedback from UK Stakeholders

Questionnaire relating to New Build: Technical Challenges

3	<p>What is your current level of investment in nuclear energy R&D? What proportion of that is with UK universities, your supply chain, overseas universities and suppliers? How is this likely to change over the coming years?</p>
	<ul style="list-style-type: none"> • Consultancy work attracts about £1m/year in R&D contracts. About 20% of this is sub-contracted to universities. Most of the work is in the fields of structural integrity, materials and NDE. • Some companies maintain a commitment to participation in international projects to develop Gen IV reactor projects which will result in demonstrator/ prototype reactors before 2020 and possible commercial deployment between 2030 & 2040. The commitment is mainly the time of senior personnel participating in meeting and discussions with partners in the consortia which will be developing these systems. Other involvement is in the Pebble Bed Modular Reactor (PBMR) in South Africa, the European Fast reactor (EFR), and the NGMP, and developments in Russia. There is little involvement in similar activities in China, Japan or Korea. Some companies are also heavily involved with fusion research, both at Culham and Caderache / ITER, and hope to be involved in building the first wall structure for ITER. <p>The rationale for involvement in international R&D on future reactors is a combination of:</p> <ul style="list-style-type: none"> - (i) Being in a position to capture contract opportunities to design and build the demonstrators / prototypes - (ii) Skills upgrading for their nuclear engineers <p>Exciting employment opportunities for very bright new graduates (more attractive than decommissioning work)</p> <ul style="list-style-type: none"> - (iii) Long term positioning to be involved with commercial Gen IV systems. <p>Nuclear utilities invest typically several hundred million Euros per year on R&D. A minor proportion of this investment is made to support R&D in UK universities.</p> <p>Investment in R&D in the UK supply chain is not easy to estimate following the take over of British Energy.</p>
4	<p>What are the main barriers to implementing an R&D portfolio on nuclear energy?</p>
	<ul style="list-style-type: none"> • Government commitment • Public acceptance • Commercial viability (over full lifecycle) <ul style="list-style-type: none"> - likelihood of sufficiently large incremental income from making the R&D investment - some aspects (e.g. NDE and Inspection Qualification may be regarded as an extra cost rather than a reliable means of ensuring structural integrity and safety) • There are only a limited number of courses in nuclear engineering • There is widespread disappointment with the current lack of commitment / investment by the UK Government in Gen IV research. It is hoped that recent positive comments in the DIUS Report on UK Nuclear Engineering Capabilities may reflect a change in stance. • Since the break up of BNFL there is no effective focal point for the UK's nuclear engineering activities. There was uncertainty among stakeholders as to whether the National Nuclear Laboratory will (be funded to) provide this focus?
5	<p>In which technologies is public sector intervention necessary to allow UK capacity to grow and become a leading global player?</p>
	<ul style="list-style-type: none"> • One view is to question the practicality of the UK to become a leading global player, or indeed if it is necessary given we are importing much of the technology. • In the fuel modelling sector, it is considered that experience needs to be gained with codes for PWR fuel, possibly constructing and validating our own codes and building on the codes that we have for other reactor systems. • In the control and instrumentation area, it is considered that safety critical software is required. • In the NDE area, it is considered that the development of new, and resurrection of previously developed, advanced NDE capabilities are needed. • The Government is not providing a strategy, coordination, leadership or fighting our corner for research funding from Europe in the way which CEA does for France • UK Nuclear Profile –The UK needs to project a more clear and positive profile of what it can do to promote the nuclear renaissance and publicise special areas of expertise which can create wealth from the new nuclear build in the UK and overseas. This point was made by Lord Mandelson in discussions with the UK Industry delegation which visited India to discuss nuclear engineering. 'What can the UK offer'. Mandelson is seen as a powerful supporter of nuclear power. Stakeholders expect more activity from BERR to define what the UK can offer to support the new nuclear build programme. Past surveys, even relatively recent ones, need to be updated.

Questionnaire relating to New Build: Technical Challenges

6	In which of the relevant technologies is the UK leading? e.g. modelling, NDE, remote handling systems?
	<ul style="list-style-type: none"> • The UK may be considered to be leaders in many aspects of structural integrity. For example, the British Energy development led R6 procedures, for assessing the significance of crack like defects in structures and the R5 procedures, for assessing the structural integrity of high temperature components, are applied in many countries on nuclear components. Much of the UK structural integrity related R&D programmes are aimed at further developing these procedures. • The UK has a strong capability in modelling AGR and fast reactor fuel (of various types). This has only borderline relevance to PWR New Build however. • The UK has strong leadership in Cost effective Inspection Qualification. • UK Universities still produce the best metallurgists and solid state physicists. Advanced Computer modelling of reactor cores leading to new and improved codes of operation is seen as a particular strength of UK universities (Imperial & Manchester) and also Simulation of Irradiation Damage & Derivational of Inter-Atomic Potentials (Imperial). • Other relevant strengths include Computational Fluid Dynamics, Thermal Hydraulics, NDE, Structural Integrity, Corrosion, Waste management, Decommissioning and Decontamination. • The UK is seen to have unique facilities, eg X-Ray Tomography for Materials Science at Oxford University, Titan at Imperial, The Diamond facility at the Rutherford Appleton lab. • Lancaster is rated world class for neutron detectors and Liverpool for gamma detectors. Liverpool is highly regarded for work on pressure vessel steels. • Some stakeholders perceive opportunities for the UK to increase activity on nuclear fuel reprocessing and in particular MOX fuel production but this is not within the UK Government Focus (DECC and BERR) on new nuclear build. It was recognised that further commercial activity on spent fuel recycling would be politically difficult and may impair the current mood of support for the nuclear revival. There does not appear to be a strategy for dealing with the accumulated store of plutonium.
7	Where are the main gaps in the UK's technological capabilities? Discuss R&D, practical experience, manufacturing gaps and weaknesses.
	<ul style="list-style-type: none"> • The UK has probably failed to have retained the culture or experience necessary to manufacture heavy pressure vessels to nuclear standards without significant assistance from overseas. • It is thought that the R&D base will need to grow significantly in most areas to support a major expansion of the nuclear industry. • There is a lack of practical experience in running a fleet of PWRs, and modelling PWR fuel. There are quality problems in the manufacture of MOX fuel, and apparent paucity of long-term contracts to supply fuel. • Day to day operational experience of modern PWRs is seen as a most obvious gap. • The supply chain must be weak in view of the long gap since the building of Sizewell B and the limited success of UK companies in securing overseas nuclear work. (Exceptions quoted are Amec – formerly NNC, and Rolls-Royce for turbines and pumps for 'non-nuclear' equipment for PWRs.) • Some stakeholders were not aware of any hot cell facilities for details examination of irradiated materials.
8	In which technologies should the UK not attempt to lead? Should it attempt to collaborate with overseas partners in these areas and if so how and with whom?
	<ul style="list-style-type: none"> • It is considered that the UK may only need to take the lead on those technologies needed to support the approaches to licensing plants under the UK regulatory framework. In other areas, partnerships with vendors probably constitute the most practicable way forward. • UK cannot lead in the new build of PWRs. Collaboration is essential. • In waste management, although the UK has good experience there would still be benefits from collaboration with French and Belgian experts

Appendix 5: Feedback from UK Stakeholders

Questionnaire relating to New Build: Marketing Opportunitites

1	<p>Can you quantify the size of the market for nuclear engineering over the next 20 years and what share of this do you hope to capture?</p> <ul style="list-style-type: none"> • This is very difficult to ascertain without a detailed study being carried out. • The world market for nuclear engineering is huge – around 300 new reactors to be built at a cost £2 billion each and 250 to be decommissioned at around £1 billion each, i.e. £855 billion • It is huge. Probably 1,000 billion euros.
2	<p>Are these opportunities in new nuclear build in the UK and other countries sufficient to justify an increase in your R&D expenditure?</p> <ul style="list-style-type: none"> • The R&D supply change has yet to see a significant increase in nuclear R&D spending. • At least one potential operator of new nuclear stations is increasing its nuclear R&D spending
3	<p>What public sector interventions do you expect to assist you to capture the opportunities?</p> <ul style="list-style-type: none"> • Continued funding of strategic R&D. • Possible financial and organisational assistance in further developing and exploiting major overseas nuclear market in India/ China. • Helping in the setting up of industrial/academic partnerships. • Increased support for international exchange schemes for academic researchers • Training for experienced engineers in the oil and chemical process engineers to be able to be able to work in the nuclear industry
4	<p>What spill over benefits can you envisage from R&D in the nuclear fields into other industrial sectors? How big is the market and are you able to access it?</p> <ul style="list-style-type: none"> • Nuclear structural integrity and NDE tends to lead the field but eventually the same approaches become adopted elsewhere. • In some areas (e.g. reactor chemistry), it would be expected that spill over to other industrial sectors would be limited because of the differences in culture between the nuclear sector and others that also involve capital intensive plant. • Many techniques employed in the nuclear industry, e.g. NDE, Structural Integrity Monitoring, Modelling, Digital Control Systems, are directly applicable in other industries.

Feedback from Workshop to review UK R&D Capabilities in Nuclear Engineering on 18th June 2009 at University of Manchester.

An important part of the workshop was to gather participants' views on the need for and benefits of public sector investment in nuclear R&D. Three questions were posed to each of 3 discussion groups and the amalgamated responses are summarised here.

1 Where & how can public sector investment in nuclear R&D make a difference?

Materials:

- Archive material testing from decommissioned systems
- Underpinning materials research to benefit across entire nuclear sector
- R&D for life extension of existing reactor systems
- NDE, condition monitoring

Underpinning technology:

- Safety case development & licensing
- Promote safety expertise/R&D/training
- Support for projects with long term payback – e.g. prototype & demonstration reactors
- Encourage industry to invest in R&D beyond the short-term
- Fuel manufacturing
- Manufacture of nuclear components (pumps, valves, instruments etc.)
- Instrumentation
- Common design codes

Knowledge management:

- Support knowledge infrastructure – e.g. IT & databases; data harvesting
- Management of historic knowledge and archives
- Participate in international forums & R&D initiatives

Skills development:

- Promote communication & networking – KTN model (sensors already & energy soon to happen)
- Stimulate academia
- Fill skill gaps – use R&D programmes to develop & retain people
- Support to mobilise skills from elsewhere
- Maintain skills that meet long term needs (but have no short-term support from industry)
- Should we have an ETI for nuclear or put nuclear into ETI?
- Align various capability reviews
- Encouragement for women to develop careers in the nuclear field

Social and economic aspects:

- Support for shared facilities
- Increase public understanding - Invest in social science R&D
- Public/private co-funding
- Co-ordinate investment from different public sources
- Support for technology transfer (spin-in/spin-out)

2 Where would investments lead to opportunities beyond nuclear?

Technology topics:

- Underpinning technology – NDE, condition monitoring, instrumentation, etc.
- Underpinning materials research
- Nuclear hydrogen & fossil fuel synthesis
- Application of nuclear-generated heat
- Technology demonstrators

Mechanisms to assist spin-in/spin-out:

- Form a nuclear technology transfer agency
- Support for shared facilities - Space for SMEs to do research projects
- Support knowledge infrastructure – e.g. IT & databases; data harvesting
- Management of historic knowledge and archives
- SMEs need help with accreditation & contracts; Example of Sellafield's market days
- Spin-offs & cross-fertilisation can arise from personnel brought back into the nuclear sector
- Need to link to other sectors & promote transfer of knowledge (energy, high technology, highly regulated)

3 What are your top priorities for investment in nuclear technology?

- Fuel manufacturing
- Safety case development
- Manufacture of nuclear components
- Support knowledge infrastructure – e.g. IT & databases; data harvesting
- R&D for life extension of existing reactor systems
- Archive material testing from decommissioned systems
- Underpinning technology – NDE, condition monitoring, instrumentation, etc.
- Underpinning materials research to benefit across entire nuclear sector

It was recognised that to justify public sector funding linkage needs to be made to strategic drivers, energy security and skills development.

Appendix 6: Feedback from International Stakeholders

Technical Challenges

1	<p>What do you see as the key technical challenges with the new nuclear build programme? Discuss Gen III and Gen IV+?</p> <ul style="list-style-type: none"> • There are limited technical challenges since the designs are licensed overseas • It is expected that the UK regulators will need an R&D capability independent of the vendors • Improvements in performance through development of fuels - Fuels could be modified to ensure higher / more efficient burn up but if the fuel enrichment goes much above 5% then much more expensive production facilities will be needed. This is related to fuel criticality and the amount of U235 which can be released into the production environment. • Gen IV systems, Fast reactors, Fast breeders, VHTRs, etc. will not be commercially significant before 2040 and are therefore unlikely to attract any support from industry unless there is public funding for demonstrator plants. • Thorium cycle technology is inherently more expensive due to the need to shield high energy gammas.
2	<p>Is the UK R&D base capable of responding to these challenges? Discuss strengths and weaknesses of UK Universities, UK supply chain and their own R&D activity.</p> <p>International perceptions of the UK's technical strengths are:</p> <ul style="list-style-type: none"> - 1. Fuel cycle technology. - 2. Decommissioning and Decontamination. - 3. Waste Processing. <ul style="list-style-type: none"> • Gas Reactor Experience • LMFR Experience • Fuel Manufacture • Fuel Modelling • PIE • SNF & Pu storage • Separations • Reprocessing • Waste Management • D&D • Thermal hydraulics • Graphite • Working at scale • NNL Central Laboratory • Physical protection of nuclear infrastructure <p>Perceptions of the UK's Weaknesses:</p> <ul style="list-style-type: none"> • The skill base is ageing & research capability has been lost • There are only limited R&D programs in the areas of <ul style="list-style-type: none"> - Advanced Fuel Cycle - Advanced Reactors • There is a need for technical understanding of ALWR Designs, development of Technical Infrastructure for Regulatory Reviews, Development of a trained workforce, increase in qualified sub-suppliers <p>Suggestions:</p> <ul style="list-style-type: none"> • Become an active participation in international collaborations

Technical Challenges

3	<p>What is your current level of investment in nuclear energy R&D? What proportion of that is with UK universities, your supply chain, overseas universities and suppliers? How is this likely to change over the coming years?</p> <ul style="list-style-type: none"> • Major companies, e.g. utilities & vendors generally invest significant sums in R&D within their own organisations, in research collaborations such as EPRI and universities. • It is perceived that the academic base in nuclear is weak - relatively few professors, researchers and students • Recent organisational changes, break-up as well as consolidations in UK Industry have reduced capabilities
4	<p>What are the main barriers to implementing an R&D portfolio on nuclear energy?</p> <ul style="list-style-type: none"> • Inconsistent Government Policy regarding nuclear energy • Limited Funds • Limited R&D Infrastructure • Cost of R&D • Failure to commission glovebox and HA cell facilities in the>NNL • Limited experience in open competition for R&D funding <p>Need consistent Energy Policy supportive of nuclear energy</p> <ul style="list-style-type: none"> • Establish a Robust Competitive R&D Program with Stable Funding • University • National Laboratory • Industry • Overcome impression that nuclear engineering is a dying profession in the UK
5	<p>In which technologies is public sector intervention necessary to allow UK capacity to grow and become a leading global player?</p> <ul style="list-style-type: none"> • A Government Funded Kick-Start is needed to increase domestic R&D capability & re-establish the UK as a major player in nuclear. • There is a consistent impression of a need for the UK to re-engage with international collaborations. • This would provide mentorship of UK researchers' incentives to students for majoring in nuclear engineering. Other capability building would be regulatory capabilities & development of the UK workforce <ul style="list-style-type: none"> • Reactor Life Extensions • Invest in selected Gen IV Technologies • Fuel • T/H Analysis • Materials • Design Evaluations • Monitoring & Diagnostics • Safety Analysis • Closing the Fuel Cycle <ul style="list-style-type: none"> • Seed funding needed to generate and test early stage ideas

Appendix 6: Feedback from International Stakeholders

Technical Challenges

6	In which of the relevant technologies is the UK leading? e.g. modelling, NDE, remote handling systems?
	<ul style="list-style-type: none"> • In terms of supporting the new nuclear build programme, building new manufacturing facilities for nuclear fuel production is one of the lowest cost options in terms of capital investment and could solve a perceived “pinch point” in the supply chain. • UK strengths in gas reactor technology & graphite are relevant to high temperature reactors but not new build of advanced light water reactors. • One view was that the new build programme needs an efficient reliable reprocessing facility at Sellafield and investment to solve current production problems is recommended and could yield a high return.
7	Where are the main gaps in the UK’s technological capabilities? Discuss R&D, practical experience, manufacturing gaps and weaknesses.
	<ul style="list-style-type: none"> • The UK’s greatest weakness is its paucity of operating experience with LWRs, hence the infrastructure and skill-base is weak accordingly. <ul style="list-style-type: none"> - Limited LWR experience - Limited Regulatory Capability • Perceptions of potential remedies included – increasing the market focus of the R&D community, reinvigorating university R&D and adopting a new innovation model
8	In which technologies should the UK not attempt to lead? Should it attempt to collaborate with overseas partners in these areas and if so how and with whom?
	<ul style="list-style-type: none"> • The international perception of the overall ranking of the UK R&D Capabilities was unflattering - Generally last among France, Japan, Korea, India, China, U.S., and Canada. Sometimes below Germany • Collaboration and partnering is a necessity • Limited international participation during the last 10 years has limited outside knowledge of UK capabilities. • It is not necessary to lead, more important to play a significant role in collaborative R&D • The constructors of new nuclear build capacity would be prepared to consider joint ventures to ensure that the necessary investment is available for new production facilities for fuel and improved re-processing facilities.

Marketing opportunities

1	<p>Can you quantify the size of the market for nuclear engineering over the next 20 years and what share of this do you hope to capture?</p>
	<ul style="list-style-type: none"> • Many countries are planning to expand their nuclear programmes. • There is an expectation of 200-300 new reactors, worldwide • Plans for new nuclear power plants in India and China dwarf other countries' plans
2	<p>Are these opportunities in new nuclear build in the UK and other countries sufficient to justify an increase in your R&D expenditure?</p>
	<p>Not relevant to the international organisations consulted</p>
3	<p>What public sector interventions do you expect to assist you to capture the opportunities?</p>
	<ul style="list-style-type: none"> • Remote systems • Nuclear Materials • Advanced Simulation & Modelling • Gas cooled reactors in collaboration with reactor vendors • Strengthen International Collaboration • Programmes to assist in gaining know-how in water reactor technology • Strengthen the regulatory framework • Gas cooled reactor opportunity in high temperature reactors- somewhat limited due to lack of UK based reactor vendor
4	<p>What spill over benefits can you envisage from R&D in the nuclear fields into other industrial sectors? How big is the market and are you able to access it?</p>
	<ul style="list-style-type: none"> • Remote systems • High-temperature materials • High-temperature chemical process technology • Digital Instrument & Controls • Diagnostic techniques (NDE/testing) • Prognostics • Quantitative Risk Assessment • Human factors engineering • Thermal/hydraulic analysis

Appendix 7: Materials Nuclear R&D Capacity, Opportunities and Spill-over Benefits

A H Sherry, Dalton Nuclear Institute, The University of Manchester

C A English, National Nuclear Laboratory/The University of Manchester

P E J Flewitt, Magnox North/Bristol University

1.0 Scope of Study

The sponsors have set four questions¹² as a basis to review the opportunities for UK organisations to develop and deploy innovative technologies to support the civil nuclear industry:

- 1 Is there a UK and global market opportunity for exploitation?
- 2 Is there a UK capacity to develop and exploit the technology and become a leading global player?
- 3 Does the technology have potential for impact in the right timeframe?
- 4 Is there a clear role for public sector intervention and support that adds value above and beyond that of private investment?

The information presented in the main report has addressed Question 1 and Table 3 of the main report provides a summary that supports the view that there is a UK (and by implication a global) market opportunity with respect to both materials R&D and also the material aspects of component supply. This Appendix provides information that supports this view, and specifically considers the remaining three questions in more detail with respect to the UK materials capacity to develop and exploit the technology, the opportunities for short-term impact (i.e. within 5 years) including spill-over benefits and role for public sector investment.

The UK materials capability is critical for underpinning the following five strategic national nuclear goals over the short- (within 5 years), medium- (5 to 20 years) and long-term (beyond 20 years):

- Plant-life extension of existing Magnox, AGR and PWR power stations
- New nuclear build of PWR power stations
- Safe and reliable operation of new Gen III PWR power stations
- Development of Gen IV and fusion reactor systems
- Decommissioning, management, interim storage and geological disposal of nuclear waste

Experience has been obtained over the last 60 years in the UK in managing the complete life cycle of civil nuclear reactors. This has demonstrated that an essential requirement for maintaining a fleet of operating reactors, for assessing and commissioning new plant designs, and for developing appropriate waste management strategies, is that in-depth knowledge, understanding and supporting materials data are used effectively to predict the evolution of materials properties throughout and beyond plant life. The UK materials community – including the skills, technology and infrastructure – should support this essential requirement.

In the context of the sponsors' remit, this appendix focuses primarily on opportunities afforded by the new UK nuclear build agenda in respect of the 'nuclear island'. In particular, in supporting operation of new build plant through life; i.e. the focus is therefore on the design, fabrication, commissioning, and operation of new nuclear plant. Indeed, the UK's Nuclear Installations Inspectorate (NII) is currently assessing the safety and acceptability of two new nuclear reactor designs under their Generic Design Assessment (GDA) process.

These are the AP1000 PWR (Westinghouse) and the European pressurised water reactor (EPR) (EDF/Areva). Whilst opportunities exist, e.g. in the development of life-prediction approaches based on materials degradation processes, the appendix does not focus on plant life extension of AGR reactors or the continued operation of the Sizewell 'B' PWR; neither does it address opportunities associated with decommissioning, waste management and geological disposal, or fusion technology.

The appendix is structured as follows. Section 2 summarises the UK Materials Capacity and provides an answer to Question 2, Section 3 provides a UK Materials Roadmap and within this responds to Question 3. Section 4 summarises the opportunities for public sector intervention, while Section 5 highlights briefly spill-over benefits of the high priority opportunities. Finally, a summary and recommendations is provided in Section 6. It is to be noted that the main recommendations from this Appendix are carried forward into the main report.

¹² These have been re-ordered (compared to the proposal) to fit the logic of this section

2.0 UK Materials Capacity

This section provides a response to Question 2; namely “Is there a UK (materials) capacity to develop and exploit the technology and become a leading global player?” This section aims to capture specific elements of the UK materials capacity that could be exploited for public sector intervention with respect to the new nuclear build agenda.

Two aspects of the capacity are discussed: firstly, the materials supply chain for manufacturing and fabricating key structural components for the next generation of nuclear power stations, and secondly the capability for exploiting advanced materials technology. This discussion makes use of core competencies required to address the technological materials challenges inherent in new build. These core competencies were identified in Section 5 of the Materials UK assessment of the priority research needs in nuclear energy materials [13], and include the capacity to determine in-service changes in material microstructure and properties, the ability to predict the behaviour of materials over a range of scale lengths using theoretical modelling, and access to both proxy and neutron irradiation facilities to develop underpinning materials data for model validation and safety case development.

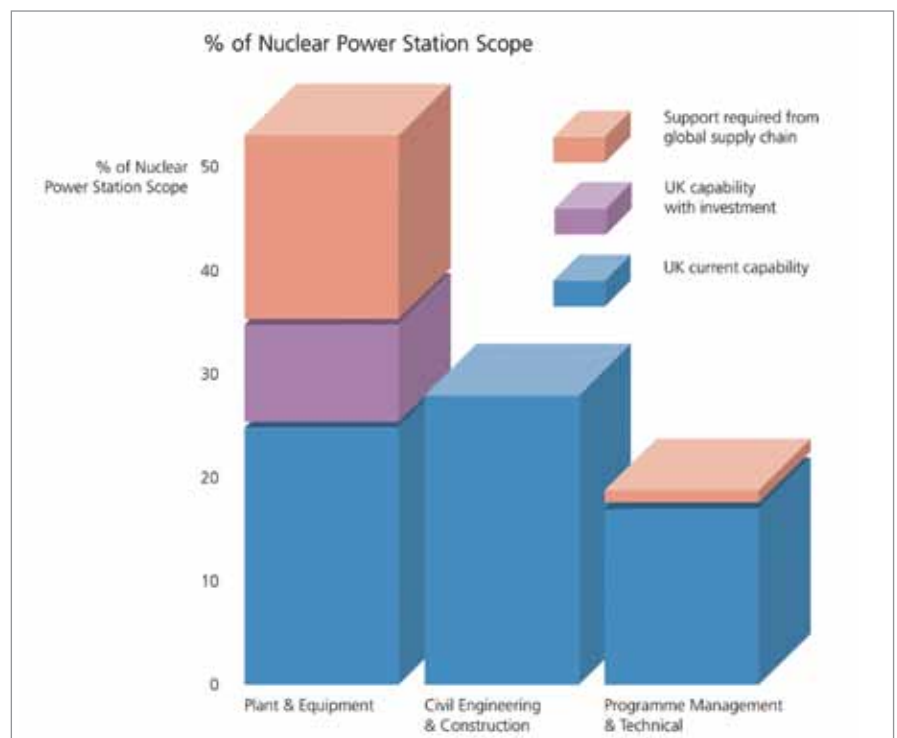
2.1 Materials supply chain

Materials UK have undertaken a mapping of the materials supply chain in relation to the UK's power generation sector [14]. Chapter 3 of this reference provides a focus on nuclear energy. In addition there has been a Nuclear Industry Association (NIA) study on the UK capability to deliver a new nuclear build programme [15, 16]. This section highlights the major points from these reviews on the importance of the materials supply chain to new build and highlights the strengths and weaknesses of the UK materials capability for the manufacture and fabrication of components.

The NIA study did not focus on materials specifically but did consider the area of ‘Plant and Equipment’ which is of most relevance to the materials supply chain (other areas being ‘civil engineering & construction’, and ‘programme management & technical’). The report indicates that ‘Plant and Equipment’ typically comprise approximately 55% of a nuclear power plant build. The NIA reports indicate that current UK industry capability to support approximately half of the ‘Plant & Equipment’ necessary for new nuclear power plant build. With investment, they considered that this might be expanded to approximately 70% of the required capability, Figure A7-1. This points to the potentially important role investment in the materials supply chain could play in exploiting the opportunities that are arising from new build.

Reference [3] notes that when the Sizewell B PWR power station was built in the early 1990s most components, apart from the heavy section forging, could be fabricated in the UK. Since that time, whilst there has been no further civil nuclear build in the UK, ongoing support for the nuclear fleet, plant modifications to support life extensions, new plant build at Sellafield, alongside decommissioning work has enabled the UK fabrication and manufacturing sector to maintain a significant capability. However, a detailed analysis of the capability to supply the key engineering components (see Table A7-1) for new nuclear power plant in the UK was included in the Materials UK study. The analysis demonstrated that aside from the large pressure vessel forgings, the UK has capability to provide most other key engineering components^[17]. It is to be noted that there are supporting organisations in the UK such as specialist steel makers, e.g. CORUS, or R&D organisations focusing on specific aspects of fabrication and joining, e.g. TWI, who enhance the ability of the UK supply chain to supply advanced material solutions.

Figure A7-1
NIA analysis of UK capability to support new nuclear power plant build



13. I Cook, C English, P E J Flewitt and G Smith, “Nuclear energy materials research”, Materials UK Energy Review, 2007.

14. S A Court, “The mapping of materials supply chains in the UK's power generation sector”, Materials UK Energy Review, 2008.

15. Nuclear Industry Association, “The capability to deliver a new nuclear build programme”, NIA Report, 2006.

16. Nuclear Industry Association, “The UK capability to deliver a new nuclear build programme 2008 Update”, NIA Report, 2008.

17. Recently Sheffield Forgemasters have announced that they are considering installing a £140m 15,000-tonne steel press that can manufacture such large forgings

Appendix 7: Materials Nuclear R&D Capacity, Opportunities and Spill-over Benefits

Key engineering components
Containment Building
Reactor Pressure Vessel (RPV)
Reactor Pressure Vessel Head
Reactor Pressure Vessel Internals
Steam Generators
Pressuriser
Pumps and Valves
Generic Fabricated Metal Components (inc. forgings, pipework)
Other Components
Fuel

Table A7-1 Key engineering components [1]

Capacity relates to both the expertise required to support the advanced materials technology and the infrastructure necessary to develop it.

Firstly, with respect to infrastructure; since the review was published in 2008, a number of new nuclear research academic initiatives have been established that have significantly strengthened the UK infrastructure for advanced research into high temperature materials, modelling of materials performance, fuels technology, radiation damage, and graphite technology¹⁹.

Further it should be stressed that there are UK strengths in a number of the core competencies and facilities that were identified in [1] as key to meeting the challenges inherent in new build. These strengths include: (i) experimental techniques for characterising microstructural changes and their influence on bulk physical, mechanical, and corrosion properties during service, (ii) modelling techniques that enable simulation of materials behaviour across a range of scale lengths, and (iii) facilities that allow the examination of activated or contaminated materials.

However, as pointed out in [1] there is the increasing need for proxy irradiation facilities, including ion beams, to provide model validation data, and assured access to irradiation facilities in materials test reactors where there are limitations in UK capability. This need is being addressed, in part, within the Government's Energy Coast Masterplan²⁰ including the establishment of the UK National Nuclear Laboratory with state-of-the-art 'hot cells' for the testing and examination of irradiated materials and through a partnership between the Nuclear Decommissioning Authority and The University of Manchester in the development of the Dalton Cumbrian Facility which will house new research facilities for radiation science research.

Reference 2 also included a SWOT¹⁸ analysis of the UK materials and manufacturing input to the civil nuclear industry. This analysis emphasises that opportunities for UK business lie in the ability to respond to the new nuclear build agenda by investing to: (a) reinstate facilities and skills and (b) increase the scope and capacity of existing manufacturing plant to support the UK and worldwide renaissance in new nuclear build, including, for example, large-scale forgings and nuclear fuel.

In summary, UK companies are (potentially) able to supply a large proportion of the key components for new nuclear build. This is important from a sponsor's perspective as it demonstrates that there may be clear benefits from public intervention. For example, an important focus might be from stimulating the use of improved manufacturing techniques for nuclear plant, including welding and joining, surface technology and modularisation. This is particularly important for the Reactor Pressure Vessel (RPV), reactor integrated head package, RPV internals, steam generators, pressuriser and primary circuit pipework.

2.2 Advanced Materials Technology

In 2008, the nuclear materials R&D capacity was reviewed in the UK [2] by Materials UK. The major conclusions were that:

- Nuclear fission related R&D in the UK has declined steadily over the past 20 years or so and, since the 1980s, public investment in nuclear fission R&D has dropped by more than 95% and the industrial R&D skill base has decreased by more than 90%.
- The UK maintains leading materials expertise across both the academic and industrial sectors, with key initiatives such as The Dalton Nuclear Institute (The University of Manchester) the EPSRC's "Keeping the Nuclear Option Open" (KNOO), The National Nuclear Laboratory (NNL), the Northwest Nuclear Research Centre and Nuclear Fusion activities associated with the International Thermonuclear Experimental Reactor (ITER) concentrating UK efforts.
- It will take significant effort to build up the required resources (skills) within the timescale for licensing and contract awards; within a period which is likely to be no longer than 5 years.

18 SWOT is an acronym for Strengths, Weaknesses, Opportunities and Threats

19 Nuclear Engineering Doctorate Centre: supported by the EPSRC and led by The University of Manchester in partnership with Imperial College London and supported by the universities of Bristol, Leeds, Sheffield and Strathclyde. Systems Performance Centre: at the University of Bristol supported through links with British Energy, Serco and Imperial College London to undertake research into the mechanical performance of high temperature materials, and systems reliability (Control and Instrumentation Nuclear Industry Forum). Atomic scale modelling research group at Imperial College London. The Centre for Nuclear Energy Technology (CNET): supported through a £4.2M grant from the NWDA and based at The University of Manchester, CNET will include research into fuels technology, radiation damage, high temperature materials and graphite technology. Modelling and Simulation Centre: supported by EDF at The University of Manchester aimed at strengthening research and skills development in materials and structures modelling alongside computational fluid dynamics modelling. RC-NDE. An EPSRC-sponsored collaboration between industry and academia to coordinate research into NDE technologies.

Secondly, with respect to expertise, the UK has significant skills in various elements of advanced materials production, near service condition testing, materials characterisation (both at the start of, through life, and end of life) and predictive modelling and assessment.

Since the Materials UK review [2] there have been a number of initiatives, particularly within the academic sector, aimed at developing higher level skills in the nuclear materials area via:

- Existing materials courses being broadened to implicitly include a nuclear component, and
- New “with nuclear” degrees being introduced at undergraduate level,
- Masters level training in nuclear subjects²¹

Further, higher level skills in nuclear materials are being developed through post graduate research programmes including the materials work package in the EPSRC Keeping the Nuclear Option Open programme, materials research within the EPSRC Nuclear Engineering Doctorate programme, EPSRC Doctoral Training Colleges in Fission (Manchester and Sheffield), Advanced Metallic Materials (Sheffield and Manchester) and Materials modelling (Imperial College London).

In addition the National Skills Academy for Nuclear (NSAN) aims to supply many nuclear training products and services, including for example programmes for secondary schools, accreditations for industry and particularly nuclear top up modules for trade apprenticeships.

These initiatives may be viewed within the context of a ‘skills pyramid’ as shown in Figure A7-2.

Overall in the UK we estimate that there are currently ~ 40 undergraduates specialising in courses directly related to nuclear materials, 175-200 people involved in M.Sc or Ph.D courses/projects or acting as post-doctoral research assistants.

There is a research income of £6-7M per annum associated with the latter. We also note that four or five years ago these numbers would have been dramatically smaller, however, the level of activity still remains low with respect to the declared and perceived requirements across utilities, manufacturers and the supply chain.

We have emphasised above the growing skill base in the UK for nuclear materials arising from the increased training opportunities. However, the non-prescriptive regulatory regime in the UK, where the plant operator has to demonstrate the safety of the plant rather than comply with externally imposed design/operating codes, imposes significant requirements on

the level of expertise in all elements of the supply chain [22]. In particular, there needs to be suitably knowledgeable and experienced people available. In reference [23] it was noted that many of the current experts are approaching retirement age. This emphasises the need for not only training a new generation of experts but taking steps to ensure the expertise of current experts is captured for subsequent generations.

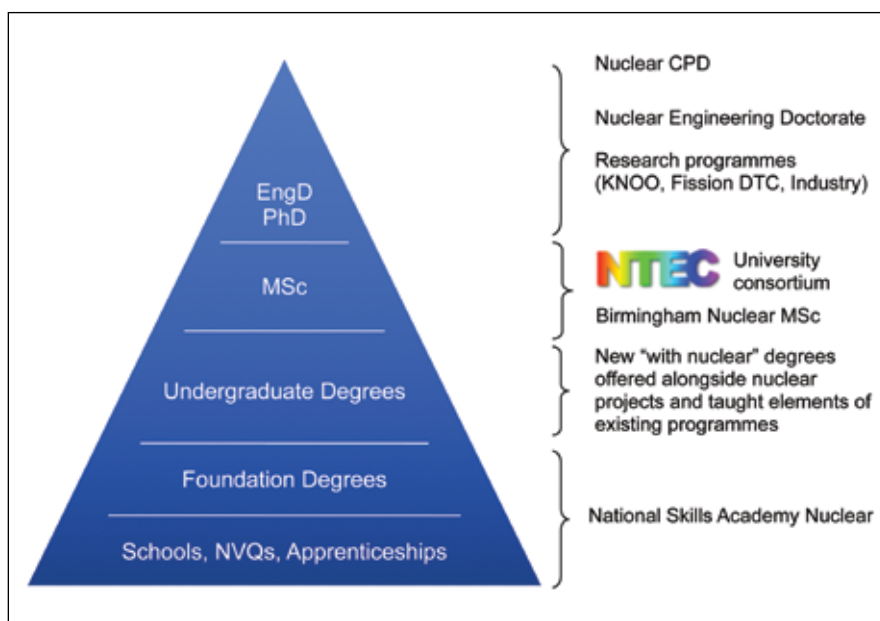


Figure A7-2 Nuclear skills pyramid [3]

20. “Britain’s energy coast / a Masterplan for West Cumbria – executive summary”

21. For example, Imperial College London is offering three new MEng Nuclear Energy Engineering degrees in Chemical with Nuclear Engineering, Materials with Nuclear Engineering and Mechanical with Nuclear Engineering from 2010. Lancaster University has introduced a Nuclear Engineering degree that includes courses on ‘Strength and Materials’. The University of Manchester is also introducing a new Engineering (Nuclear) and Engineering with Nuclear degrees that include a course on nuclear materials, as well as a new “with Nuclear” integrated Masters degree offered to all students within the Faculty of Engineering and Physical Sciences.

At Masters level, the MSc in Physics and Technology of Nuclear Reactors at Birmingham University has continued, and the new NTEC MSc in Nuclear Science and Technology includes a specific model on, “Reactor Materials & Lifetime Behaviour”.

22. HSE Safety Principles for Nuclear Facilities 2006 Edition Redgrave Court Bootle Merseyside L20 7HS

23. P Howarth, BNFL Energy Unit Skills Report 19, 2006

Appendix 7: Materials Nuclear R&D Capacity, Opportunities and Spill-over Benefits

It is noted that contractors and Small and Medium Enterprises (SMEs) are reacting positively to new nuclear renaissance in UK²⁴ and worldwide. Some larger organisations have already increased recruitment in the materials area, e.g. Serco Technical and Assurance Services, whilst others have set clear business objectives to increase expertise in nuclear field (including materials), e.g. Rolls-Royce²⁵, NNL, and there is evidence that companies are considering recruitment and retention strategies carefully, e.g. BAE Systems [26].

In summary there is an increasing UK capacity for advanced materials technology with specific areas of real materials expertise that can be exploited. However, this increasing capacity follows a period of decline. Thus, in terms of capability for advanced materials technology, TSB funding may be used to stimulate new industrial organisations entering the supply chain through appropriately directed Knowledge Transfer Partnerships.

2.3 Interim summary

In response to Question 2 the position reviewed in this section has demonstrated that there is a UK materials capacity to develop and exploit the technology and become a leading global player. Specific areas which are suitable for public intervention include:

- Stimulating the use of improved manufacturing techniques for nuclear plant, including welding and joining, surface technology and modularisation.
- Stimulate new industrial organisations entering the supply chain through appropriately directed Knowledge Transfer Partnerships.
- Stimulating technologies/methodologies for capturing expert knowledge

These areas are further developed in Section 4.

3.0 Impact of Advanced Materials Technology

This section provides a response to Question 3; namely “Does the (materials) technology have potential for impact in the right timeframe?”

This section aims to identify priorities for new build materials in light of UK and International experience. It should be noted that there are strong synergies between the research needs in developing materials for application in fission reactors and for application in fusion reactors. Although the reactor concepts are different, there is a wide range of commonalities in the materials issues. For example, there is strong overlap in the classes of material employed and in the effects responsible for the material and component in-service performance. Further, the research methods (both experimental and theoretical) are similar for a broad range of issues. In fusion technology specific additional problems arise in the case of plasma facing components, due to the damage caused by the impacts of high-energy ions [1].

3.1 New build materials technology priorities

There is no UK analysis that focussed on specifically developing a roadmap for materials technology development associated with new build. The overall materials research priorities identified in the Materials UK assessment of the priority research needs in nuclear energy materials [1] addressed the full nuclear fuel cycle, and were summarised as follows:

- Mechanisms of in-service and in-repository corrosion and degradation of materials,
- Predicting the behaviour of welded structures subjected to high temperatures and complex loadings,
- Predicting irradiation damage effects in fission and fusion materials, and

- Developments of new and improved methods for non-destructive monitoring and evaluation of materials in service.

Specific research opportunities and challenges associated with the full nuclear lifecycle were identified. Those associated with the new nuclear build technology are summarised in Table A7-2. It is also considered important that research associated with improved manufacturing technology should emerge as a new research priority in the light of the new build agenda.

Materials technology is being developed worldwide to support the management of ageing Light Water Reactor (LWR) plant and the build of a new generation of nuclear plant. Many of these national LWR programmes have also highlighted the importance of the research needs identified in [1] and given above. Of particular note are the following programmes:

In the USA^[27, 28, 29, 30], there is a focus on the development of a scientific basis for understanding materials degradation processes, providing the materials data and the assessment methods to enable long-term performance of materials to be predicted. Specific degradation mechanisms being addressed include irradiation effects on microstructure (late blooming phases), properties including environmentally-assisted cracking, fatigue and fracture.

Materials technology development in Japan^[31, 32] address six degradation mechanisms in relation to LWR materials degradation: (i) neutron irradiation embrittlement of the RPV, (ii) stress corrosion cracking including IGSCC, PWSCC and IASCC³³, (iii) fatigue, (iv) thinning of piping by flow-accelerated corrosion and erosion, (v) insulation degradation of electrical cables, (vi) degradation of concrete properties for strength and shielding.

24 There are currently almost 100 UK-based nuclear-related jobs being advertised by Nuclear Energy Recruitment Solutions in areas including project and mechanical engineering, human factors and business analysis.

25 For example, Rolls-Royce have established a new civil nuclear business and are aiming to recruit a broad range of nuclear skills including: Electrical Controls & Instrumentation Engineers, Fluid Systems Design Engineers, Nuclear Environmental Engineers, Nuclear Safety Case Engineers, Mechanical Design Engineers, Reactor Physicist Engineers, and Thermo-Fluid Engineers.

26 “Engineering: turning ideas into reality - Innovation, Universities, Science and Skills Committee”, Memorandum 105, Submission from BAE Systems, March 2008.

27 Idaho National Laboratory, “Strategic Plan – leading the renaissance in nuclear energy: 2007-2016”, 2007.

28 Idaho National Laboratory, “Light Water Reactor Sustainability Program Plan: Fiscal Year 2009”, September 2008.

29 EPRI, “2009 Research Portfolio: Research Offerings to Shape the Future of Electricity”, 2008.

Within Europe, the joint EDF-EPRI-TEPCO Materials Ageing Institute was recently launched to develop materials technology in relation to nuclear plant³⁴. Areas of current focus include: (i) Understanding and modelling of physical phenomena, including thermal ageing, irradiation, physical modelling of corrosion, prediction of chemical and radiochemical behaviour, (ii) Research related to specific materials, including concrete, polymers and new materials.

It is clear that there is an international consensus of the degradation mechanisms that require investigation. Further, it is apparent that, internationally, it is recognised that it is necessary to undertake collaborative industrial and research programmes to support the licensing and managing of the long-term, safe and economical operation of current and future nuclear power (LWR) plants. However, such programmes should also include condition and surveillance monitoring of key components. Within this there is also the need for advanced NDE techniques and the development of advanced tools for the assessment of realistic defects in aging components under plant loading conditions.

Thus to address the advanced materials technology requirements for new build we need to consider:

- 1 Materials degradation, structural integrity and life prediction including:
 - a. Understanding mechanisms of material corrosion in-service, including behaviour within nuclear power reactors.
 - b. Understanding and predicting radiation effects on materials, including microstructural, microchemical, and environmental aspects that influence dimensional stability, mechanical performance, fracture properties and electrochemical behaviour.

	Behaviour at high temperature	Irradiation damage
Main materials of interest	<ul style="list-style-type: none"> Austenitic and ferritic steels. High nickel alloys. Zirconium alloys 	<ul style="list-style-type: none"> Austenitic and ferritic steels. Zirconium alloys
Main problems	<ul style="list-style-type: none"> Thermal cycling. Joining and interface technology. 	<ul style="list-style-type: none"> Irradiation creep. Swelling. Irradiation enhanced segregation. Crack propagation and embrittlement. Irradiation assisted corrosion and environmental degradation. Joining and interface technology.
Key methods for solution of problems	<ul style="list-style-type: none"> Modelling and its validation. Advanced materials characterisation. Advanced measurement and testing techniques. Advanced plant monitoring techniques. 	<ul style="list-style-type: none"> Modelling and its validation. Advanced materials characterisation. Proxy irradiation (e.g. ion beams). Advanced measurement and testing techniques. Advanced plant monitoring techniques.
Most promising immediate opportunities	<ul style="list-style-type: none"> Modelling validated by microscopic characterisation, plant service data and long-term experiments. Exploit research synergies for fission, fusion and fossil-fuel plant materials. 	<ul style="list-style-type: none"> Modelling validated by microscopic characterisation, proxy irradiations, plant service data and long-term experiments. Exploit research synergies for fission, fusion and fossil-fuel plant materials.
Key gaps in capabilities	<ul style="list-style-type: none"> Lack of irradiation facilities. 	<ul style="list-style-type: none"> Lack of irradiation facilities.
Components	<ul style="list-style-type: none"> Primary and secondary circuit in PWRs. 	

Table A7-2 Research opportunities and challenges for new nuclear build [1]

- 2 Condition monitoring and preventative maintenance to enhance safe life and reduce downtime alongside establishing new and improved techniques for the applied metrology of material state and non-destructive monitoring of nuclear plant, systems, and components. Such condition monitoring includes improved surveillance schemes to monitor the in-service properties of specific components such as the reactor pressure vessel.
- 3 Developing new component and fuel manufacturing capability including materials, processing and joining technologies.

30. "Life beyond 60 Workshop Summary Report", NRC/DOE Workshop on Nuclear Plant Life Extension R&D, Bethesda, Maryland, USA, February 19-21, 2008.
 31. N Sekimura, "Future Direction of Ageing Management Future Direction of Ageing Management and Maintenance of Nuclear Power Plants in Japan", presentation to ISaG-2008, The University of Tokyo, Japan, July 2008.
 32. Y Tsuchihashi, "Safety Research Activities of INSS on Ageing Problem of Nuclear power Plants", Proceedings of the International Symposium on Research for Ageing Management of Light Water Reactors, Fukui City, Japan, pp. 123-129, Oct 22-23, 2007.
 33. IGSCC = intergranular stress corrosion cracking, PWSCC = primary water stress corrosion cracking and IASCC = irradiation assisted stress corrosion cracking.
 34. "International Energy developments around the globe", EPRI Journal, Spring 2008.

Appendix 7: Materials Nuclear R&D Capacity, Opportunities and Spill-over Benefits

3.2 Interim summary

In response to Question 3, there is strong evidence that materials technology development has the potential for impact in the right timeframe, including supporting the licensing and managing the long-term, safe and economical operation of current and future nuclear power plants.

Further, there is a clear consensus amongst the international community regarding the key materials technology challenges associated with new nuclear build. More specifically, there are opportunities to maximise the impact of materials technology through a structured and proactive approach to international collaboration.

4.0 Opportunities of relevance to TSB/Regional Development Agencies (RDAs)

This section explores specific opportunities for public sector intervention in relation to materials technology in support of the new nuclear build agenda in the UK. Firstly, particular areas for public sector intervention are summarised in relation to infrastructure-based and technology-based opportunities. Secondly, potential mechanisms for intervention are explored.

4.1 Areas for public sector intervention

Infrastructure-based opportunities

Section 1 of this appendix identified the opportunity to stimulate the use of improved manufacturing techniques for nuclear plant, including welding and joining, surface technology and modularisation. Given the new nuclear build agenda, it is recognised that the UK manufacturing capability will be strengthened through the formation of a UK Advanced Manufacturing Research Centre for Nuclear to address high value manufacturing by the supply chain (see 6.2.1 of the main report). The Nuclear Industry Association (NIA) map of indicates the distribution of the UK capacity to engage in such an initiative, Figure A7-3. In addition, a recent review of the nuclear capability within UK universities has been published by Dr John Roberts and indicates that indicates over 200 academics with nuclear research interests in over 30 universities across the UK³⁵. A number of the academic institutions listed could contribute significantly to such an initiative.

Key aspects to be addressed by an initiative like this would include:

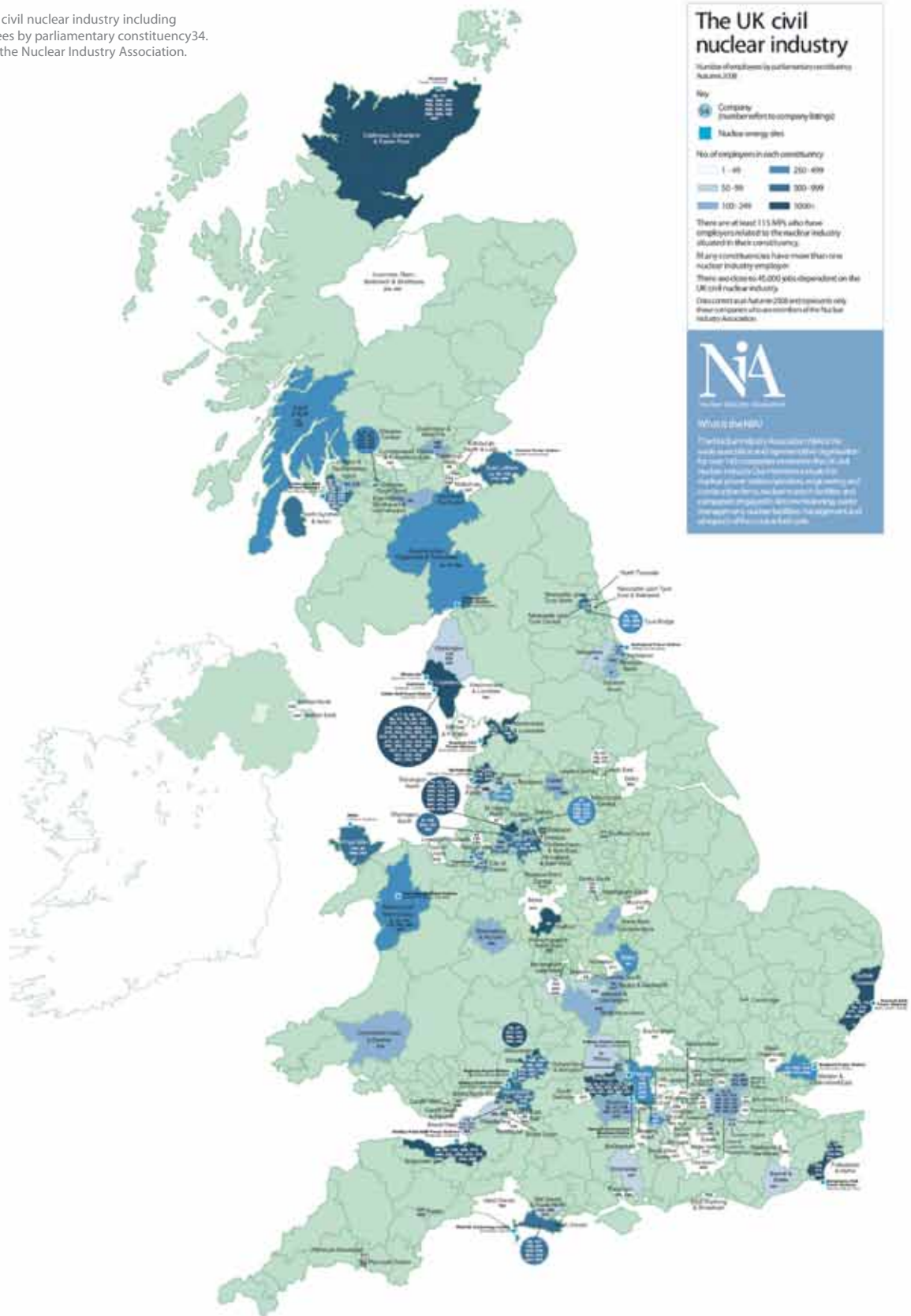
- Production Readiness: proving of current methods
- Process Improvement: cost reduction through cell demonstration
- Process Qualification: proving of current methods
- Non-destructive testing: demonstration, Development, & Qualification

Unique aspects of a centre to support new nuclear build in the UK include the ability to handle large structural components, thick welds and associated inspection, cladding and nuclear-specific materials.



35. Available at www.nuclearliaison.com/directory.

Figure A7-3 The UK civil nuclear industry including number of employees by parliamentary constituency³⁴. Picture courtesy of the Nuclear Industry Association.



Note, the above diagram is illustrative and there are a significant number of other organisations and universities that can support new nuclear build that may not be represented on the NIA map.

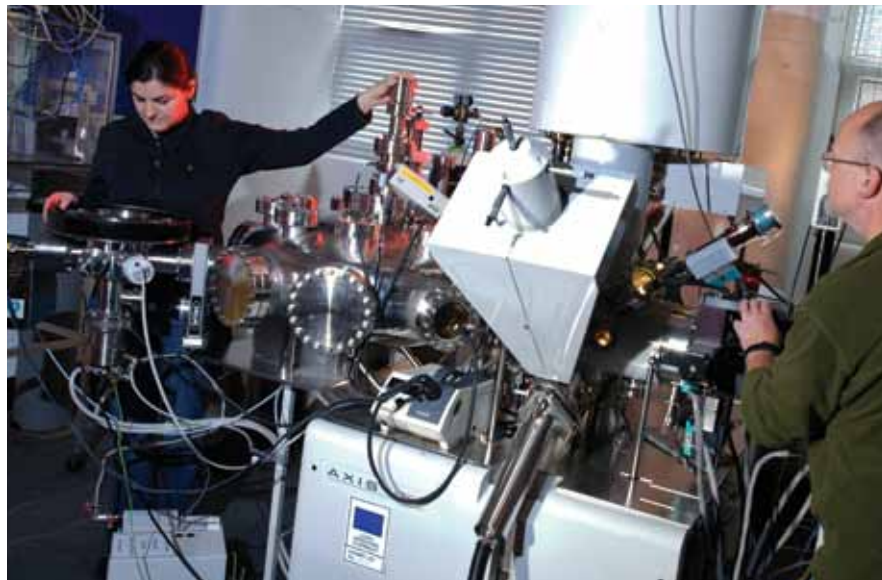
Appendix 7: Materials Nuclear R&D Capacity, Opportunities and Spill-over Benefits

Technology-based opportunities

Section 2 of this appendix identified the increasing UK capacity for advanced materials technology with specific areas of real materials expertise that can be exploited. Areas of specific opportunity were summarised in Section 3 as relating to: (i) materials degradation, structural integrity and life prediction, and (ii) condition monitoring of nuclear plant.

Within these two areas specific opportunities exist for public sector intervention that builds on current materials research and development programmes in the UK including:

- Improved understanding and prediction of materials degradation
 - Build on research undertaken within the EPSRC Keeping the Nuclear option Open programme to use proxy irradiation techniques as a means to develop corrosion sensors for irradiated material.
 - Establish use of new corrosion-resistant materials through minor alloying additions such as platinum group metals.
 - Build tools for the application of advanced assessment methods to extend linear elastic fracture mechanics-based approaches to predictive models based on materials degradation methods, e.g. automated approaches for creating finite element models of three-dimensional crack tips, post-processors to derive model parameters and predictive capabilities.
- Improved fabrication techniques
 - The development of improved modelling and measurement approaches for residual stress characterisation and weld improvement, including improved constitutive models and supporting data for weld simulation using advanced three-dimensional finite element analysis and measuring approaches such as the contour method and deep hole drilling.



- The development of new surface technology for nuclear components including laser and water-jet peening, electropolishing, and combinations thereof.
- Improved structural integrity approaches
 - Build on research and development within the R6 development programme³⁷ to strengthen the assessment of subcritical crack growth (see above), the influence of residual stress effects on fracture and load history effects.
- Improved non-destructive examination
 - Build on research undertaken within the EPSRC Keeping the Nuclear option Open which aims to physically connect ultrasonic generators and receivers to the component via a solid, but flexible, 'waveguide', thus removing sensitive equipment away from 'hot' areas of interest, where the high temperatures and radiation field are detrimental to the equipment.

Within these areas it is recognised that there is strong international consensus regarding the priority themes for materials technology development and as a consequence a structured and proactive approach to international collaboration would maximise the impact of materials technology. In particular, collaboration with the joint EDF-EPRI-TEPCO Materials Ageing Institute³⁸ would strengthen the impact of investment relating to the understanding and prediction of material degradation.

37. R6 Revision 4, "Assessment of the integrity of structures containing defects", British Energy Generation Ltd, 2006.

38. The EDF-EPRI-TEPCO Materials Ageing Institute at Les Renardières (France), is a collaborative research facility that will examine the critical link between materials science and power plant component performance and degradation. As stated in the associated press release, "The Materials Ageing Institute's mission is to explain and anticipate the ageing of materials in existing power production facilities, to improve knowledge of high-temperature materials behaviour in future power plants, and to maintain expertise and skills on materials science. Among the areas that will be analyzed are equipment corrosion, component and material degradation due to irradiation, non-metallic material performance (e.g., polymers), and concrete ageing."

4.2 Support mechanisms

Knowledge Transfer Partnerships (KTP)

The TSB considers that KTPs “are a tried and tested method of enabling companies to obtain knowledge, technology or skills which they consider to be of strategic competitive importance, from the further/higher education sector or from a research and technology organisation”. The knowledge sought is embedded into the company through a project or projects undertaken by a good quality individual recruited for the purpose to work in the company.

It is recognised that KTPs are a particularly useful vehicle to enable SMEs with a relevant skills base (possibly derived from involvement in non-nuclear industries) to enter the nuclear supply chain. This appendix has highlighted the potential for advanced fabrication techniques to make an impact within the timescales relevant to TSB/RDA intervention. In particular KTPs should be established in areas such as the following:

- Develop and apply best practice for welding plant components and for fabricating new plants. This includes applying robust computer simulation tools for weld modelling including supporting material property data and validation.
- Apply surface technology, including peening (glass bead, laser, and water jet), electropolishing, etc., to develop corrosion and wear resistant components.
- Development of new approaches for large component fabrication including hot hydrostatic pressing.
- Apply advanced non-destructive testing include ultrasonic waveguides and phased arrays, eddy current methods for pipe wastage, and development of methods for the measurement of residual stress and fatigue damage.

Collaborative Research and Development Programmes (CRD)

The TSB's collaborative research and development programmes are designed “to assist the industrial and research communities to work together on R&D projects in strategically important areas of science, engineering and technology - from which successful new products, processes and services can emerge.”

It would be beneficial for the TSB to stimulate CRDs in the one or more of the following advanced materials technology areas:

- 1 Neutron irradiation effects on microstructure and properties,
- 2 Environmentally-assisted degradation in nuclear plant components including corrosion-fatigue, PWSCC and IASCC37,
- 3 Non-destructive examination of nuclear plant components

In addition, it is recognised that the UK Research Centre in Non-Destructive Evaluation (RC-NDE) leads the research and development in the area identified under number 3 in the list above, and can provide a significant contribution in this area.

Stimulating increased collaboration: Knowledge Transfer Network (KTN)

A Knowledge Transfer Network is a “single over-arching national network in a specific field of technology or business application which brings together people from businesses, universities, research, finance and technology organisations to stimulate innovation through knowledge transfer”.

The objective of a Knowledge Transfer Network is to improve the UK's innovation performance by increasing the breadth and depth of the knowledge transfer of technology into UK-based businesses and by accelerating the rate at which this process occurs. The Network must, throughout its lifetime, actively contribute and remain aligned to the goals of the Technology Strategy Board.

As part of our recommendation in the main report relating to the establishment of a Nuclear Special Interest Group within the Energy Generation & Supply KTN, it would be beneficial for the TSB to consider supporting the international collaboration in the field of advanced materials technology in relation to new nuclear build. As noted in Section 3.1 of this appendix, there is a clear consensus amongst the international community regarding the key materials technology challenges associated with new nuclear build. There are clear opportunities to maximise the impact of materials technology through a structured and proactive approach to international collaboration. In particular, it is recommended that a proactive approach be taken to international collaboration including the Euratom Framework programmes, links with the EDF-EPRI-TEPCO Materials Ageing Institute, and other international players including INL, EPRI and JAEA. In such a network there are also clear benefits from stimulating technologies/methodologies for capturing expert knowledge

4.3 Interim summary

This section has provided further detail regarding the opportunities for public sector intervention in the materials field including infrastructure- and technology-based opportunities, and has summarised the mechanisms that could be exploited for intervention. It is recognised that there are specific opportunities relating to advanced manufacturing research to support the new nuclear build agenda, and in the understanding and predicting of materials degradation, fabrication and joining, structural integrity and condition monitoring areas that build on recent research supported by the EPSRC and other funding bodies. Specific mechanisms for support have been identified including KTPs, CRDs and KTNs which would enable considerable benefit to be taken from international developments in this area.

Appendix 7: Materials Nuclear R&D Capacity, Opportunities and Spill-over Benefits

5.0 Spill-over Benefits

It is recognised that there are significant ‘spin-in’ and ‘spin-out’ benefits from TSB/RDA investment in the materials technology- and infrastructure-based opportunities highlighted in the previous section.

Within the nuclear industry this includes the strong synergies that exist between the civil PWR programme and the UK Naval Propulsion Programme in areas including materials and chemistry as well as structural integrity of current and future propulsion plant.

Within the power industry this includes particular benefits associated with component fabrication and materials degradation related to the secondary steam-raising plant and the electricity-generating components, including steam turbines. For example Report 2 on Materials UK assessment of the priority research needs for materials used in fossil fuelled plant⁴⁰ emphasised the need for research in many of the themes identified above, e.g. surface protection coatings, and advanced NDE techniques. Similarly, the report on materials for Alternative Energy Technologies identified as a priority developing high strength, corrosion resistant heat exchanger alloys and coatings for biomass and waste systems⁴¹.

To judge the benefits to other industrial sectors we refer to the TSB materials strategy. More specifically, the TSB has developed a strategy which outlines ways in which the materials sector can continue to innovate and grow⁴⁰. Three priority areas, based on an analysis of common market sector drivers, have been identified as channels for technology inspired activities; these are described as Energy, Sustainability and High value Markets⁴³. Further, in this strategy the need is recognised “for continued investment in underpinning and emerging generic materials technology development, and exciting thrust areas have been identified which are anticipated to have a major impact in the key challenge areas” [19]. These thrust areas are listed in Table A7-4 in terms

of their relevance to the three priority areas. It can be seen that several of the thrust areas have been identified in this Appendix as being key to materials for new nuclear build; for example, materials to withstand more aggressive environments, surface engineering and coating technologies, joining technologies, and predictive modelling through the full life cycle, including lifetime prediction. Given this synergy it appears that developing advanced materials and components for application in new build plant should have benefits to other sectors that require high performance materials that operate in harsh environments.

Table A7-4
Technology thrusts in each of the key challenge areas [19].

	Energy	Sustainability	High Value Markets
Lightweight materials and structures, including composites and hybrids	●	▲	◆
Materials to withstand more aggressive environments (eg high temperature, corrosive, erosive)	●	▲	◆
Electronic and optical functional materials	●		◆
Smart and multifunctional materials, devices and structures	●	▲	◆
Surface engineering and coating technologies	●	▲	◆
Particulate engineering: near net-shape manufacturing	●	▲	
Fibre and textile-based technologies	●		◆
Bioresorbable, bioactive and biocompatible materials			◆
Natural and bio-based materials		▲	◆
Joining technologies	●	▲	◆
Materials for portable power sources (batteries/fuel cells)	●		◆
Nanomaterials	●	▲	◆
Materials with reduced environmental impact through life		▲	
Materials designed for reuse/recycle/remanufacture		▲	
NDE/SHM/condition monitoring	●	▲	◆
Predictive modelling through the full life cycle, including lifetime prediction	●	▲	◆

37 PWSCC = primary water stress corrosion cracking and IASCC = irradiation assisted stress corrosion cracking.

40 D.J.Allen et al, "Fossil Fuel materials research"; Report 2 Materials UK Energy Review, 2007.

41 Materials UK Energy Review 2007, Report 4 Alternative Energy Technologies Edited J. Oakley, and C Bagley.

42 Technology Strategy Board: Advanced Materials, Key Technology Area 2008-2011. Executive Summary, 2008.

43 Energy: secure, clean and affordable energy supply, distribution and usage; Sustainability: focused on transport, construction and the 'reduce, reuse and recycle' agenda, including packaging and High value markets: including technologies for Healthcare, the Creative Industries, and Defence and Security.

6.0 Summary and Recommendations

This section provides a summary of the findings of this appendix in relation to three key questions identified by the sponsors; namely:

- 1 Is there a UK capacity to develop and exploit the technology and become a leading global player?
- 2 Does the technology have potential for impact in the right timeframe?
- 3 Is there a clear role for public sector intervention and support that adds value above and beyond that of private investment?

Further, we provide recommendations for consideration by the TSB and the RDAs in relation to priority areas and mechanisms for intervention.

1. Is there a UK capacity to develop and exploit the technology and become a leading global player?

In summary there is an increasing UK capacity for advanced materials technology with specific areas of real materials expertise that can be exploited. However, this increasing capacity follows a period of decline. Thus, in terms of capability for advanced materials technology, TSB funding may be used to stimulate new industrial organisations entering the supply chain through appropriately directed Knowledge Transfer Partnerships. Out of the analysis undertaken there are specific areas which are suitable for public intervention. These include: Stimulating the use of improved manufacturing techniques for nuclear plant, including welding and joining, surface technology and modularisation through the formation of an Advanced Manufacturing Research Centre for Nuclear.

- Stimulate new industrial organisations entering the supply chain through appropriately directed Knowledge Transfer Partnerships.
- Stimulating technologies/ methodologies for capturing expert knowledge

2. Does the technology have potential for impact in the right timeframe?

There is strong evidence that materials technology development has the potential for impact in the right timeframe, including supporting the licensing and managing of the long-term, safe and economical operation of current and future nuclear power plants.

Further, there is a clear consensus amongst the international community regarding the key materials technology challenges associated with new nuclear build. More specifically, there are opportunities to maximise the impact of materials technology through a structured and proactive approach to international collaboration (see 3.2 below).

Analysing these materials challenges has indicated the following priority opportunities in relation to new nuclear build on a 5-year timescale:

- Technology-based opportunities
 - Materials degradation, structural integrity and lifetime prediction including water chemistry and doping to reduce corrosion and advanced materials
 - Condition monitoring and preventative maintenance to underwrite safe life and reduce downtime
 - NDE/NDT to accelerate new build programme reduce in-service inspection times.
- Infrastructure-based opportunities:
 - Advanced Manufacturing Research Centre(s) for Nuclear to address high value manufacturing by the supply chain.
 - Advanced fuel manufacturing processes including more efficient fuel and fuel recycling.

3. Is there a clear role for public sector intervention and support that adds value above and beyond that of private investment?

It is recognised that there are specific opportunities relating to advanced manufacturing research to support the new nuclear build agenda, and in the understanding and predicting materials degradation, fabrication and joining, structural integrity and condition monitoring areas that build on recent research supported by the EPSRC and other funding bodies. Specific mechanisms for support have been identified including KTPs, CRDs and KTNs.

There are opportunities to maximise the impact of materials technology through a structured and proactive approach to international collaboration, including links to the EDF-EPRI-TEPCO Materials Ageing Institute, and other international players including INL, EPRI and JAEA.

There are significant spill-over benefits from investment in these opportunities to both Naval Propulsion Programmes and to other Power Generation industries.

Appendix 7: Materials Nuclear R&D Capacity, Opportunities and Spill-over Benefits

Recommendations

Based on this review of nuclear materials R&D and fabrication opportunities associated with the new nuclear build programme, alongside a study of the UK materials capacity, the following recommendations are made:

- 1 Co-invest with industry in advanced materials technology for the new nuclear build programme and, in particular, create a centre of excellence which brings together the expertise of the UK in industry and the universities in the minimisation, detection and prediction of materials degradation to be deployed in the new nuclear reactors and thereby increase the lifetime, efficiency and safety of nuclear power.
- 2 Co-invest with industry in the UK R&D base to take novel NDE/ NDT and Condition Monitoring techniques and instruments (including residual stress measurements) from Technology Readiness Levels (TRL) 4/5 to TRL 7.
- 3 Co-invest in an Advanced Manufacturing Centre for the components and systems needed for the new nuclear build programme. The Centre should focus on novel manufacturing techniques for SMEs in niche areas such as hot isostatic pressing, welding and joining, and surface technologies including the application of nanotechnology to nuclear engineering.
- 4 Examine ways of building up the manufacturing capabilities of the UK for advanced fuel production with higher burn up capability and lower waste generation.

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