NUCLEAR INNOVATION AND RESEARCH ADVISORY BOARD

UK Nuclear Innovation and Research Programme Recommendations

NIRAB-75-10

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Executive Summary

The UK Government and industry, as well as other leading nations worldwide, recognise the importance of nuclear energy and its ability to provide low carbon electricity. As a safe, secure, affordable and sustainable source of energy it will form part of the UK's future energy mix that will be essential if we are to meet carbon emission reduction targets for 2050.

The worldwide nuclear industry is expected to grow significantly in the coming decades through large and small modular reactor build. This growth brings the potential to gain significant economic benefits for the UK through fuel production, manufacturing and reactor design. The UK is a leading nuclear nation whose companies will compete in this future global market.

To facilitate a route to a future where nuclear energy plays a key role in the UK by the middle of the century, Government established the Nuclear Innovation and Research Advisory Board (NIRAB) to advise where publicly-funded research and innovation is best focused to unlock the full potential of the nuclear energy sector. NIRAB's remit includes the whole fuel cycle including existing generation, decommissioning, waste management and disposal, nuclear new build, small modular reactors, Generation IV reactors and their fuel cycles.

NIRAB has developed recommendations for research which can be grouped into five key programmes. These seek to develop the UK's current position by targeting research, development and innovation at future markets whilst securing and developing critical high-value skills and jobs that will support and sustain the sector as a whole. These have been designed to complement publically funded nuclear R&D currently commissioned by Research Councils, Innovate UK and the Nuclear Decommissioning Authority. These five programmes are:

- **The UK's Strategic Toolkit:** Underpinning decisions on which emerging nuclear technologies are brought to market to give the best economic return for the UK.
- **Future Fuels:** Making more efficient, safer nuclear fuels of the future.
- **21st Century Nuclear Manufacture:** Advanced materials, manufacturing and modular build in nuclear factories of the future.
- **Reactor Design:** Delivering the people, processes and tools to make the UK the partner of choice as the world designs SMRs and 4th generation nuclear power plants.
- **Recycling Fuel for Future Reactors:** Developing cost effective technologies to deliver a secure and sustainable low carbon fuel supply.

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1. Introduction

Background

This document sets out nuclear innovation and research recommendations that have been developed by the Nuclear Innovation and Research Advisory Board (NIRAB) which is charged with ensuring that the publicly-funded programmes of Research and Development (R&D) are aligned to underpin the UK Government's strategic energy and industrial policies and maximise synergies across the portfolio.

The recommendations have been closely aligned to the needs of the UK nuclear industry, academia and national laboratories to promote economic growth, skills development and scientific excellence. The programme is also designed to harmonise with on-going programmes to deliver the UK decommissioning objectives.

They provide a long-term strategic technical view, providing direction to the UK's nuclear funding and research community with details of the recommended activities to be undertaken in the next five years. Coordination of R&D programmes is critical and these recommendations will be used to guide Innovate UK in future supply chain competitions, shape the nuclear aspects of the Research Councils Energy Programme and inform the provision of new capital investments such as the National Nuclear Users Facility (NNUF).

Nuclear Power's Contribution to a 2050 Low Carbon Economy

Nuclear power has been a reliable source of low carbon electricity in the UK for 60 years, providing around 20% of the UK's electricity in 2015 and it is expected to continue to be an important source of electricity into the future. Decarbonisation of the energy supply is an important policy issue that has been incorporated into a legally binding commitment to ensure that by the year 2050 net UK CO_2 emissions are at least 80% lower than the 1990 baseline[1]. At the United Nations Climate Change Conference 2015 (COP21) in Paris-Le Bourget the UK Government committed to a doubling of investment in low carbon energy innovation spending and became one of 20 countries to launch Mission Innovation. These are challenging objectives. Although the Government has not set specific targets for different energy sectors, analysis[2] has shown that nuclear energy is likely to be required to provide significantly more than the current new nuclear build target of 16 GWe.

Independent analysis by the Energy Technologies Institute (ETI)[3] has identified that if large Light Water Reactors (LWRs) are deployed cost effectively and at scale, nuclear power can play a significant role in the UK's transition to a low carbon economy alongside renewables and fossil fuelled thermal plants fitted with carbon capture and storage. This would be enhanced by a substantial Small Modular Reactor (SMR) construction programme that could

[1] Climate Change Act 2008
[2] The Carbon Plan: Delivering our low carbon future, HM Government, December 2011
[3] Nuclear: The role for nuclear within a low carbon energy system, ETI, October 2015.

deliver baseload electricity, balance the variable output from renewable sources and could also make use of waste heat as part of a UK heat network.

Nuclear Research, Development and Innovation

The UK has a significant track record in nuclear research and an international reputation built up from historic experience. An on-going programme of publicly funded R&D investment is needed to allow the UK to maintain and develop these engineering skills so they can play a significant role in developing and regulating an expanded nuclear energy base.

Strengthening the skills base and developing nuclear technologies will enable the UK to grow from its current position of primarily being an importer of nuclear technology to establish a role as manufacturer and seller of nuclear reactor equipment and fuel. Future markets also present significant opportunities for the UK in nuclear engineering consultancy and nuclear services that can contribute to the growth of the UK economy.

The Government has recently taken steps to reinvigorate the nuclear R&D base through investment in equipment and facilities. In the 2015 Spending Review the Government announced funding for new research programmes and a vision to build one of the first SMRs in the world.

Although the recommendations provided in this report are targeted on delivering the Government's Nuclear Industrial Strategy (NIS) the research has synergies with other hi-tech, safety led industrial sectors, such as aerospace and oil and gas. The research at these touch points will be used to maximise the pan-sector benefits, providing support the wider UK industry.

Future Nuclear Markets and Industrial Focus

NIRAB's recommendations identify where publicly funded nuclear R&D and innovation can further develop the UK nuclear industry's capability and capacity to play an increasingly significant role in current and future nuclear markets.

Developing new, game-changing technologies and methods will enable UK companies to grow their domestic and global market share and break into established nuclear supply chains. Achieving this will require effective development across supply chains, involving larger companies and Small and Medium Enterprises (SMEs). NIRAB's recommendations have been structured to support development across the supply chain and UK businesses of all sizes are expected to be involved in their implementation.

To ensure close alignment with the UK nuclear industry the recommendations in this report have been developed in conjunction with representatives from across the sector including; a nuclear utility, a fuel enrichment company, a fuel manufacturer, a major nuclear engineering consultancy, a manufacture of nuclear technologies, a nuclear decommissioning company and a nuclear engineering SME. The markets for operation and maintenance of current reactors and the decommissioning market continue to be a significant focus for British

Industry. The following additional nuclear markets also being targeted for UK businesses to expand into:

Nuclear New Build

The investment focus in this case should be on developing the UK's manufacturing base to enable UK businesses to play a much more significant role in the supply chain for reactor build programmes. This will be particularly true for future nuclear new build in the UK and overseas where there is likely to be more opportunity to increase UK content through manufacturing improvements that can bring cost efficiencies and programme risk reduction. This encompasses the full spectrum of reactor technologies being considered for deployment within the UK, including PWRs and BWRs. Targeted investment in fuel research can support the sustainability of the UK's extant indigenous fuel supply chain and further investment in reactor design and manufacture innovation will ensure the UK grows a competitive capability for the regulation, construction, commissioning, operation and maintenance of nuclear plants. A key opportunity for UK industry will be providing consultancy services to reactor vendors in areas such as safety cases, supporting analysis and regulation.

Small Modular Reactors

There is potentially a significant global market[4] for SMRs that could provide commercial opportunities for the UK. The UK is an attractive location for international SMR vendors to deliver first-of-a-kind plants given Government support, the international reputation of our Regulator and the availability of potential sites. UK involvement in 'design for manufacturing and construction' and fuel supply presents an opportunity to develop exploitable design and manufacturing Intellectual Property (IP) providing direct benefit from export sales as well as UK deployment. The SMR market presents a route to exploitation for a large portion of NIRAB's R&D recommendations and the development of SMR technologies is a stepping stone to involvement in Generation IV (Gen-IV) reactor collaboration programmes.

Very Small Modular Reactors or micro-reactors are those rated below 30MW and address a different market to SMRs. With a much lower power output, micro-reactors could supply heat and power for industrial application on a local site basis. Some micro-reactor technologies use fuels that have synergy with the high temperature gas-cooled Gen-IV reactor technology.

Generation IV Reactors

NIRAB's investment strategy is to develop the UK's capability in advanced fuels, manufacturing and reactor design to maximise the opportunities for the sector to play a meaningful role in the design of Gen-IV reactor systems and components.

Development of the next generation of nuclear reactors is progressing within the international collaborative arrangements of the Gen-IV International Forum (GIF). Two of the candidate reactor technologies under development within the GIF, Sodium-cooled Fast Reactors (SFR) and High Temperature or Very High Temperature (HTR/VHTR) gas-cooled reactors align closely with areas of the UK's expertise and experience. Sustaining and developing these

[4] Small Modular Reactors (SMR), National Nuclear Laboratory. December 2014

capabilities within the UK industry provides a viable route to placing the UK at the forefront of Gen-IV reactor design.

Generation of Recommendations

These R&D recommendations have been developed through a wide-ranging and detailed consultation with the members of NIRAB, its Subgroups and the wider UK nuclear sector. This has built upon the programme recommendations made in the NIRAB Annual Report 2014[5] and covers many of the same areas. Consultation has covered the entire fuel cycle and involved individuals from the full spectrum of academia, national research organisations and industry, from large multinationals to SMEs. Those that have assisted in generating and reviewing these NIRAB recommendations are listed in the Contributors Section of this report.

During the development of these recommendations NIRAB and the Nuclear Innovation and Research Office (NIRO) have liaised with The Carbon Trust to share information in support of their review of the LCICG's Nuclear Technology Innovation Needs Assessment (TINA)[6]. This has ensured consistency between the TINA and NIRAB's programme recommendations.

It is advised that the recommendations made in this report are reviewed on a regular basis to ensure that they remain consistent with contemporary Government policies, the status of the UK nuclear industrial landscape, align with on-going programmes of work and the maturity of nuclear technologies.

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5 NIRAB-35-4 NIRAB Annual Repot 2014, February 2015

6 Technology Innovation Needs Assessment, Nuclear Fission Summary Report, April 2013

Programme Areas

To provide structure to NIRAB's recommendations and to help simplify communicating the programme to stakeholders the R&D and innovation recommendations provided by NIRAB have been grouped into the following five programme areas:

- **The UK's Strategic Toolkit:** Underpinning decisions on which emerging nuclear technologies are brought to market to give the best economic return for the UK.
- **Future Fuels:** Making more efficient, safer nuclear fuels of the future.
- **21st Century Nuclear Manufacture:** Advanced manufacturing and modular build in nuclear factories of the future.
- **Reactor Design:** Delivering the people, processes and tools to make the UK the partner of choice as the world designs SMRs and 4^{th} generation nuclear power plants.
- **Recycling Fuel for Future Reactors:** Cost effective technologies to deliver a secure and sustainable low carbon fuel supply.

These programmes cover the full range of fuel cycles and play to the strengths of the UK nuclear sector. There is broad alignment between these areas and the product streams required to exploit future nuclear opportunities. These are summarised in Figure 1 which illustrates how the programme areas will feed into future reactor development, construction and operation markets.

Whilst NIRAB's recommendations are allocated to five programmes with a number of programme areas within each, there are critically important interactions between them. To maximise impact on IP and UK jobs, NIRAB recommend that these should be treated and managed as a single integrated programme to maximise synergies and interactions across the individual projects and not delivered through a piecemeal approach which would severely curtail such interactions.

However, it is recognised that there is the potential for a mismatch between the level of ambition embodied in the NIS and the level of programme funding made available to fund these recommendations and there may be a need to prioritise critical research and innovation activities. Options are available for the implementation of the recommendations and NIRAB has explored how the programme can be scaled or phased to match funding availability.

A programme of implementation can be flexed to provide a focus on particular technologies or benefits as dictated by Government and NIRAB/NIRO can assist Government as required with this process.

International Collaboration

International collaboration can deliver significant benefit and additionality to any major scientific research and development programme. The cost for nuclear technology developments, such as new reactor designs, are substantial and collaborations between nations is considered the most viable route for pursuing major nuclear programmes in the future. In addition very few nations have retained the technical capability to deliver an entire reactor development as the drive to sustain a wholly indigenous nuclear industry has diminished. It is imperative that strong international collaboration forms a key part of the UK's nuclear research and innovation programme going forward and is coordinated to maximise the benefits it can deliver.

One of NIRAB's main objectives is overseeing the development of an international engagement strategy, in conjunction with Government and the UK nuclear industry. This will form a key element during the implementation of these activities.

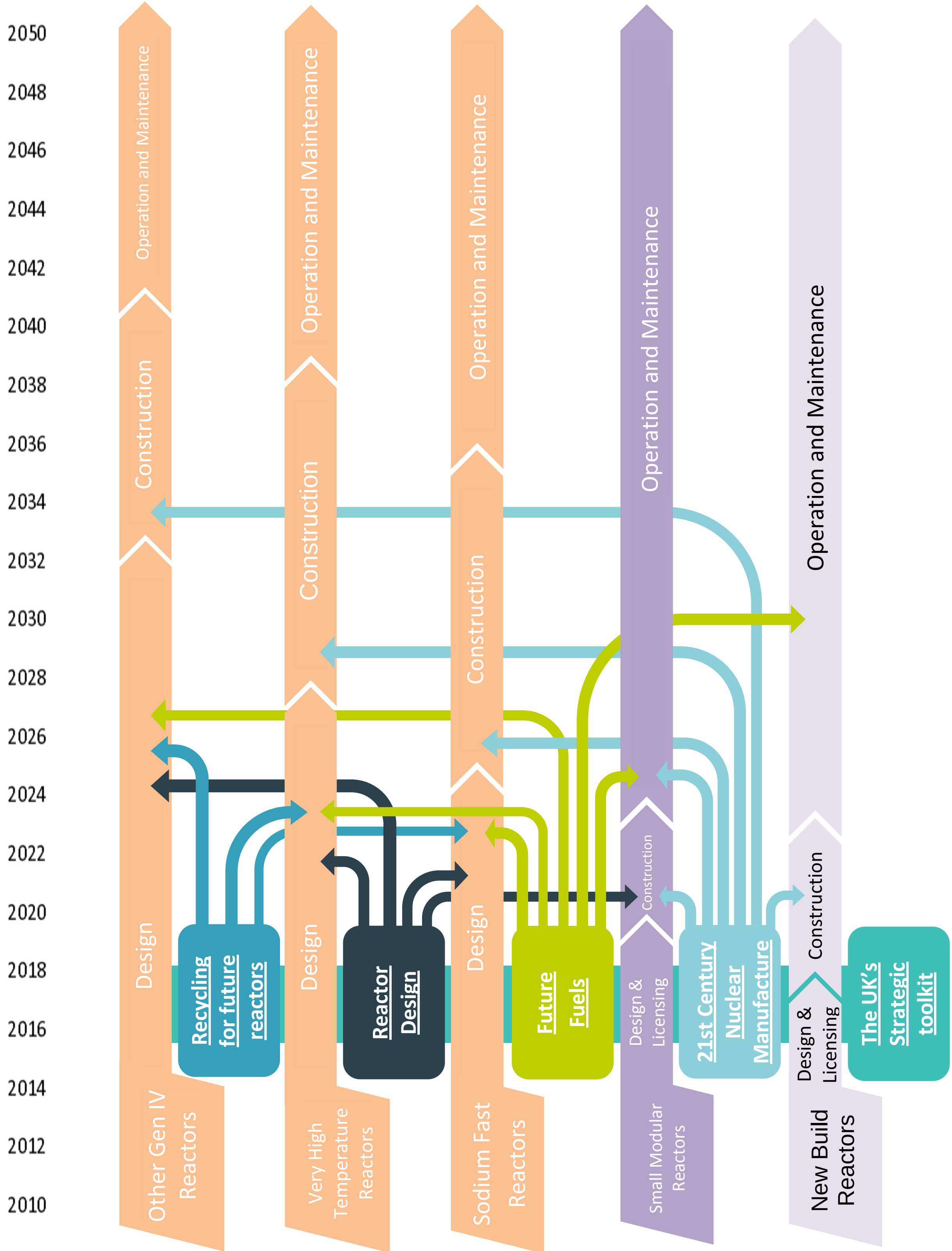

Figure 1 NIRAB Programmes Support to Future Nuclear Markets

2. Strategic Aims and Objectives

The 2015 Spending Review and Autumn Statement builds on the previous Government's Nuclear Industrial Strategy[7] (NIS), published in 2013, which was developed by Industry and Government working together. The NIS vision for 2050 is:

> *"Together Government and Industry have a clear and ambitious vision to ensure the development of a vibrant UK nuclear industry that is an area of economic and strategic national strength, providing the UK with a safe, reliable and affordable supply of low-carbon electricity."*

The NIS defined a series of objectives and interim milestones that could be used to monitor progress across the intervening years towards the delivery of this vision. The milestones that are relevant to R&D and innovation are presented in Figure 2 and NIRAB's recommendations are consistent with these.

NIRAB's recommendations have focused on the R&D and innovation required in the five year period up to 2020 which is critical in stabilising the nuclear R&D community and providing a strong footing on which to base a long-term programme that can deliver the NIS 2050 vision. The NIS presents the following objectives for the Government and industry to achieve by 2020. These will be delivered partly through the implementation of a programme of R&D:

- UK playing a significant role in advanced fuel cycle technologies through national and international research collaboration
- UK engaged in collaborative design projects for new reactors (Generation IV and SMR), building on its existing and growing design expertise
- UK exports manufactured components, provides services and operational support
- The UK influences the programme of international harmonisation of codes and licensing
- UK-based industry secures a significant share of the work to deliver first new plants
- Advanced manufacturing programmes progress, supported and underpinned by R&D
- More advanced techniques in construction, programme and project management deployed and embedded in the UK supply chain.

It is acknowledged that there are other 2020 objectives presented in the NIS that are not related to a programme of R&D.

[7] The UK's Nuclear Future; Industrial strategy; government and industry in partnership, BIS/13/627, March 2013

2020	2030	2040
UK establishes capability to supply fuel competitively to the PWR market both in the UK and overseas.	UK fuel fabrication capacity fully utilised in supplying PWR markets.	UK supplying the fuel needs of Gen-III+ and any Gen-IV and SMRs.
UK playing a significant role in advanced fuel cycle technologies through national and international research collaboration.	UK engage in national and international R&D programmes providing ‘proof of concept’ for future fuel cycles and reactors.	UK nuclear industry will have a strong domestic capability from fuel enrichment, fuel manufacture, reactor technology, operations, recycling, waste minimisation, storage and disposal. UK to service an international market for current and emerging technologies.
UK engaged in collaborative design projects for new reactors (Generation IV and SMR), building on its existing and growing design expertise.	Lessons learned in reactor delivery at home and abroad positively impacts on UK collaborative research into new designs.	
UK exports manufactured components, provides services and operational support. The UK influences the programme of international harmonisation of codes and licensing.	UK involved in new build and maintenance overseas based on comprehensive export offering. UK to supply fuel for overseas PWR market.	
Advanced manufacturing programmes progress, supported and underpinned by R&D. More advanced techniques in construction, programme and project management deployed and embedded in the UK supply chain.	Maturing R&D results in new plant with significant UK design content and manufactured parts deployed in the UK. Lessons learned from construction of the first wave of new build fed back into further R&D supporting Gen-III+ construction and operation overseas. Development of advanced techniques allows UK manufacturers to supply components and assembly for a commercial deployed SMR for overseas clients.	
UK-based industry secures a significant share of the work to deliver first new plants.	UK working as “smart host nation” improving delivery with vendors – providing end to end nuclear delivery solutions, to time and budget. UK industry builds on success of the construction of new plants to grow capacity in longer term O&M provision. UK-serviced plants achieve zero failures and extremely high availability. UK operations, maintenance and training skills gain overseas market.	Expansion of domestic generation beyond 16GW using a combination of Gen-III+, Gen-IV and SMR technologies. Major UK design capability is backed up by a strong supply chain. A ‘packaged’ offering of life-cycle management will be delivered for UK-collaboratively designed Generation IV or SMR technologies.

2020	2030	2040
UK contribution achieves a higher profile within international programmes on GDF and decommissioning R&D.		Decommissioning at UK sites delivered on programme and with reducing costs, with land remediation activities in place where possible.
UK industry to make demonstrable progress on high hazard legacy waste management, facilities and reactor decommissioning and geological disposal.		
UK industry develops its reactor decommissioning experience on existing reactors in the UK.		UK industry to have delivered the design, construction and commissioning of the GDF.
UK will carry out surface based assessments of sites for a GDF location, and make significant progress optimising the efficiency of waste conditioning and storage.	UK will have completed the R&D required to finalise a decision for the siting of the GDF, and construction work commenced.	
A vibrant, commercial UK industry develops, supporting the domestic market.	UK having a clear competitive edge in waste management and decommissioning technologies in domestic market, driving down costs through innovation and experience.	An established vibrant UK industry that is the global benchmark in waste management and decommissioning.
UK industry developing indigenous IP in wet and dry spent fuel storage and looking to carve out international market share.	UK nuclear industry delivering wet and dry extended storage solutions for existing and new build reactors with Government support to export these technologies.	
UK industry to gain an increasing share in international waste management and decommissioning markets.	Continued global market growth with innovative UK supply chain sought out by international markets. Move up the value chain internationally and export Tier 1 capability to foreign sites requiring decommissioning.	Strong presence as a global leader and established exporter of waste management and decommissioning markets solutions. UK will be a global leader in GDF technology, advising and providing assistance to other nations.

Figure 2 Summary of NIS Aims and Objectives Related to R&D and Innovation

NIRAB has introduced a vision for 2020 that provides a stepping-stone towards achieving the main aims and 2050 objective of the NIS. This vision is:

> *"To establish the innovative R&D programmes, high-level skills and leading-edge facilities needed to set the UK on course to deliver its 2050 vision for nuclear energy, creating a renowned UK capability with a strong international presence."*

The ***NIS 2020 Objectives*** and the ***NIRAB 2020 Vision*** have been used to generate a series of ***2020 Research Objectives*** that have been used to define and structure a programme of R&D and innovation activities and outputs. These provide clear benefits to the UK, enabling elements of Government policy to be delivered. The 2020 R&D objectives are:

The UK's Strategic Toolkit

- S1: To develop the tools, methods and data to provide the evidence needed to inform future decisions on UK nuclear energy programmes including reactor technologies and fuel cycles
- S2: To deliver new understanding, guidance and tools that can be used to enhance public engagement on all aspects of nuclear power.

Future Fuels

- F1: To develop and test accident tolerant fuels for irradiation in a materials test reactor
- F2: To develop the capability to fabricate test fuel pellets for an advanced reactor
- F3: To retain and further develop the UK's capability and infrastructure to model, design, manufacture and test future fuel technologies.

21st Century Nuclear Manufacture

- M1: To develop the UK's advanced materials and manufacturing research capability to deliver new nuclear technologies
- M2: To develop a suite of advanced component manufacturing technologies
- M3: To deliver a suite of modular construction techniques and technologies to enable effective nuclear plant build.

Reactor Design

- R1: To develop the UK's reactor system and component design, analysis and verification capability
- R2: To deliver the infrastructure and facilities needed to support next generation reactor design, component performance and safety research
- R3: To develop the UK's capability to provide nuclear consultancy and through life support services.

Recycling Fuel for Future Reactors

- E1: To deliver the infrastructure and facilities needed to develop advanced recycling technology
- E2: To demonstrate a safe, economic, efficient and proliferation resistant aqueous LWR fuel recycle technology at laboratory scale using active experiments
- E3: To demonstrate components of a fast reactor fuel pyroprocessing recycle technology inactively at laboratory scale
- E4: To demonstrate effective waste immobilisation technologies for the waste forms generated by advanced fuel and recycling technologies.

Figure 3 shows how the NIS objectives map onto the NIRAB programme areas and Figure 4 shows how each 2020 R&D objective maps across to the NIS objectives.

Figure 3 Mapping of NIS Objectives to NIRAB Programme Areas

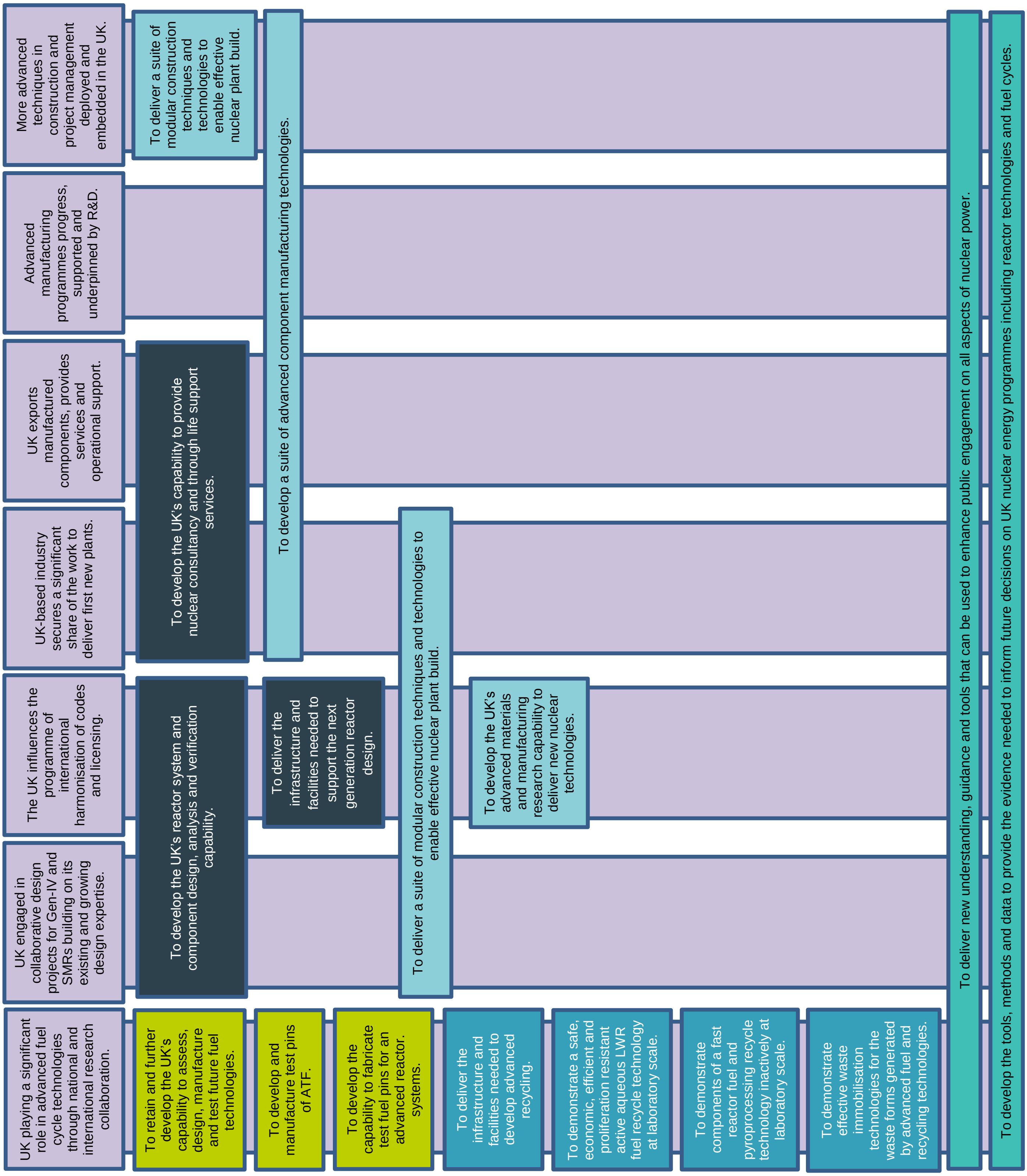

Figure 4 NIRAB Programme 2020 Objectives Mapped to NIS Objectives

3. R&D Recommendations

NIRAB's recommended nuclear R&D and innovation is described within this section for each of the five programmes. Following a brief introduction to the area, the vision and objectives are presented alongside a description of the various projects and activities that have been defined to deliver the objectives. Finally indicative programme and capital funding requirements are provided for each area. A bottom up review of the resources required to deliver the total programme has estimated that around £250m will be required, including £160m programme and just under £90m capital funding. It should be noted that the recommendations in this document were developed in advance of the Government's Spending Review and Autumn Statement 2015 [8]. Further work is required to determine the extent to which the recommendations presented in this document are compatible with the funding and nuclear research mission announced in the Spending Review.

[8] Spending Review and Autumn Statement 2015, Cm 9162, November 2015

The UK's Strategic Toolkit:

Underpinning decisions on which emerging nuclear technologies are brought to market to give the best economic return for the UK.

3.1 The UK's Strategic Toolkit

The long lead times associated with delivering major nuclear infrastructure, such as nuclear reactors or recycling facilities, mean that a long-term, strategic view must be taken when formulating policy decisions on how nuclear power should support UK energy needs. Such decisions require authoritative techno-economic input based on the best available data and expert interpretation. Providing a structured set of credible data that reflects changes in governing factors and the tools for interpretation will allow policy makers to assess more effectively the most appropriate route for the UK industry. This R&D will underpin a credible and cost effective national programme of nuclear focussed R&D within the UK.

Societal acceptance of nuclear energy is also critically important for the effective and efficient delivery of nuclear within the UK energy mix, underpinning the political ability to support a nuclear energy policy. Public engagement must therefore be a priority in UK nuclear programmes. This has been underpinned by the publication in 2015 of the UK nuclear sector's Concordat on Public Engagement[9] which commits the sector to 'best practice'. NIRAB therefore recommends a programme of R&D to ensure that the UK remains at the forefront of public engagement with nuclear energy.

The UK's Strategic Toolkit 2020 Vision

The NIRAB vision is that by 2020 the UK will have a suite of tools and the underpinning data to assist decision-making regarding which nuclear technologies should be developed by the UK along with the tools to engage the public.

The UK's Strategic Toolkit 2020 Objectives

S1 To develop the tools, methods and data to provide the evidence needed to inform future decisions on UK nuclear energy programmes including reactor technologies and fuel cycles

It is critically important that the UK strengthens its capability to take a long-term strategic view on future energy policy with respect to nuclear technology. This requires the ability to model the nuclear fuel cycle for a range of scenarios and to assess the strengths and weaknesses of various nuclear reactor systems, fuel cycle options and overall fit within the domestic energy system. This requires the development of nuclear energy-futures modelling tools to help Government understand the pathway options to a low carbon economy. A range of potential nuclear fuel scenarios and of candidate reactor systems will be simulated providing information on systems, future fuel use, resource requirements, economic factors and level of CO_2 emissions.

9 "Nuclear Energy and Society: a Concordat for Public Engagement", Nuclear Industry Council, 2015.

S2 To deliver new understanding, guidance and tools that can be used to enhance public engagement on all aspects of nuclear power

The UK needs to develop social science skills to engage in international programmes assessing public understanding of nuclear energy and engage in effective public engagement programmes. This R&D will be used to enhance outworking of the UK nuclear sector's Concordat on Public Engagement, providing new understanding and approaches to better engage the public on current and future nuclear programmes including the range of R&D proposed by NIRAB.

The UK's Strategic Toolkit Research

The recommended research project areas to deliver each of the 2020 objectives in the UK's Strategic Toolkit area are presented in Figure 5 and described below.

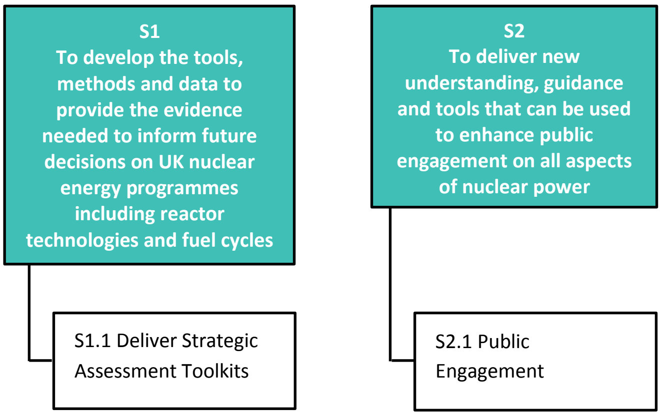

Figure 5 The UK's Strategic Toolkit Project Breakdown

S1.1 Deliver Strategic Assessment Toolkits

A credible source of data is critical to ensure that appropriate decisions are taken on the future of the UK nuclear energy research and to provide the evidence base needed to inform the Government's future energy, environmental and security policies. This data is of particular importance when determining the funding required for a national programme of R&D. Specific research requirements identified include:

- ***High Level Framework* -** There are a number of existing models and techniques used to provide assessment of emerging technologies, fuel cycles and future energy scenarios. A high level framework is required under which these models can operate together and postulate various scenarios
- ***Generic Feasibility Assessments (GFA)* -** The existing GFA technique should be applied to the latest crop of new, emerging nuclear technologies. This will enable technologies to have fair comparisons and to be assessed for their potential future benefits and challenges faced

- ***Revision of Existing Models -*** A number of existing models are in use through the UK to model future energy scenarios, for example the UK's ORION fuel cycle modelling tool. Many of these can be used to provide baseline data to the high level strategic assessment framework. These models require a revision to bring them up to date
- ***Base Level Model Development -*** Additional models are required to provide base data to inform the high level framework, for example decommissioning and disposal.

S2.1 Public Engagement

This project area will draw together the nuclear research community with social sciences and humanities to understand the underlying reasons for public attitudes to nuclear energy, how these attitudes are shaped by events and the underlying misconceptions that have developed over time. R&D will address how communications on nuclear matters can be more effective, what industry can learn from other sectors and what communication channels and tools can help address current and emerging issues. Specific research requirements identified include:

- ***Tool Development -*** Develop evidence-based tools to inform and enhance the delivery of a national strategy on public engagement in nuclear energy and embed these within the delivery programme for the Nuclear Industry Council communications strategy
- ***Public Data Gathering*** - Develop new understanding of the underlying reasons for public attitudes to nuclear energy at national, regional and individual level, how these have emerged over time and how these are shaped by events. R&D will provide an evidence base to inform the development and delivery of a UK strategy for public engagement that builds wider international links to strengthen the UK programme.

While these specific activities will be carried out on understanding the public perception of the nuclear energy industry all R&D activities will be used to engage the public.

The UK's Strategic Toolkit Indicative Costs

An indicative cost to deliver the UK's Strategic Toolkit is given in Table 1.

Table 1 The UK's Strategic Toolkit Indicative Costs

	Title	2016-21 Cost /£m		
		Programme	**Capital**	**Total**
S1	Deliver Strategic Assessment Toolkits	4.50	-	**4.50**
S2	Public Engagement	2.50	0.5	**3.00**
	Total	**7.00**	**0.5**	**7.50**

Future Fuels:

Making more efficient, safer fuels of the future.

3.2 Future Fuels

The UK has strong history of developing and manufacturing a wide range of nuclear fuels including those for all generations of power and test reactors. Advanced Gas-Cooled Reactor (AGR) and LWR fuel is currently manufactured in the UK on the Springfields site. The UK has not only an academic research base in this field, but also research laboratories located on nuclear licensed sites which can handle significant quantities of nuclear materials, including alpha active laboratories able to produce plutonium containing fuels. This capability has been enhanced through Government investment in the Nuclear Fuel Centre of Excellence (NFCE) positioning the UK as an attractive partner for international collaboration.

Future Fuels 2020 Vision

NIRAB's vision for the fuel programme is that by 2020 the UK will have a strong nuclear fuels R&D base that can attract international investment, support retention of the UK's fuel manufacturing capability and subsequently deliver nuclear fuels to the domestic and international markets. This will be used to launch future fuel developments, stimulate economic growth and sustain key skills across the fuel cycle.

The UK's nuclear fuel supply chain aims to maintain its AGR fuel manufacture capability in the UK for the next 15 years and make the UK attractive for overseas investment in new fuel facilities by establishing a world class fuel manufacture, design and enrichment research environment. Research and development into new fuel types in conjunction with investment in new fuel lines will support a transition from AGR fuel manufacture towards an increase in fuel manufacture capacity for new build LWRs and a range of SMRs. This is a significant increase over the UK's current capability and revenue streams.

Accident Tolerant Fuel (ATF) would be a game changing technology within the global nuclear fuel supply market and the existing installed reactor base. UK owned ATF design and manufacture IP would help secure future private investment in UK fuel manufacturing, deliver a UK owned product that can be sold into a world market and act as a stepping stone for the UK industry to supply Gen-IV fuels in the future.

Future Fuels 2020 Objectives

F1 To develop and test accident tolerant fuels for irradiation in a materials test reactor

There is considerable international interest in developing ATF in the wake of the Fukushima incident. International collaboration opportunities exist and the UK could take the lead in key areas. Delivering cost effective ATFs will represent a considerable enhancement in nuclear safety if these fuels are deployed in the current generation of new build LWRs, future SMRs and Gen-IV reactors. The UK is well positioned to be the first to establish a manufacturing route for ATF technology. Playing a significant role in a first to market ATF will demonstrate the capability required to justify hosting a full scale fabrication facility. The UK will explore routes towards this end via R&D on new fuels, improved fuel cladding and coated particle fuel technology.

F2 To develop the capability to fabricate test fuel for an advanced reactor system

Developing a capability to deliver test fuel for a fast reactor will give the UK an opportunity to re-engage with the GIF. Such a programme will focus on plutonium-based fuels for fast reactor technologies and an assessment of thorium-based fuels. The UK is well-placed to undertake R&D in this area, having historic capability in fast reactor and alternative fuels and the facilities and residual expertise to drive R&D in this area.

F3 To retain and further develop the UK's capability and infrastructure to model, design, manufacture and test future fuel technologies

Carrying out R&D programmes in ATF, coated particle fuels and fast reactor fuels will advance the UK's capability to manufacture and test future fuel technologies. However to support these programmes an infrastructure of physics modelling, access to key facilities and nuclear databases are required. This will support not only research programmes focusing on advanced systems but also ongoing in-service support of the current nuclear fleet and UK's defence nuclear programmes.

Future Fuels Research

The recommended research project areas to deliver each of the 2020 objectives in the Future Fuels programme and individual project area are presented in Figure 6 and described below.

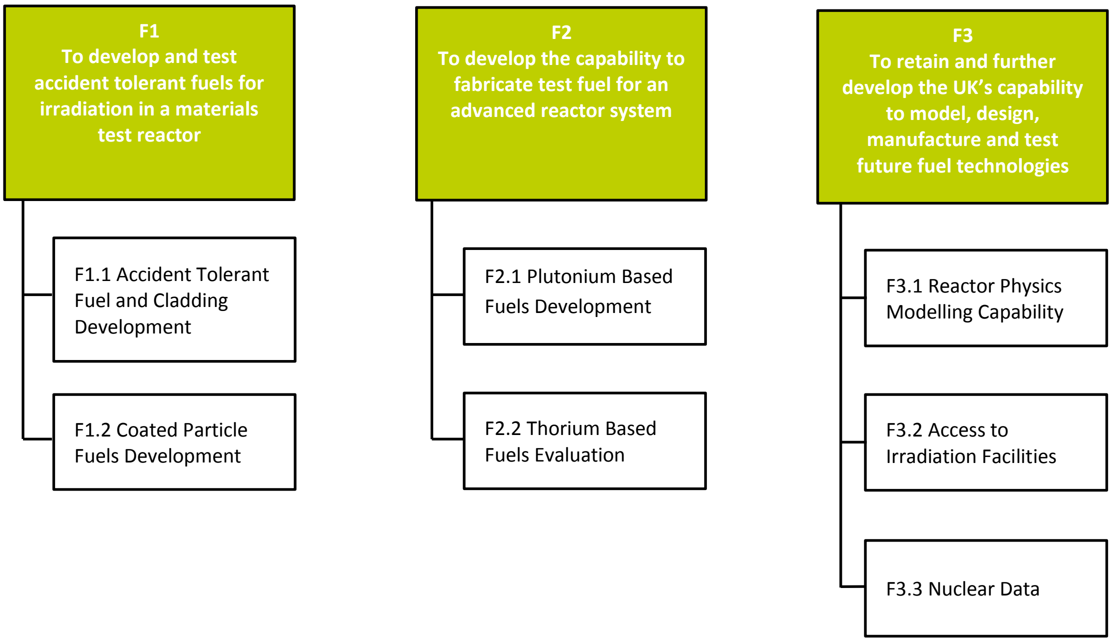

Figure 6 Future Fuels Project Breakdown

F1.1 Accident Tolerant Fuels and Cladding Development

The two main elements to the programme relate to fuel pellets and to cladding and these will be augmented by material performance data fed from both study areas into nuclear data evaluations of integrated products and fuel performance assessments. All elements of the work will develop IP whilst contributing to international ATF down-selection programmes.

The fuel pellet component of the programme will develop a fabrication route that can be operated at an industrial scale and is compatible with existing PWR fuel manufacturing infrastructure, in contrast to existing laboratory routes. The aim is to produce test fuel for irradiation trials to confirm in-reactor performance and validate fuel performance modelling simulations. The cladding element of the programme will identify and develop materials with enhanced tolerance of conditions that can develop in accidents. Factors in discriminating between candidate cladding materials will be their fabricability and performance in the reactor environment.

F1.2 Coated Particle Fuel Development

Coated Particle Fuels (CPFs) are exceptionally robust and have been proposed for use in a range of reactor types including PWRs, VHTRs and micro-reactors. The concept under development offer opportunities for a strong UK supply chain contribution.

This project area will re-establish a capability to manufacture and characterise a range of kernel and coating materials and to investigate production of fuel elements in prismatic, pebble, or rod/pellet form.

F2.1 Plutonium Based Fuels Development

This project area will install and commission equipment necessary to undertake R&D on fast reactor fuel. As equipment becomes available, research will develop this fuel and associated technology for large scale fabrication. The viability of this fuel is also related to recycle technology and will require input from nuclear data experiments and fuel performance assessments.

F2.2 Thorium Based Fuel Evaluation

Evaluation of thorium based fuels in the broader context of the fuel cycle will give the UK a greater understanding of the potential benefits, timescales and implications of deploying thorium fuel technology. Provision of a capability to assess the performance of thorium-based fuels will be needed, requiring the generation and evaluation of experimental data. There are many opportunities for the UK to engage in international thorium based fuel programmes. These programmes will bring added benefits to other priority fuel R&D.

F3.1 Reactor Physics Modelling Capability

This project area will develop and validate innovative techniques to model the physics associated with new reactor fuel types developed under the Future Fuels programme. The new techniques will take more account of 3D effects including coupling with other phenomenological models, by exploiting High Performance Computing and parallelisation software techniques. These will be applied to performance modelling of new fuel types as a critical part of their validation ahead of reactor testing. Once complete the new fuel and core models will be integrated with thermal hydraulics models to develop a whole reactor modelling capability.

F3.2 Access to Irradiation Facilities

Access to irradiation facilities is essential to delivering the development programmes for new fuels to carry out performance testing and validation of prototype fuels under both normal operating conditions and transient conditions. This current route to this capability is recognised to be through the Halden Reactor project.

F3.3 Nuclear Data

This project area will ensure access to the nuclear data needed to underpin the computer simulations needed to support the safety and economic cases for advanced reactors and fuel cycles. However, whilst adequate for current reactor systems, existing nuclear data is not adequate for the assessment of advanced fuels (in current reactors); advanced reactors (Gen-IV and beyond); and for understanding the wastes arising from these systems. This project area will focus on new data, better accuracy and understanding of its uncertainties and their correlations, and how best to use these data on modern computing platforms with more efficient methods.

The project area will engage with international nuclear data programmes, including both data generation and evaluation to enhance the data for advanced fuels and to retain the skills base in this important area.

Future Fuels Indicative Costs

Indicative costs for R&D and innovation required to implement the recommendations in each of these areas is given in Table 2.

Table 2 Future Fuels Indicative Costs

	Title	2016-21 Cost / £m		
		Programme	**Capital**	**Total**
F1.1	Accident Tolerant Fuels and Cladding	8.00	4.80	**12.80**
F1.2	Coated Particle Fuels	9.25	5.00	**14.25**
F2.2	Plutonium based fuel development	5.50	2.00	**7.50**
F2.2	Thorium Based Fuel Evaluation	0.50	-	**0.50**
F3.1	Reactor Physics Modelling	6.15	0.50	**6.65**
F3.2	Irradiation Facility (based on Halden access)	0.50	-	**0.50**
F3.3	Nuclear Data	1.50	-	**1.50**
	Total	**31.40**	**12.30**	**43.70**

21st Century Nuclear Manufacture:

Advanced manufacturing and modular build in nuclear factories of the future.

3.3 21st Century Nuclear Manufacture

The UK's current strengths in the civil nuclear reactor sector are focused mainly on operations and maintenance services, with the domestic nuclear manufacturing base being comparatively weak. The manufacture and supply of high value nuclear components is a growing global market and one towards which the UK industry aspires. This includes increasing the UK manufactured content of reactor plants being constructed domestically as well as accessing opportunities in overseas markets.

There are substantial barriers to entry into the market for manufacture of nuclear components and systems including large capital investment, the need for specialised facilities, uncertainty of future orders, low production rates, high standards of production and quality assurance and the need for a highly qualified and skilled workforce. However, a targeted R&D and innovation programme aimed at developing new nuclear structural materials, manufacturing technologies linked with modular construction processes would position UK industry to deliver a capability that is fit for the 21st Century. Whilst the programme focuses on high value reactor components, it has wider applicability to, for example, nuclear decommissioning and other industries in the energy sector. This represents significant opportunity to strengthen the nuclear supply chain to grow a more sustainable and stable manufacturing base in the UK.

The main focus of manufacturing R&D within the UK nuclear sector is the Nuclear Advanced Manufacturing Research Centre (NAMRC) facilities at the Universities of Sheffield and Manchester. These provide opportunities for UK R&D programmes to deliver the innovation in materials understanding, manufacturing and construction required. This work will build on projects such as the EPSRC-funded New Nuclear Manufacturing (NNUMAN) programme.

21st Century Nuclear Manufacture 2020 Vision

NIRAB's vision for the advanced manufacturing programme is by 2020 the UK will have established a strong materials and manufacturing R&D base that is driving advanced techniques into the UK supply chain.

Technologies such as additive manufacturing and electron beam welding have the potential to make the UK nuclear manufacturing supply chain competitive in the growing international nuclear market. This will allow businesses to increase the proportion of UK content in high value reactor components for nuclear new build and SMR production. Once the route into this market has been established this capability can be applied to the development and manufacture of Gen-IV reactor technologies.

A key element in establishing a broad, innovative and healthy nuclear manufacturing supply chain with an internationally competitive capability is the development of SMEs. This will be the focus of much of the manufacturing development programme outlined by NIRAB, following on from previously successful programmes within the NAMRC.

Bringing modular construction techniques common in other industries into nuclear projects will remove risk and deliver cost and schedule certainty. This will provide UK industry with capabilities and capacity to support nuclear new build, the SMR and decommissioning markets.

21st Century Nuclear Manufacture 2020 Objectives

M1 To develop the UK's advanced materials and manufacturing research capability to deliver new nuclear technologies into the supply chain

The UK needs to sustain and advance its capability to develop new materials and advanced manufacturing techniques to reduce costs and enhance through-life component performance. This development will require targeted R&D, the development of facilities and the associated skilled workforce. Focused on new materials and manufacturing technologies for SMRs and future Gen-IV systems, this project area will work at a laboratory scale, engaging internationally to develop the materials performance data and fundamental understanding necessary. Bringing new materials and manufacturing techniques to the nuclear sector will provide IP for UK industry and give UK industry capabilities attractive in the future design and manufacturing of SMRs and Gen-IV reactors.

M2 To develop a suite of advanced component manufacturing technologies

The opportunities for the UK arise from manufacturing development programmes that could be implemented for new build, SMR designs and subsequently for Gen-IV reactor designs. These include scaling up advanced machining, welding and near net shape manufacturing from the laboratory to component scale manufacture in factory. Given the long lead times associated with the full development of reactor components from fundamental material research this work needs to be continued from the base provided by the NAMRC. Crucial to the use of new materials and manufacturing techniques will be the fundamental understanding and associated data within new code cases to enable international acceptance of new technologies. Understanding modularisation and designing new factories to deliver modular build will be an important element to the programme.

To exploit these advanced materials and manufacturing technologies they must be adopted by the supply chain. Spreading this capability through the NAMRC to the UK manufacturing base in conjunction with other Government funded initiatives will be a key element of this programme.

M3 To deliver a suite of modular construction techniques and technologies to enable effective nuclear plant build

Delays in on-site construction present the biggest risk of cost escalation for nuclear plant. Implementing advanced manufacturing with an increase in off-site modular assembly will revolutionise the way power stations are manufactured, making nuclear more attractive to investors and lowering the cost of electricity to consumers.

Off-site assembly in a clean manufacturing environment gives greater control of the quality of final products, the ability to work with a stable workforce and drives down costs, particularly for n^{th}-of-a-kind components. When integrated with design and manufacturing, modular construction will be a game changer in assuring delivery to time and cost of major nuclear projects. This is applicable from the smallest components to 1,000 tonne modules with the option of complete nuclear systems being factory built and subsystems delivered to site ready for installation. This is expected to deliver particular benefit to the construction and delivery of SMRs and the design of Gen-IV reactors.

21^{st} Century Nuclear Manufacture Research

The recommended research project areas to deliver each of the 2020 objectives in the 21^{st} Century Nuclear Manufacture programme area are presented in Figure 7 and described below.

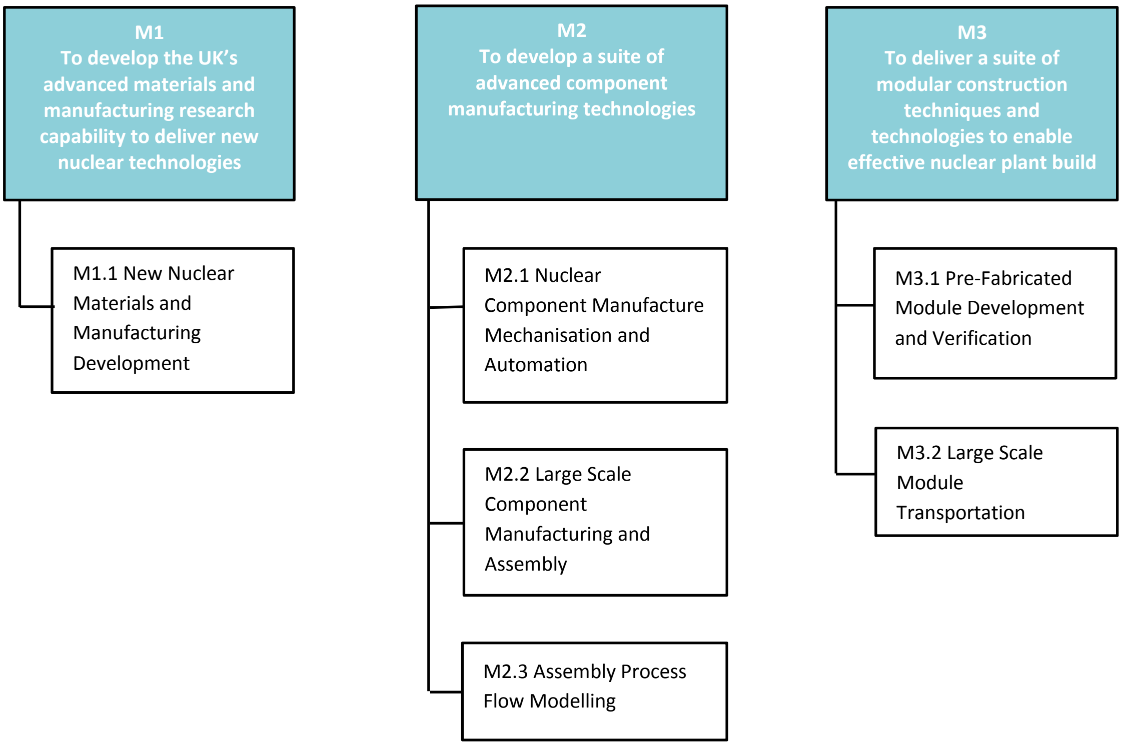

Figure 7 21^{st} Century Nuclear Manufacture Project Breakdown

M1.1 New Nuclear Materials and Manufacturing Development

To deliver the materials and manufacturing capability for the next generation of high value components for SMRs and Gen-IV reactor systems research must be carried out into advanced materials and manufacturing technologies to reduce cost and enhance performance in the challenging environment within the reactor.

Research is needed to understand the effect of advanced manufacturing processes on the subsequent behaviour of the material during operation including environmentally-assisted degradation, and creep/creep-fatigue. Specific requirements include:

- ***Materials Development* -** Candidate structural materials, manufacturing processes and testing environments will be selected for targeted R&D. These will be based on the material requirements of SMRs and selected Gen-IV reactors
- ***Materials Test Programme* -** Candidate materials will be tested in reactor environments to enhance mechanistic understanding. This will include testing for irradiation damage and post-irradiation examination, environmentally-assisted degradation and high temperature creep and creep/fatigue
- ***Materials Modelling Development* -** Advanced modelling approaches, validated against experimental data, will be developed to simulate manufacturing processes and predict materials performance in normal and off-normal conditions. Models will build on a mechanistic understanding of materials behaviour in reactor environments
- ***Manufacturing Development and Test Facilities* -** A suite of new facilities, complementing those that already exist, will be developed to provide the materials testing and manufacturing infrastructure required. These will build on recent investment in materials examination, high temperature testing and nuclear fuels.

M2.1 Nuclear Component Manufacture Mechanisation and Automation

Some of the key challenges to introducing automated techniques to the manufacture of nuclear components are maintaining component quality levels and enabling codification of new techniques to nuclear standards. Advanced component manufacturing techniques such as electron beam welding, diode laser cladding and hot-isostatic pressing have the potential to provide UK industry with a competitive advantage in the international market place. The application of automated manufacturing techniques that are prevalent in other high-precision manufacturing sectors, such as aerospace and automotive, into nuclear component production require targeted R&D.

Automated component manufacturing will lead to a reduction in lead times and an increase in throughput. This will help achieve the economies required to make reactors, in particular SMRs, economically viable and attractive. UK owned IP in this area could be exploited across a wide range of applications and markets. The replacement of manual artisan manufacture can also lead to an increase in repeatability of manufacturing quality. This will reduce the number of rejected components (decreasing waste and enabling cost reduction) and will increase the overall quality and safety of the product. Specific requirements include:

- ***Performance Testing/Process Reliability and Robustness* -** Determine the performance of advanced and automated joining, forming, casting and machining techniques on nuclear components
- ***Automation Standardisation* -** Supporting investigations should be carried out that enables the subsequent use of codes and standards of these automated techniques, for example, establishing online monitoring and inspection regimes

M2.2 Large Scale Nuclear Component Manufacturing and Assembly

The challenges associated with the manufacture and assembly of large, complex, integrated nuclear components for SMRs and key components such as steam generators are complex and R&D will identify technical solutions to overcome these, including:

- ***Large-Scale Metrology -*** R&D will address the tolerance build-up across SMR modules during their assembly to gain an understanding of how this can be managed and techniques developed for the associated inspection. The ability to measure large assemblies quickly and accurately, such as coordinate measuring machines will be key enabling technologies
- ***Complex Machining of Large Scale Components -*** Research to address the challenges associated with precision machining of large scale components
- ***Integrated Unit Inspection -*** Inspection and measurement techniques, particularly Non-Destructive Examination (NDE) techniques that are less intrusive and rapid will be developed to enable inspections during and following the integration of large complex assemblies. Techniques such as advanced ultrasonics and radiography will help manage quality and demonstrate compliance with codes and standards
- ***Distortion Control and Mitigation*** **-** Developing techniques to control and mitigate distortion during the machining of large nuclear components such as SMR modules will be an enabler to manufacturing. Techniques from other industries, such as shipbuilding, will be assessed for their applicability in a nuclear manufacturing context.

M2.3 Assembly Process Flow Modelling

The increase in throughput required to underpin the economic case for SMRs will require both a reduction in manufacturing process cost and time but also a rethink in how assembly plants are sited, arranged and operated. Innovative large scale assembly and manufacturing solutions must be integrated with design to generate a cost effective manufacturing plant for large nuclear assemblies.

R&D will model and inform the design of new nuclear factories, particularly assembly plants to manufacture SMRs. Process flow modelling techniques, prevalent in automotive and aerospace construction and assembly, and the use of virtual reality will be applied to large (100 Tonne) and very large (1000 Tonne) scale nuclear module construction lines.

M3.1 Pre-Fabricated Module Development and Verification

This project area will develop solutions to enable off-site modular construction of significant elements of nuclear facilities. The outputs of this work will be aimed at increasing the certainty of the cost and programme for constructing nuclear facilities, reducing risk and strengthening the case for financial investment.

This work will address the challenges of manufacturing, transporting and installing modules of up to 1000 Tonnes in weight. Underpinning R&D and verification will develop large scale concrete plant modules. This will investigate the challenges associated with large pre-fabricated nuclear structures such as providing Loss Of Cooling Accident (LOCA) tight ability for containment boundaries. This will lead to developing solutions and the technical capability for modularisation of nuclear construction. This will include solutions for the off-site inspection and verification of critical to quality features within large modules to demonstrate compliance with the relevant standards and nuclear quality.

M3.2 Large Scale Module Transportation

This project area will determine strategies and solutions for the transportation and installation of large modules that are compatible with nuclear testing and verification regimes. Building new civil construction capabilities and capacity within the UK will support nuclear new build, SMRs and Gen-IV reactor programmes and major decommissioning activities. This work will be expected to generate background IP and facilities for the UK and will leverage technologies from the construction and shipbuilding industries into the nuclear sector.

21st Century Nuclear Manufacture Indicative Costs

Indicative costs for the R&D and innovation required to implement these recommendations is given in Table 3.

Table 3 21st Century Nuclear Manufacture Indicative Costs

	Title	2016-21 Cost / £m		
		Programme	**Capital**	**Total**
M1.1	New Nuclear Materials and Manufacturing Development	15.80	8.50	**24.30**
M2.1	Nuclear Component Manufacture Mechanisation and Automation	6.50	2.50	**9.00**
M2.2	Large Scale Nuclear Component Manufacturing and Assembly	9.00	0.50	**9.50**
M2.3	Assembly Process Flow Modelling	2.50	2.50	**5.00**
M3.1	Pre-fabricated Module Development and Verification	1.75	0.25	**2.00**
M3.2	Large Scale Module Transportation	1.75	0.25	**2.00**
	Total	**37.30**	**14.50**	**51.80**

Reactor Design:

Delivering the people, processes and tools to make the UK the partner of choice as the world designs SMRs and 4th generation nuclear power plants.

3.4 Reactor Design

The UK has a historic track record in the design and development of a range of civil reactors including fast reactors. Today the UK's reactor design expertise is largely restricted to the defence sector. With the development of SMRs and prototype Gen-IV reactors, engineering design is a high value proposition though knowledge and compliance with the relevant nuclear codes and standards presents a high barrier to entry. Companies that are at the cutting edge of front-end design of future nuclear systems and components will hold critical IP that can be exploited during product manufacture and in-service support for decades.

The development of a reactor system is a substantial undertaking and there is no suggestion that the UK should independently develop a new reactor design. The high level aim is to develop a capability in 'design for manufacturing and construction' that can collaborate with international parties in areas where the UK can grow and exploit expertise.

Reactor Design 2020 Vision

NIRAB's vision for the reactor design programme is by 2020 the UK will be capable of making a credible contribution to international collaborations in the design, construction and commissioning of reactors, in particular SMR and Gen-IV systems.

Using modern digital engineering design and verification capabilities UK companies will become the international partners of choice in the implementation of new reactor technologies worldwide. The UK currently generates significant revenue from its world class modelling and simulation capability and licencing of previously developed thermal hydraulics codes. Targeted research will allow UK companies to develop the next generation of these codes, expanding the UK's offering and maintaining a marketable resource base.

Innovative in-service inspection and support technologies will afford UK industry the access to the significant reactor in-service operation and maintenance market, estimated at £260m a year for a typical large reactor. Having a credible design for in-service capability with innovative products, services and technologies will present the UK with a route to collaboration in future reactors developments and the in-service market. There are opportunities for disruptive technologies to enter the market where they can deliver a significant increase in quality and safety or a reduction in cost or dose.

Reactor Design 2020 Objectives

R1 To develop the UK's reactor system and component design, analysis and verification capability

Over the next decade the opportunity exists for the UK to become an active member of the international teams designing and developing new nuclear power station designs including SMRs, micro-reactors, and large Gen-IV systems. This will require the development of reactor systems and component design capability, virtual engineering and prototyping, understanding and development of nuclear Codes and Standards for future systems, understanding coolant chemistry and re-establishing the UK's active knowledge base of its historic fast reactor programme. Building on existing expertise will develop the UK's design capabilities for nuclear systems and components with a focus on digital design techniques and systems engineering. By investing in a reactor design, analysis and verification capability, the UK can be at the forefront of delivering major collaborative nuclear engineering programmes including one of the first SMR builds in the world.

R2 To deliver the infrastructure and facilities needed to support the next generation reactor design, component performance and safety research

Design analysis and verification is an essential step in the development of any nuclear product, from the smallest component to a full reactor. Demonstrating correct operation during normal and fault conditions are of absolute importance. Analysis and verification is carried out through a range of techniques including computational modelling, simulation and validation testing. This area of nuclear engineering has always been strong in the UK, most notably the development of Computational Fluid Dynamics (CFD) codes and structural integrity procedures that have widespread global use.

In performing R&D to deliver a leading-edge capability in reactor design, performance and safety, the UK will contribute more effectively to the next generation of reactors enabling the supply chain to benefit from the worldwide surge in the development of new nuclear plant.

R3 To develop the UK's capability to provide nuclear consultancy and through life support services

Taking on the role of supplier of components for nuclear plants will give UK companies a competitive advantage in winning future long-term operation and maintenance contracts. This will cultivate the growing UK nuclear services sector and ensure it is capable of supporting the projected global expansion of nuclear power. Key to this will be a strong capability in nuclear security and safeguards, in-service inspection and repair including robotics, safety, and robust Control & Instrumentation (C&I) design.

For example, by 2020 structural health monitoring and simulation techniques should allow operators to better predict and plan maintenance during scheduled shutdowns. Introducing these technologies into the nuclear sector could have a significant impact on reducing nuclear operating costs.

Reactor Design Research

The recommended research project areas to deliver each of the 2020 objectives in Reactor Design area are presented in Figure 8 and described below.

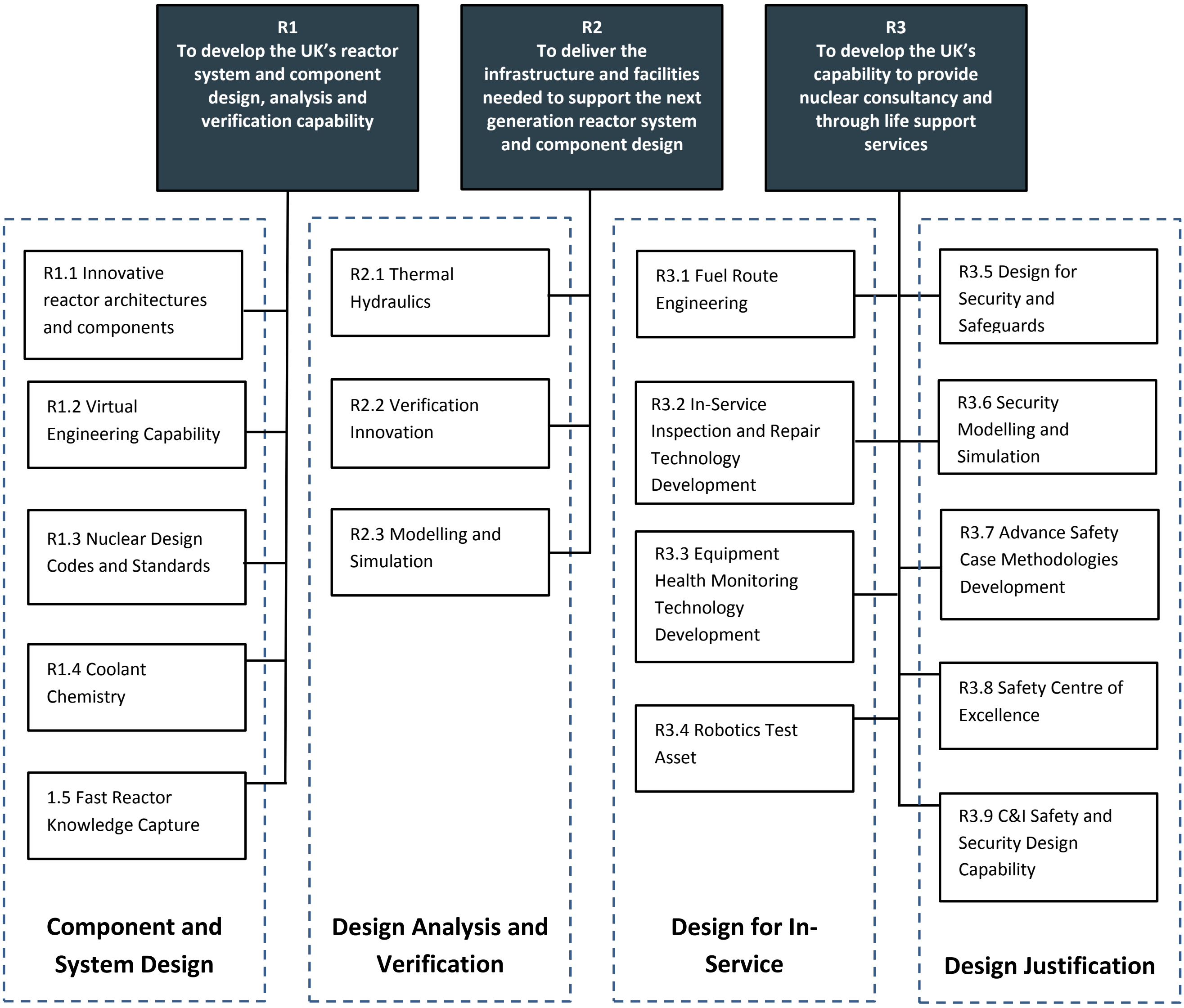

Figure 8 Reactor Design Project Breakdown

R1.1 Innovative Reactor Architectures and Components

A number of technical challenges will form the basis of an R&D programme to deliver innovative reactor architecture and components for SMRs and Gen-IV reactors. International programmes exist in these areas and the UK will engage via appropriate routes.

For SMRs the R&D priorities include:

- Accurately forecasting the behaviour of passive cooling and emergency systems
- Modelling and methods of manufacturing for integral steam generators which will be subjected to a different environment than external steam generators

For high temperature reactors the R&D priorities include:

- Direct and indirect cycles including reactor compatible turbine materials for the former and high temperature heat exchange materials and design for the latter
- Alternative power conversion systems (Brayton, supercritical CO_2)
- High temperature process heat take-off (and development of nuclear process applications).

For sodium-cooled reactors the R&D priorities include:

- Sodium-water heat exchangers (steam generators) that reduce the probability for sodium-water interaction in a SFR
- Sodium-gas heat exchangers and gas compatibility with sodium
- Mechanical pumps and large high-efficiency electrical pumps.

R1.2 Virtual Engineering Capability

Virtual engineering and its associated technologies are widespread across many other high-technology industries and bringing these into the nuclear sector will enhance design, increase productivity and deliver a step change in the way that nuclear design and development programmes are delivered.

The R&D requirement is to demonstrate how these technologies will be employed to deliver real benefits within the envelope of nuclear product development. Demonstration of the capabilities of virtual engineering and overcoming the challenges of implementing such technology in a security and safety led industry will be a catalyst to increase the widespread uptake of modern digital engineering practices within the nuclear industry. It will also be the first steps towards a broader UK capability in nuclear computing.

R1.3 Nuclear Design Codes and Standards

Nuclear codes and standards are a critical element in the design and development of nuclear products. The suite of international codes and standards that govern the design and manufacture of reactors are agreed internationally. The UK will engage to ensure that they best meet the requirements of the UK industry. This will be achieved through a combination of knowledge capture of the UK current capabilities, active materials and manufacturing R&D and UK membership of the relevant bodies responsible for the development and promulgation of codes and standards e.g. ASME. Specific R&D requirements include:

- ***Align UK Best Practice -*** Collecting and consolidating the international best practice of existing rules for the design, manufacture, construction, operation, decommissioning and disposal of components used in new reactors
- ***International Engagement -*** Engaging in international activities aimed at qualifying materials, such as engagement through the GIF, the Electric Power Research Institute (EPRI) or through European programmes, such as the current Joint Programme on Nuclear Materials.

The knowledge gained through this research will be used to develop the international codes and standards that will be used in the design and development of SMR and Gen-IV reactors.

R1.4 Coolant Chemistry

The material choices made for new components will be directly influenced by the environment to which these materials are to be exposed and coolant chemistry control is optimised to minimise material degradation, including corrosion, wear, stress corrosion cracking and environmentally-assisted fatigue. It is therefore strongly linked to the materials R&D proposed under topic M1. Specific R&D requirements include:

- ***PWR Materials Compatibility -*** Evaluate coolant chemistry/materials compatibility issues (including effects of radiation) relating to candidate water-cooled SMR designs and define necessary R&D to support opportunities for UK to contribute to future developments
- ***High Temperature Coolant Chemistry -*** Provide overview of primary coolant chemistry, materials compatibility and tribology issues associated with HTR systems in the context of current Gen-IV concept designs
- ***Gen-IV Coolant Chemistry -*** Provide guidance document on coolant chemistry, materials compatibility and tribology issues for all of the Gen-IV designs
- ***Molten Salt Chemistry -*** Carry out fundamental research on molten salts to both understand the practical challenges associated with molten salt reactor design and engineering and inform research on pyroprocessing
- ***Reactor Chemistry Development Programme -*** Identify and procure required facilities for a phased approach for a detailed R&D programme on and materials compatibility for candidate Gen-IV reactor and SMR systems.

R1.5 Fast Reactor Engineering Knowledge Capture

The UK has developed a wealth of knowledge on the design, manufacture, operation and decommissioning of sodium cooled fast reactors during the implementation of the Dounreay fast reactor projects from the 1960s to the present day. This knowledge is a valuable asset to the future development of Gen-IV reactors and much of the “front end” knowledge is now in danger of being lost through the retirement (in some cases many years ago) of key individuals. Carrying out a targeted knowledge capture from remaining available data and individuals will allow it to be organised and disseminated as appropriate to the UK industry, maximising its value.

R2.1 Thermal Hydraulics

Thermal hydraulics will be key to the overall system integration and design of reactor plants and it is important to build this capability now to position the UK to take advantage of nuclear new build, SMR deployment and Gen-IV reactor development.

Specific requirements to support a strong thermal hydraulics capability in the UK are:

- ***UK National Nuclear Thermal Hydraulic Facility -*** Delivering a national thermal hydraulic experimental facility to develop and validate new thermal hydraulic models. An experimental facility will be critical in underpinning the safety case for new reactor designs, including SMRs

- ***Model Development and Validation Programmes -*** Devising and implementing new thermal hydraulics models, able to accurately predict passive flows and regimes associated with SMRs and Gen-IV reactors will aid the design, development or evaluation of future reactor designs.

R2.2 Verification Innovation

The increased capability of computing technologies enables a step change in the approach to how verification testing is carried out within the nuclear sector. High Performance Computing (HPC) enables greater fidelity to be introduced to the key modelling techniques used in the development of reactor plants such as thermal hydraulics and physics modelling. The innovative application of the next generation of instrumentation and computing power to nuclear verification facilities will complement the system design and design verification capabilities.

Specific R&D requirements include:

- ***Improved Measurement Techniques -*** The validation of higher fidelity models will require an improvement in the measurement techniques available on the associated test rigs to measure temperatures, pressures and flows
- ***Verification 'Big Data' Management -*** Thermal hydraulics test rigs used to verify modelling behaviours will produce vast quantities of data. Innovation is required in the methods used to manage this 'big data' during the analysis and successful validation.

R2.3 Modelling and Simulation

Modern reactors are designed using a modelling process that relies on integrated design and assessment models to combine the various important phenomena in a single unified approach. Such integrated models can predict the whole system response to a range of internal and external initiating events. R&D is required to establish integrated models of future reactor systems in the UK. The following areas of R&D are required:

- ***Multi-Scale Structural Performance Modelling -*** Develop and validate multi-scale, multi-physics modelling of whole life structural performance of key reactor components
- ***Code Integration -*** Develop a capability to improve the fidelity of nuclear reactor simulations by integrating radiation modelling codes and CAD models of reactor

components. The capability will enable industry researchers to benchmark existing codes against a state-of-the art integrated software/hardware capability.

R3.1 Fuel Route Engineering and Interface with Core Mechanics

Fuel route engineering is an important area that is easily overlooked at the conceptual design stage of a reactor. The operability and reliability of the fuel route impinges directly on the economic performance of the reactor.

This project area will develop understanding of the mechanical behaviour of the cores of SMRs and Gen-IV reactors (VHTRs/SFRs). This will be used to develop innovative concepts for potential refuelling systems to optimise the economics in terms of trade-off between capital cost and outage duration, whilst being cognisant of the core mechanical behaviour, safety and operator dose. Engineering solutions that turn refuelling in a simple routine operation will provide improved plant capacity factors that will lead to an improvement in the overall economics of reactors.

R3.2 In-Service Inspection and Repair Technologies

In-service inspection and repair is a large part of the on-going operation and maintenance costs for large reactors. This supports many aspects of the safety case and can impact greatly on the economics of the plant. R&D will develop new inspection and repair technologies to put the UK at the forefront of this market and become a key player in future collaboration. These technologies also have a number of applications in the nuclear decommissioning and waste management field and development can be shared across this sector. Solutions are required that cover three different areas within this field:

- ***Sensors -*** Technologies that can detect and measure the physical environment and relay this information to an operator or autonomous system
- ***Positioning Systems -*** Robotic or manipulator systems are used to remotely position inspection sensors or repair tools where they are needed within the reactor building or within larger reactor components
- ***Repair Toolset -*** Tools to carry out maintenance or repair for example welding, scoop sampling, cutting and debris capture and removal.

R3.3 Equipment Heath Monitoring

Equipment Health Monitoring (EHM) is prevalent in many industries, including nuclear, to monitor changes in a system or equipment behaviour that may be the early warning signs of problems with equipment performance or health. Software can be configured to notify plant personnel of detected problems allowing for diagnosis and repair prior to failure.

EHM can be separated into two fields, equipment for sensing parameters on the plant, for example acoustic or vibration monitoring, and the analysis of the signals that determines the health of the equipment under test. Innovation is required to adapt sensing technologies for use within the nuclear sector and specific health analysis technologies to position UK at the forefront of this market and become a key player in future reactor development collaborations.

Developing a capability to characterise the equipment in nuclear plants will be significant in enabling the widespread uptake of EHM within the nuclear industry. This programme will develop valuable IP and solutions from industry will highlight the UK as a route to collaboration in future reactors developments and the in-service market.

R3.4 Robotics Test Asset

Several parts of the fuel cycle already make use of and will need in the future to make use of remote handling and robotics systems; it is a candidate for future in situ inspections of radioactive plants. The Robotics and Autonomous Systems Special Interest Group is a cross sector industrial initiative set up by Innovate UK and is developing a national strategy for the advancement and application of modern robotics technologies. The nuclear industry is a member of this group, providing the experience and expertise of operating robotics in harsh environments and the requirements of high integrity systems.

To support the full development and commercialisation of robotic technology within the nuclear sector a nuclear focussed asset is required that can be used to test the operation and performance of candidate technologies. Developing an asset at a nuclear licensed site will give developers a training ground that will present some of the challenges faced in providing robotic products into such locations. This will include some of the environments challenges as well as the administrative barriers and safeguards.

R3.5 Reactor Design for Security and Safeguards

Nuclear safety has always been an integral part of the design process for nuclear power plants, however, nuclear security and safeguards requirements have historically been treated as "bolt-on" activities and not treated as a fundamental part of the design. Including the nuclear security requirements into the design of nuclear facilities is becoming a more recognized approach that will ensure that the future nuclear safety, nuclear security and safeguards are optimized in facility design, but will also deliver the skills to allow the UK to maintain its ability to be an intelligent customer for the import of foreign technologies.

A research programme is required to look at how nuclear safety, nuclear security and safeguards requirements can be delivered through the design process and the potential to develop a new approach to design substantiation for an integrated safety case.

The outcome of this research programme could be a better understanding of:
- How nuclear security requirements can be delivered through the design process
- The implications of optimizing nuclear safety, nuclear security and safeguards in relation to overall risk to the workers and the public
- How the traditional "safety case" can be expanded to substantiate a design in relation to nuclear safety, nuclear security and safeguards requirements.

R3.6 Security Modelling and Simulation Assessment Methodologies

Modelling and simulation has been the traditional approach to the evaluation of nuclear safety performance during both the design and operation of nuclear facilities. The modelling and simulation of nuclear security performance is in its infancy. There is a requirement to develop new approaches and tools that can help both designers, operators, the armed guard force and the regulators evaluate the effectiveness of nuclear security measures including design approaches, operator actions, and the human performance of intruders, insiders and armed guard force personnel.

R3.7 Advanced Safety Case Methodologies

The overall structure and format for a modern standard safety case are now well established within the UK. The individual methods for generating both numerical and non-numerical elements of the safety case present opportunities for improvement and advancement to provide the UK a competitive edge.

A programme of safety engineering led R&D will provide a tool kit of advanced safety case techniques and methodologies that can deliver cost effective safety cases. Specific opportunities are:

- Treatments of uncertainties in Probabilistic Safety Analysis (PSA)
- Natural hazards into PSA
- Human reliability and its incorporation into PSA
- Failure data acquisition and exploitation
- Severe accidents analysis
- Passive systems

R3.8 Safety Centre of Excellence

Delivering new safety case methodologies is only part of the picture when building a world-leading UK capability for safety case consultancy. Developing skills, experience and expertise in safety case production is equally important. NIRAB recommend that a group is proactively brought together that can be used to deliver the Advanced Safety Case Methodologies research and help embed these new methodologies with the UK industry.

This group should begin as a Safety Engineering knowledge network including academic, national laboratory, industry and regulatory expertise, which can facilitate greater communication and collaboration in the safety engineering community across different industries. This group will be used to deliver R&D on the capabilities of safety assessment application in the UK and that of overseas competitors, to provide a well-informed understanding of the UK's opportunities in advanced systems (such as SFR, HTR and SMRs).

R3.9 C&I Safety and Security Design Capability

The use of programmable electronics should be considered for all aspects of control and instrumentation (C&I) for new nuclear plants. The increased functionality that is capable by using programmable C&I systems can also open up new possibilities to better support the operation and maintenance activities in the plant. The challenge for the nuclear industry is to develop a framework to allow successful regulation of these technologies for implementation within nuclear plants. To build the UK's capability research is required in the following areas:

- ***C&I Safety Process -*** R&D is required to develop an approach to providing a safety justification for programmable C&I systems that will meet the expectations of global regulators. This must meet the requirements for new nuclear build
- ***Software Reliability -*** R&D is required to identify best practice worldwide in the incorporation of the reliability of software in safety assessments
- ***C&I Test Facilities -*** A laboratory environment is required to provide support to C&I integrity testing. This will comprise a virtual reactor simulator with which to investigate human factors and behavioural phenomena, together with a sensors/component/firmware statistical testing facility incorporating a high-performance workstation for software integrity testing
- ***C&I Security -*** Programmable C&I technology brings with it a number of potential security threats. Understanding these and being able to provide defence against them is critical to the advancement of programmable C&I technologies within nuclear facilities. R&D is required to identify methodologies for managing C&I security and specifically their interactions with safety systems (i.e. safety vs security).

Reactor Design Indicative Costs

Indicative costs to deliver the Reactor Design project are given in Table 4.

Table 4 Reactor Design Indicative Costs

	Title	2016-21 Cost / £m		
		Programme	Capital	Total
R1.1	Innovative Reactor Architectures and Components	2.50	-	**2.50**
R1.2	Virtual Engineering Capability	4.50	1.50	**6.00**
R1.3	Nuclear Design Codes and Standards	1.00	-	**1.00**
R1.4	Coolant Chemistry	6.50	3.00	**9.50**
R1.5	Fast Reactor Engineering Knowledge Capture	0.50	-	**0.50**
R2.1	Thermal Hydraulics	15.50	26.00	**41.50**
R2.2	Verification Innovation	0.50	-	**0.50**
R2.3	Modelling and Simulation	0.50	0.15	**0.65**
R3.1	Fuel Route Engineering and Interface with Core Mechanics	0.35	-	**0.35**
R3.2	In-Service Inspection and Repair Technologies	1.50	1.50	**3.00**
R3.3	Robotics Test Asset	0.50	-	**0.50**
R3.4	Equipment Heath Monitoring	1.00	0.50	**1.50**
R3.5	Reactor Design for Security and Safeguards	0.75	-	**0.75**
R3.6	Security Modelling and Simulation Assessment Methodologies	0.25	0.15	**0.40**
R3.7	Advanced Safety Case Methodologies	1.15	-	**1.15**
R3.8	Safety Centre of Excellence	0.90	-	**0.90**
R3.9	C&I Safety and Security Design Capability	2.35	0.50	**2.85**
	Total	**40.25**	**33.3**	**73.55**

Recycling Fuel for Future Reactors:

Cost effective technologies to deliver a secure and sustainable low carbon fuel supply.

3.5 Recycling Fuel for Future Reactors

The UK is one of the very few countries to have reprocessed irradiated fuels from thermal and fast civil reactors on an industrial scale and the UK has world-leading understanding of spent fuel recycling technologies, built up over decades of R&D and operations. Spent fuel recycling is an essential component of a closed fuel cycle, particularly in scenarios that include fast reactors. In such scenarios fuel from thermal reactors is recycled to provide the initial fast reactor fuel and fast reactor fuel is recycled throughout the life of the reactor. To support future energy scenarios, including a bounding case of delivering up to 50GWe, it remains possible that the UK will need to operate a closed fuel cycle, resuming large scale fuel reprocessing by the middle of this century.

However, industrial-scale reprocessing activities are due to cease with the closure of the THORP reprocessing facilities circa 2018 and Magnox reprocessing circa 2020. The UK will still have the understanding and R&D laboratories on nuclear licensed sites that are capable of supporting the full breadth of recycle development as well as an academic research base. This cessation of spent fuel reprocessing poses a risk that the UK will lose its internationally respected spent fuel reprocessing skills and capability in recycling. This is against a global backdrop of opportunities to develop transformative recycling technologies that can be deployed mid-century in the UK or internationally. These skills and facilities are a valuable national asset that the UK should safeguard until the medium-term role of spent fuel recycling in the UK fuel cycle is clear.

Recycling Fuel for Future Reactors 2020 Vision

NIRAB's vision for the recycle and waste management programme is for the UK to sustain its capability to design, develop and commercialise innovative spent nuclear fuel recycle technologies with demonstrable radical improvements in economics, proliferation resistance, waste generation and environmental impact. Research will build upon the UK industry's capabilities in these areas to service a growing global nuclear market and provide complementary waste management techniques for new fuel technologies.

This programme has the potential to create commercial opportunities for UK companies in the global recycling market and maintain the UK's position as a 'top-table nation' in spent fuel reprocessing.

It is imperative that the research activity in this area aligns closely with the NDA's strategies and on-going work programme.

Recycling Fuel for Future Reactors 2020 Objectives

E1 To demonstrate a safe, economic, efficient and proliferation resistant aqueous LWR fuel recycle technology at laboratory scale using active experiments

By 2020 the UK should demonstrate reprocessing technologies with substantially improved proliferation resistance, waste minimisation, environmental performance and economics compared with existing spent fuel recycling processes. The development of an R&D programme in this area will maintain and strengthen reprocessing as a cost competitive option for managing spent fuel from the new build fleet. This will include the development of flexible flow-sheets that can reprocess mixed oxide as well as uranium oxide fuels.

E2 To demonstrate components of a fast reactor fuel pyroprocessing recycle technology inactively at laboratory scale

Molten salts and electrometallurgical treatments can be used to reprocess fuels for which aqueous processing may not be appropriate. Development of pyroprocessing may bring significant benefits: opening up alternative fuel cycle options, including molten-salt reactors or integral fast reactor island sites in which a metal-fuelled fast reactor and pyroprocessing facility are integrated on the same site.

The UK has the capability to modernise this approach, building upon our history of fast reactor recycling, to deliver innovative yet industrially deployable processes that are suited to the unique characteristics of fast reactor fuel recycling. The UK will then be well placed to exploit new markets in Gen-IV systems that could develop in the mid-21st century and ensure that safe and proliferation resistant fuel cycles are adopted as international best practice.

E3 To demonstrate effective waste immobilisation technologies for the waste forms generated by advanced fuel and recycling technologies

Recycling offers the potential to reduce future high level waste volumes, the heat loading in a repository and the time over which the waste must be isolated significantly reducing the size and complexity of a geological disposal facility and having a positive impact on public acceptability. In the case of an expanded UK nuclear new build programme, recycling may be an essential requirement to manage the burden of geological disposal.

This R&D will demonstrate that the wastes arising from future fuel cycles can be managed safely and effectively. This will include minimisation at source as well as proving that new waste streams can be treated such that discharges and emissions will comply with future regulatory requirements and that each segregated waste stream can be effectively immobilised into a durable waste form for geological disposal. Integrated approaches will be followed so that the waste management infrastructure can be minimised and thus the costs of waste management will not be a “show stopper” to deployment of future recycle technologies.

E4 To deliver the infrastructure and facilities needed to develop advanced recycling technology

Maintaining expertise through a programme of cutting edge research will ensure that the UK has the information necessary to inform policy on whether closing the fuel cycle and deploying fast reactors makes economic and strategic sense. Without investment the UK could lose this decision-making capability in the next five years. The R&D will build on existing internationally-recognised expertise in spent fuel recycle to position the UK as a world leader and train the next generation of subject matter experts to ensure the continuity of knowledge and skills. Critical to delivering future R&D programmes will be the establishment of new facilities to supplement the UK's existing laboratory capability.

Recycling Fuel for Future Reactors Research

The recommended research project areas to deliver each of the 2020 objectives in the Recycling Fuel for Future Reactors programme are presented in Figure 9 and described below.

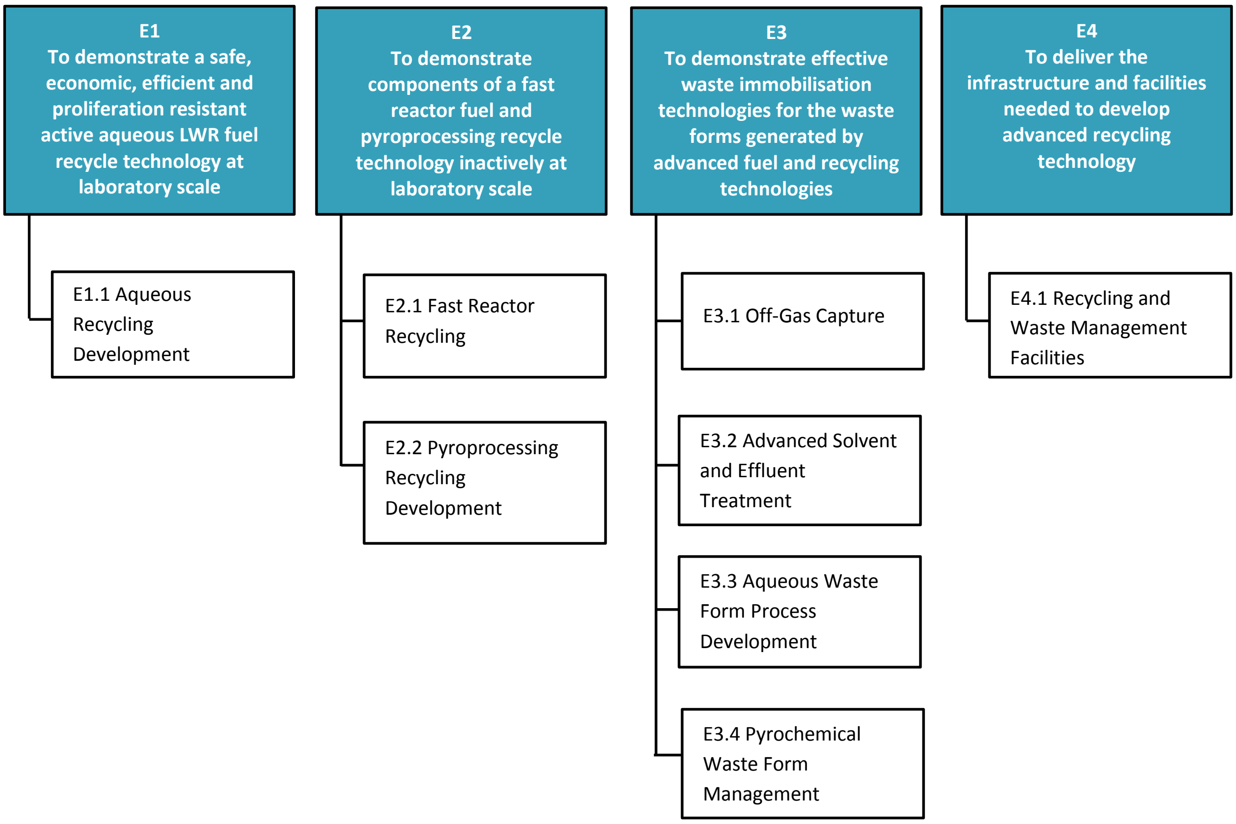

Figure 9 Recycling Fuel for Future Reactors Project Breakdown

E1.1 Aqueous Recycling

An evolution of the current PUREX process is required to address proliferation concerns and improve the overall economics of operation, making it commercially attractive. The conventional PUREX process, as used at Sellafield, generates separate high purity uranium and plutonium streams as well as significant quantities of wastes. The objective of this project area is to demonstrate a process which does not produce such high purity fissile materials. The R&D programme will complete "end to end" laboratory scale testing of a process that achieves demonstrable and substantial improvements in economics, is proliferation resistant and reduces the wastes generated/environmental impact at source.

These tests will use kilogram quantities of spent fuel and capital investment will be needed to set up the Highly Active facilities required.

E2.1 Fast Reactor Fuel Recycling

Whilst the aqueous based technologies used for recycling LWR fuel can be used for the recycling of fast reactor fuels there are some specific challenges that need to be addressed; notably the high plutonium contents, high radiation levels and heat generation.

This project area will test and commercialise an innovative flowsheet for fast reactor fuel recycling, demonstrating scenarios under which aqueous reprocessing is a competitive, proliferation resistant and safe technology. A recycle process based on the GANEX process will be developed to recycle uranium, plutonium and minor actinides for burning in fast reactors. The R&D will fully explore the fundamental chemistry and design flowsheet options using advanced process modelling and simulation tools. This will be followed by testing of the flowsheet options at a laboratory scale using realistic quantities of nuclear materials and radiation sources to define the operational envelope of the GANEX process and hence the future fuel cycle scenarios in which it could be deployed. There are clear opportunities to collaborate internationally and leverage funding in this area.

E2.2 Pyroprocessing Recycling

Dry reprocessing technologies potentially offer a step change in approach with some advantages for some fuel types or fuel cycle scenarios. Of the dry processes that have been proposed, pyroprocessing in molten salts is the leading choice worldwide as the main alternative to aqueous processing. In particular, pyroprocessing of metal fuels from fast reactors using electro-refining techniques are the most heavily investigated (USA, Japan, and South Korea) and are being demonstrated for uranium recovery at pilot scale at the Idaho National Laboratory.

This project area will enable the UK to understand under which specific scenarios advanced fuel cycles with pyroprocessing could be advantageously deployed in the UK. To reach this objective, R&D will regenerate its capability in pyroprocessing to produce flowsheets for key stages of the processes and to use its process engineering experience to show how it can be deployed at industrial scales.

E3.1 Off-Gas Capture

This project area will develop and demonstrate an integrated off-gas capture process to entrain iodine species, carbon-14, tritium and semi-volatile fission products proposing enhanced processes relevant to aqueous recycle.

E3.2 Advanced Solvent and Effluent Treatment

This project area will develop a suite of interconnected processes for the management of medium active liquid effluents, including solvents, arising from new recycling techniques.

This will include demonstration of the achievable decontamination factors and estimates of the bulk compositions, radioactive inventories and volumes of the various waste streams.

E3.3 Aqueous Waste Form Process Development

This project area will develop waste management processes for the various wastes arising from aqueous flowsheets. This is likely to involve the development of robust waste forms such as glasses or glass-ceramic. The purpose of the work in all cases will be to demonstrate the feasibility of immobilising each waste stream in a durable and heat and radiation tolerant product at a high waste loading. Treatment and immobilisation of HA wastes from HA tests of aqueous reprocessing flowsheets will demonstrate the technology under realistic environments.

E3.4 Pyrochemical Waste Form Management

This project area will develop new processes to manage new wastes loaded with fission products and salts arising from pyroprocessing recycling techniques. These processes will produce waste products suitable for disposal.

E4.1 Recycling and Waste Management Facilities

A recycle R&D programme will need access to a range of active facilities from state-of-the-art chemical analysis for studying the fundamental separation science to laboratory scale process flowsheet development to engineering scale uranium-active testing. Whilst most studies require alpha-active facilities, demonstration tests of processes with spent fuels will require access to HA cells. Building on initial Government funding for the UTGARD (Uranium & Thorium beta-Gamma Active R&D) laboratory at the University of Lancaster, the MIDAS (Materials for Innovative Disposition from Advanced Separations) facility at the University of Sheffield and a Pyroprocessing Research Laboratory at the University of Edinburgh, as well as the existing PuMA (Plutonium & Minor Actinides) facility at NNL, the UK should develop a networked series of world class recycle and waste management research facilities that will provide a focal point to attract inward investment, realise new business opportunities and international collaboration.

Recycling Fuel for Future Reactors Indicative Costs

Indicative costs to deliver the Recycling Fuel for Future Reactor project are given in Table 5.

Table 5 Recycling Fuel for Future Reactors Indicative Costs

	Title	2016-21 Cost /£m		
		Programme	Capital	Total
E1.1	Aqueous Recycling	10.00	9.00	**19.00**
E2.1	Fast Reactor Fuel Recycling	6.00	1.00	**7.00**
E2.2	Pyroprocessing	6.40	2.00	**8.40**
E3.1	Off-gas capture	7.50	1.50	**9.00**
E3.2	Advanced Solvent and Effluent Treatment	2.00	1.00	**3.00**
E3.3	Aqueous Waste Form Process Development	8.00	2.00	**10.00**
E3.4	Pyrochemical Waste Form Management	8.00	1.00	**9.00**
E4.1	Recycling and Waste Management Facilities	-	10.00	**10.00**
	Total	**47.90**	**27.50**	**75.40**

4. Contributors

This list indicates the individuals that have supported NIRAB in the development of these R&D recommendations.

Andrew Carlick - DBD Ltd
Andrew McFarlane - Atkins
Andrew Mount - University of Edinburgh
Andrew Sherry - National Nuclear Laboratory
Barry Lennox - University of Manchester
Bill Lee - Imperial College London
Bruce Hanson - University of Leeds
Cherry Tweed - RWM ltd
Chris Grosvenor - NNUF
Chris Moore - National Nuclear Laboratory
Colin Boxall - Lancaster University
Dan Mathers - National Nuclear Laboratory
Danny Fox - NDA
Darrell Morris - NDA
Dave Cummings - DBD Ltd
David Tice - AMEC Foster Wheeler
Eann Patterson - University of Liverpool
Francis Livens - Dalton Nuclear Institute
George Andrews - Ansaldo NES
Greg Willetts - AMEC Foster Wheeler
Gregg Butler - IDM Ltd
Ian Jackson - National Nuclear Laboratory
James Marrow - University of Oxford
John Eldridge - Cammell Laird
John Hurst - Atkins
John Lillington - AMEC Foster Wheeler
John Molyneux - Rolls-Royce plc
Karen Russ - AMEC Foster Wheeler
Kevin Hesketh - National Nuclear Laboratory
Laurence Williams - CoRWM
Malcolm Joyce - Lancaster University
Manus O'Donnell - EDF Energy
Martin O'Brien - Culham Centre for Fusion Energy
Matt Eaton - Imperial College London
Melanie Brownridge - NDA
Mick Gornall - Westinghouse
Mike Angus - National Nuclear Laboratory
Mike Middleton - Energy Technology Institute
Mike Tynan - NAMRC
Neil Bateman - EPSRC
Neil Hyatt - University of Sheffield
Neil Irvine - University of Manchester
Neil Smart - Sellafield Ltd
Neil Thomson - EDF Energy
Nigel Hart - Rolls-Royce plc
Paul Collings - National Nuclear Laboratory
Paul Harding - URENCO
Paul Stein - Rolls-Royce plc
Peter Wylie - Sellafield Ltd
Phil Cartwright - Laing O'Rourke
Robin Grimes - Imperial College London
Richard Clegg - Lloyds Register
Richard Stainsby - National Nuclear Laboratory
Richard Swinburn - Rolls-Royce plc
Richard Taylor - National Nuclear Laboratory
Rob Buckingham - UKAEA
Robin Taylor - National Nuclear Laboratory
Simon Walker - Imperial College London
Steve Cowley - Culham Centre for Fusion Energy
Tim Abram - University of Manchester
Vince Middleton - Newburgh Engineering

5. Glossary

ABWR	Advanced Boiling Water Reactor
AGR	Advanced Gas-Cooled Reactor
ATF	Accident Tolerant Fuels
C&I	Control and Instrumentation
CMM	Coordinate Measurement Machining
DECC	Department of Energy and Climate Change
EPSRC	Engineering and Physical Sciences Research Council
ETI	Energy Technology Institute
GANEX	Group Actinide Extraction
GDF	Geological Disposal Facility
Gen-III	Third generation of reactor design
Gen-III+	Evolution of third generation of reactors
Gen-IV	Fourth Generation of Reactors
GFA	Generic Feasibility Assessment
GIF	Generation-IV International Forum
HA	Highly Active
HPC	High Performance Computing
HTR	High Temperature Reactor
IP	Intellectual Property
LCICG	Low Carbon Innovation Coordination Group
LOCA	Loss of Coolant Accident
LWR	Light Water Reactor
MOX	Mixed Oxide
NAMRC	Nuclear Advanced Manufacturing Research Centre
NDE	Non-Destructive Examination
NFCE	Nuclear Fuel Centre of Excellence
NIRAB	Nuclear Innovation and Research Advisory Board
NIRO	Nuclear Innovation and Research Office
NIS	Nuclear Industrial Strategy
NNL	National Nuclear Laboratory
NNUF	National Nuclear Users Facility
NNUMAN	New Nuclear Manufacturing
OECD	Organisation for Economic Cooperation and Development
PSA	Probabilistic Safety Assessment
PuMA	Plutonium and Minor Actinides
PUREX	Plutonium Uranium Redox Extraction
PWR	Pressurised Water Reactor
R&D	Research and Development
SFR	Sodium-Cooled Fast Reactor
SME	Small and Medium Sized Enterprises
SMR	Small Modular Reactors
TINA	Technology and Innovation Needs Assessment
VHTR	Very High Temperature Reactor

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Further information about NIRAB is available at:
www.nirab.org.uk

Any enquiries about this report should be addressed to:
info@niro.org.uk

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