HM Government

Nuclear Energy Research and Development Roadmap: Future Pathways

Executive Summary

Introduction

Successive UK Governments have declared secure, low carbon, affordable energy as a long term objective. Various legislative instruments and mechanisms have been put in place over the last decade to facilitate delivery of this objective, including the Climate Change Act (2008) and, more recently, Electricity Market Reform (2011 White Paper).

There will be many challenges associated with the potential future deployment of nuclear energy in the UK's energy mix on a long-term timescale. Studies carried out over the last decade, both within Government and the Learned Societies, include consideration of futures with a nuclear contribution to electricity generation capacity of up to 75 gigawatts (GW) by around the middle of the 21st century; they also include scenarios with much lower contributions from nuclear energy.

The potential growth of the nuclear sector in the UK will not be driven by technology alone. A complex mix of Government policy, relative cost of nuclear power, market decisions and public opinion will influence the rate and direction of growth in the decades to come. It is this level of unpredictability that obliges Government to keep a wide range of technological options open for the future and therefore to maintain an agile and flexible Research and Development (R&D) capability.

The aim of carrying out nuclear R&D programmes is to ensure that the UK is able to make informed decisions on future nuclear options. This includes having the capability and capacity to expand or contract the contribution of nuclear energy if required, realise industrial benefits, develop and exploit intellectual property (IP) internationally, and be seen as a credible international partner, which may include hosting international facilities.

Approach

This UK Nuclear Energy R&D Roadmap (the 'Roadmap') sets out the research outcomes which would support implementation of future technology pathways. Detailed illustrative timelines have been developed as examples of these pathways. Actual pathways will be based on an integrated combination of baseline, open fuel cycle and/or closed fuel cycle pathways. All projected dates on the timelines should be treated as indicative. These three pathways are described below followed by the figure which summarises the nuclear energy technology pathway options.

Baseline Pathway

The Baseline Pathway involves operating the existing reactor fleet for the remainder of its life, the justification of lifetime extensions (where appropriate), the decommissioning and clean-up of all of the civil nuclear licensed sites in the UK and the implementation of geological disposal of higher activity radioactive wastes.

A significant programme of R&D will be required to deliver this pathway. The accountabilities for completing the decommissioning, clean-up and geological disposal programmes are already clear, but the associated research programmes will be challenging to complete.

The Baseline Pathway represents the current status quo, and *excludes* delivery of the current plans for 16 GW of new nuclear build capacity by 2025. The delivery of the current fusion R&D programme is present in the Baseline Pathway.

Open Fuel Cycle Pathway

An open fuel cycle is one in which fuel is fabricated, loaded into a reactor to generate power and subsequently stored, possibly for many decades, pending geological disposal. A proportion of the fissile material remains in the spent fuel at the point of discharge from the reactor. An open fuel cycle has a relatively high demand for fresh supplies of fissile material.

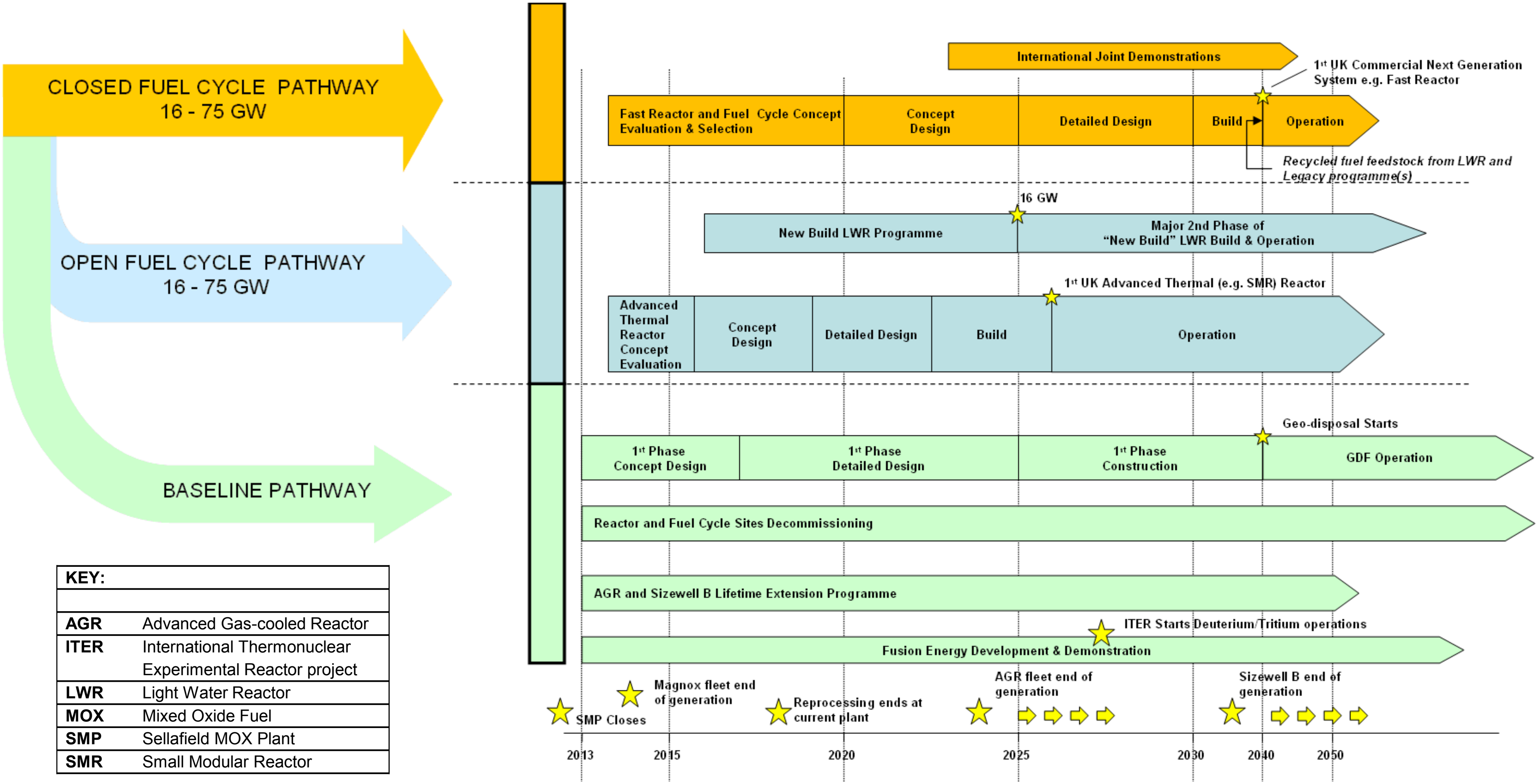
This pathway *includes* delivery of the current plans for 16 GW of new nuclear build capacity by 2025. In practice the bounding case for this pathway involves the construction of a series of reactor units with a combined installed capacity of up to 75 GW by the middle of the 21st century. This pathway includes the elements of the Baseline Pathway.

(Transition to) Closed Fuel Cycle Pathway

In a closed fuel cycle the spent nuclear fuel is treated to recover and recycle fissile material which has potential to generate further power. In some fuel cycles, options also exist to incorporate some of the long lived actinides into fuel, thus reducing the disposal challenge. Closing the fuel cycle beyond the middle of the 21st century reduces the requirement for fresh fissile material. The transition to a closed fuel cycle would not be immediate and would need to be phased in accordance with the development of advanced technologies e.g. fast reactors and advanced reprocessing methods.

This pathway *includes* delivery of the current plans for 16 GW of new nuclear build capacity on an open fuel cycle basis by 2025. In practice the bounding case for this pathway involves the construction of a series of reactor units with a combined installed capacity of up to 75 GW by the middle of the 21st century. This pathway includes the elements of the Baseline Pathway.

Nuclear Energy Technology Pathway Options



KEY:	
AGR	Advanced Gas-cooled Reactor
ITER	International Thermonuclear Experimental Reactor project
LWR	Light Water Reactor
MOX	Mixed Oxide Fuel
SMP	Sellafield MOX Plant
SMR	Small Modular Reactor

Questions

Decisions on nuclear policy in the near future range from broad policy decisions to specific choices of technologies. These will include, but will not be limited to:

- Should there be an increasing level of power generation from nuclear fission?
- Should an open fuel cycle be adopted, or would a closed fuel cycle be more appropriate?
- What should the mix of power generation from thermal power reactors and fast reactors be?
- Does a thorium fuel cycle offer strategic benefits to the UK?
- How and when could nuclear fusion technology be commercially deployed?

Actions

Evidence needs to be produced before decisions on future technologies (e.g. open vs. closed fuel cycles) can be made on an informed basis, and at the appropriate time, to ensure that nuclear energy pathway options are not inadvertently foreclosed. This Roadmap sets out the R&D programmes necessary to provide the required evidence base.

Coordination of these R&D programmes will require the UK to take measures such as:

- Strengthening facilities required to undertake R&D programmes on radioactive systems;
- Maintaining and developing the high-level skills base across these areas; and
- Collaborating internationally to leverage funding, influence international developments and capture IP for exploitation.

This Roadmap identifies near-term actions to enable informed technology choices, and to maintain the capability to deliver specific technology options. The most immediate actions are detailed below. These should be undertaken before the end of 2014 to meet specific needs and avoid missed opportunities.

Coordination

Need or Opportunity

The development of an integrated national nuclear energy R&D programme that provides evidence to inform future strategic decisions and technical capability needs to be guided by a new UK nuclear energy R&D coordinating mechanism. One of the first tasks for this mechanism should be to determine the detailed methodology by which the national R&D programme will be developed, building on the high level considerations presented in this Roadmap.

Enabling Actions

1. Establish a new UK nuclear energy R&D coordinating mechanism; and
2. Implement a start-up project for the new national nuclear energy R&D programmes.

National R&D Capability: Organisational Infrastructure

Need or Opportunity

Nuclear research requires specialist facilities and expertise to support work with radioactive and nuclear materials, and with ionising radiation. The UK already has significant capability to support such research but it is fragmented and not well focused on the needs of UK business.

The research facilities required to develop knowledge, promote innovation, build skills and deliver positive business impact from both fission and fusion research programmes need to enable research with both non-radioactive and radioactive samples from the laboratory, through pilot programmes, to the industrial scale.

The translation of research through development to deployment requires an integrated capability that connects together universities, national laboratories, and the end-users of nuclear technology.

Enabling Actions

1. Develop a longer-term mission for the National Nuclear Laboratory (NNL), coupled with changes to its remit to ensure responsiveness to the new nuclear strategy;
2. Establish organisational infrastructure (a ‘National Nuclear User Facility’ (NNUF)) to ensure access to key active research facilities, equipment and materials for the wider nuclear research community; and
3. Continue to support existing initiatives (such as the Nuclear Advanced Manufacturing Research Centre (NAMRC)).

National R&D Capability: Skills and Knowledge

Need or Opportunity

Research programmes are required to maintain the overall nuclear fission skills base, to provide a framework to develop and maintain subject matter expertise and to provide underpinning evidence to support strategic and technical decision making.

Enabling Actions

1. Establish an integrating body to oversee a national nuclear R&D skills strategy to be delivered by NNL, academia and the National Skills Academy for Nuclear (NSAN); and
2. Implement a feasibility study to develop an industry-wide Knowledge Management system building on the Nuclear Decommissioning Authority’s (NDA) Knowledge Hub.

International Collaboration

Need or Opportunity

International collaboration will be essential to the development of advanced reactors and the associated fuel cycle facilities. Several countries are active in these fields, including the US, France, Japan and South Korea. The UK will need to develop credible national R&D programmes where it wishes to participate in international R&D collaboration.

Enabling Actions

1. Department for Business, Innovation and Skills, and Foreign and Commonwealth Office networks to implement the nuclear energy R&D strategy overseas with clear objectives;
2. Increase UK involvement through programme participation in the Generation IV International Forum (GIF);
3. Develop a plan to optimise influence and participation in Euratom R&D programmes, including identification of demonstrator facilities that might be attractive for the UK to host;
4. Continue involvement in the International Thermonuclear Experimental Reactor (ITER) project through R&D contributions to position UK industry for a substantial share of the future fusion economy; and
5. Define clear objectives for bilateral relationships with, for example:
    a. The US - for Small Modular Reactor (SMR) and advanced fuel cycles opportunities and decommissioning.
    b. France - for its ASTRID sodium fast reactor and the Jules Horowitz Reactor (JHR) materials test reactor consortium; future fuel cycles, decommissioning and geological disposal.
    c. South Korea – for Generation IV fast reactors and advanced reprocessing; predominantly a business/economic opportunity.
    d. Saudi Arabia, Malaysia – examples of emerging nuclear markets with business opportunities.
    e. Japan – potential links on decommissioning, new build, Generation IV, and advanced fuel cycles.

Impact

Details of the decisions associated with the above actions, and their impact, are shown in the table below. These decisions fall under the thematic areas: reactor systems, fuel fabrication, and spent fuel recycling. The aim is to generate the information needed to inform strategic decisions on nuclear energy and to ensure that the UK remains capable of implementing the decision outcomes. The research programme will need to be modified in the light of such decisions.

Impact of decisions (2013 – 2016) to retain technology options

Decision	Date	Theme	Fuel Cycle Closed	Fuel Cycle Open	Assumption	Potential Consequence (of not making decision)	Opportunity
UK to resume active participation in the Generation IV International Forum.	2014	Next Generation Reactors, including Fast Reactor	✓	✓	First commercial UK next generation reactor could be operational in 2040.	Delay in international collaboration leading to delays in eventual implementation. Pursuing next generation reactors without collaboration could have cost implications. Not pursuing fast reactors could constrain future energy options.	Collaboration will give influence on international programmes. Opportunity to create and exploit IP. Builds on existing expertise. Hosting a demonstrator could bring revenue into the UK.
Extend capability to independently and authoritatively evaluate and regulate additional Gen III / III+ and advanced thermal reactors.	2013	Thermal Reactors - general	✓	✓	Advanced thermal reactors could be deployed in the UK.	Greater dependence on vendors / utilities. UK becomes a passive receiver of technology.	Ability to leverage industrial sector support.

Decision	Date	Theme	Fuel Cycle Closed	Fuel Cycle Open	Assumption	Potential Consequence (of not making decision)	Opportunity
Join US Dept. of Energy Small Modular Reactor (SMR) programme.	2013	Thermal Reactors – SMRs.	✓	✓	UK may wish to deploy SMR as part of the energy mix. UK industry is in a position to join a consortium that is successful in obtaining US Dept. of Energy funding.	Not participating in the US programme could increase costs. Failure to join could result in a lost opportunity for UK involvement in deployment.	Leverage UK capability to create and exploit IP. Share costs with US.
Invest in UK fuel fabrication capability and infrastructure.	2014	Fuel Fabrication	✓	✓	Lead test fuel assemblies would need to be manufactured for all future reactors.	Risk of loss of UK capability following Sellafield MOX Plant (SMP) closure. Difficult to enact current policy to use plutonium in MOX fuel manufacture.	Generate revenue by supplying fuel pins and lead test assemblies to the international market. Create wider opportunities for UK industry. Create revenue by hosting an international demonstration facility.

Decision	Date	Theme	Fuel Cycle Closed	Fuel Cycle Open	Assumption	Potential Consequence (of not making decision)	Opportunity
Invest in spent fuel recycling capability through R&D using EU and national programme.	2013	Spent Fuel Recycling	✓		A technology decision may need to be made in about 10 years' time if the UK is to adopt a closed fuel cycle.	UK loses leading technical and industrial positions when THORP (Thermal Oxide Reprocessing Plant) closes. Reduced ability to host international fuel recycling demonstration facilities.	Participation in international collaborations could enable the UK to influence those programmes. Enables UK to host an international demonstration facility to create revenue for the UK.
Invest in integration of recycling R&D programme with next generation (including fast) reactors, fuel fabrication and disposal R&D programmes to create a complete fuel cycle capability.	2016	Spent Fuel Recycling	✓		As above.	Credibility of next generation (including fast reactor) development programme weakened.	A complete capability which could extend the capacity to generate revenue for the UK. Commission laboratories that are able to handle highly active materials.

R&D Programme Activities

The Roadmap sets out pathways that the UK can follow to maintain fuel cycle and reactor technology options, with a consequent impact on decommissioning, waste management and disposal. R&D programme activities related to these pathways that are needed within the next decade include:

Baseline Pathway

- **Operations and Maintenance** – R&D to support life-cycle management technologies including advanced diagnostics, monitoring, and predictive capability to assess normal and off-normal behaviour including for life-extensions.
- **Waste Management and Decommissioning** – R&D to support high hazard legacy waste management for the UK's diverse portfolio; facilities and reactor decommissioning.
- **Geological Disposal** - the development and regulatory scrutiny of the safety cases and the development of technologies supporting geological disposal are thoroughly underpinned by transparent, robust R&D which develops confidence among all stakeholders including the public.

Future Open/Closed Fuel Cycle Pathways

- **New Nuclear Build** – R&D to support the design and manufacture of reactor components and modules and enable innovation within the UK supply chain. This would include participation in international advanced reactor programmes including SMRs and fast reactors.
- **Nuclear Fuel Cycle Services** – R&D to support manufacture of inherently safe fuels for Light Water Reactor (LWR) and advanced reactor systems and to support the development of reprocessing technologies.

The Roadmap has also identified that, due to the synergies in R&D activities between the main R&D pathways (baseline (including nuclear fusion), future nuclear fission open and closed fuel cycles), a significant nuclear energy R&D programme is required within the UK regardless of the extent of new nuclear build and of the systems and technologies deployed. These synergies are illustrated in the following matrix.

R&D Programme Synergies

	Next Generation Reactors/Fuels	Reprocessing/Recycling	Advanced Thermal Reactors/Fuels	Current Thermal Reactors/Fuels	Materials and Components	Construction and Installation	Operations	Spent Fuel and Nuclear Material	Decommissioning and Clean-up	Waste Management	Geological Disposal	Fusion Reactors/Fuels
CLOSED FUEL CYCLE PATHWAY 16 - 75 GW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
OPEN FUEL CYCLE PATHWAY 16 - 75 GW			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
BASELINE PATHWAY				✓	✓	✓	✓	✓	✓	✓	✓	✓

Contents

Figures

Tables

Glossary

ABWR	Advanced Boiling Water Reactor
ACSEPT	Actinide reCycling by SEParation and Transmutation
AGR	Advanced Gas-cooled Reactor
ASGARD	Advanced fuelS for Generation IV reActors: Reprocessing and Dissolution
ASTRID	Advanced Sodium Technological Reactor for Industrial Demonstration
CCFE	Culham Centre for Fusion Energy
DCF	Dalton Cumbrian Facility
DECC	Department of Energy and Climate Change
DTI	Department of Trade and Industry
EFDA	European Fusion Development Agreement
EPR	An advanced PWR Generation III reactor (European Pressurized Reactor)
EPSRC	Engineering and Physical Sciences Research Council
ERP	Energy Research Partnership
ERU	Enriched Reprocessed Uranium
ESNII	European Sustainable Nuclear Industrial Initiative
EU	European Union
Euratom	European Atomic Energy Community
FR	Fast Reactor
GDF	Geological Disposal Facility
GIF	Generation IV International Forum
GW	Gigawatt
HAW	Higher Activity Waste
HLW	High Level Waste
HORIZON 2020	European Commission Framework Programme for Research and Innovation
ILW	Intermediate Level Waste
ITER	International Thermonuclear Experimental Reactor project
JHR	Jules Horowitz Reactor
LLW	Low Level Waste

LLWR	Low Level Waste Repository
LWR	Light Water Reactor
MA	Minor Actinide
MOX	Mixed Oxide Fuel
NAMRC	Nuclear Advanced Manufacturing Research Centre
NDA	Nuclear Decommissioning Authority
NMM	Nuclear Materials Management
NNL	National Nuclear Laboratory
NNUF	National Nuclear User Facility
NRDAB	Ad Hoc Nuclear Research and Development Advisory Board
NSAN	National Skills Academy for Nuclear
Pu	Plutonium
PWR	Pressurised Water Reactor
R&D	Research and Development
RWMD	Radioactive Waste Management Directorate
SACSESS	Safety of ACtinide SEparation proceSSes
SFM	Spent Fuel Management
SFR	Sodium-cooled Fast Reactor
SMR	Small Modular Reactor
THORP	Thermal Oxide Reprocessing Plant
TRL	Technology Readiness Level
U	Uranium
UKTI	UK Trade and Investment
UOX	Uranium OXide

1. Introduction

The Purpose of the Nuclear Energy R&D Roadmap

The Government is committed to delivering a low carbon and affordable energy mix of renewables, new nuclear[1] and clean gas and coal, which will provide reliable low carbon electricity generation and reduce the UK's dependence on fossil fuel imports. Two of the Government's principal aims in its energy policy are to provide energy security and to decarbonise the UK economy to an 80% reduction on 1990 emissions of greenhouse gases by 2050, as required by the Climate Change Act (2008)[2].

The global nuclear renaissance provides a multi-billion pound opportunity for those industries involved in the supply of goods and services required for the construction, operation and maintenance, as well as decommissioning, of nuclear power stations and fuel cycle infrastructure.

The Government is aware of the important role that nuclear Research and Development (R&D) plays in the civil nuclear industry for the UK, helping to underpin the performance and safety cases of operational plants, inform government policy, develop innovative solutions and provide industry and regulators with a cadre of skilled people.

The potential growth of the nuclear sector in the UK will not be driven by technology alone. A complex mix of Government policy, relative cost of nuclear power to other sources of energy, market decisions and public opinion will influence the rate and direction of growth in the decades to come. It is this level of complexity that obliges Government to keep a wide range of technological options open for the future and therefore to maintain an agile and flexible R&D capability.

This Roadmap considers existing R&D programmes, the R&D infrastructure and landscape, likely R&D resources, international engagement and opportunities, and takes into account the work of others such as the Nuclear Decommissioning Authority (NDA), the Energy Research Partnership (ERP), the Engineering and Physical Sciences Research Council (EPSRC), the Royal Society and the Technology Strategy Board (TSB). It accounts for synergies with other areas of energy research, particularly nuclear fusion, and ways in which greater benefit can be gained from these to maximise UK R&D capability and capacity.

The Roadmap underpins the Strategy[3] and is supported by the UK Civil Nuclear R&D Landscape Review[4].

[1] For clarity, throughout this document, 'fission' and 'fusion' are used in specific reference to one or other technology only, while 'nuclear' is used in reference to both fission and fusion.
[2] Climate Change Act 2008
[3] HMG, Government Strategy for Civil Nuclear Power, 2013
[4] HMG, A Review of the Civil Nuclear Landscape in the UK, 2013

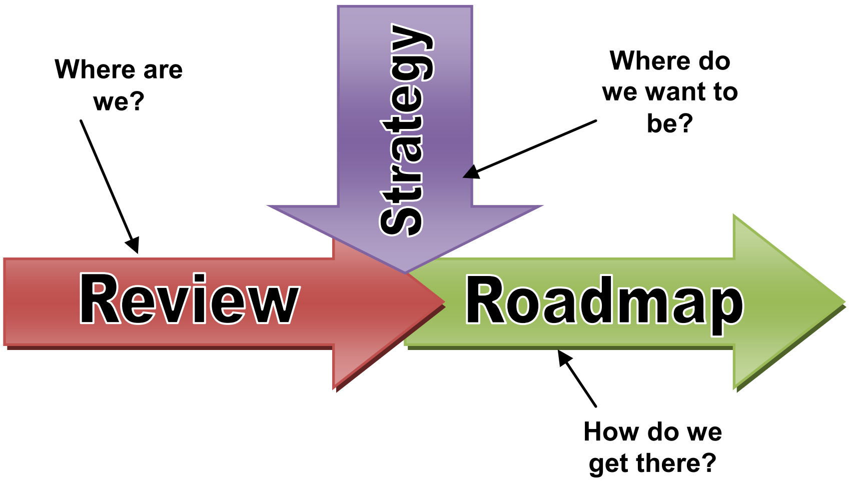


Figure 1: Relationship between Nuclear Energy Strategy ('Strategy'), Nuclear R&D Roadmap ('Roadmap'), and Nuclear R&D Landscape Review ('Review')

This document assesses the needs and opportunities for nuclear energy R&D in the UK in the context of new build of nuclear generation capacity to levels required in a range of scenarios that Government considers plausible. It sets out future R&D pathways that encompass the full range of technologies and capabilities considered capable of delivering a nuclear contribution to electricity generation capacity of up to 75 gigawatts (GW) by around the middle of the 21st century.

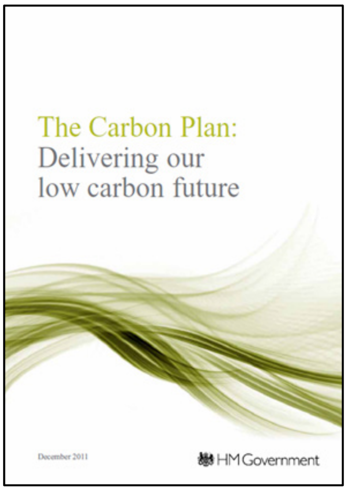
The upper level of 75 GW has been selected to align with the 'higher nuclear; lower energy efficiency' scenario in the Department of Energy and Climate Change (DECC) 2011 Carbon Plan[5]. More information regarding the underpinning data (such as the long-term availability or otherwise of fissile materials for fuels) will be required to inform key decisions.

The Roadmap considers which capabilities are required to enable this build, which technologies may be able to deliver these and the R&D skills, activities and facilities that would be required to allow the UK to deploy them. A series of focused R&D programmes are recommended to provide the means of addressing these needs and opportunities.

[5] DECC, The Carbon Plan: Delivering our Low Carbon Future, 2011

The Policy Background

Historically, the UK's civil nuclear industry focused on offering a full nuclear fuel cycle service. Following the 2002 White Paper 'Managing the Nuclear Legacy: A Strategy for Action'[6], the industry was reconfigured to focus on a decommissioning and clean-up mission, with geological disposal of higher activity wastes[7]. New nuclear energy was neither ruled in or out in the 2003 Energy White Paper 'Our Energy Future - Creating a Low Carbon Economy'[8], and was identified as a possible option in the 2008 'Meeting the Energy Challenge - A White Paper on Nuclear Power'[9].



More recently, energy policy developments have been driving substantial changes to the UK's R&D landscape, particularly on issues related to greenhouse gas emissions and energy security. These policy developments further support the need for a robust portfolio of nuclear energy R&D programmes able to respond to developing requirements. This document considers the extent to which the UK's nuclear R&D capabilities can support the UK's future nuclear energy options on an enduring basis.

The Role of Nuclear Energy in a Low Carbon Economy

Nuclear energy is a key energy source in delivering the twin aims of energy security and a decarbonised UK economy. A strong and adaptable research base will support the delivery of these objectives and, through increased industrial activity, offers the ability to make a contribution to economic growth.

The UK has a long history of deploying nuclear fission power generation and fuel cycle plant operations with a corresponding level of skills and experience in its

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[6] Department of Trade and Industry (DTI), White Paper 'Managing the Nuclear Legacy - A Strategy for Action', 2002

[7] Scottish Government policy differs from that of the UK Government, proposing 'near site, near surface' disposal of wastes, together with storage of wastes which are unsuitable for disposal in that way.

[8] DTI, Energy White Paper, Our Energy Future - Creating a Low Carbon Economy, 2003

[9] Department for Business, Enterprise and Regulatory Reform (BERR), Meeting the Energy Challenge - A White Paper on Nuclear Power, 2008

industrial, regulatory and research base. Apart from mining, this R&D experience has covered the entire nuclear fuel cycle.

Nuclear energy generation capacity could continue to play a significant role in UK energy provision and may expand significantly by the mid-21st century.

The UK has a 50 year history of nuclear fusion research. Both fission and fusion represent potential means of meeting future low carbon energy needs. The vision is for fusion to contribute to energy production after 2050. The primary focus of this document is therefore on nuclear fission R&D as the UK contribution to nuclear fusion research is described more fully elsewhere[10]. Areas of research that are common to both fission and fusion are, however, identified.

Roadmap Development

The Roadmap has been developed under the oversight of the Ad-hoc Nuclear Research & Development Advisory Board (NRDAB) and draws on inputs from academic[11], industrial, regulatory and applied research organisations. Several sub-groups reported to the NRDAB, each of which drew conclusions and made a number of recommendations relating to R&D. The recommendations of these sub-groups are presented in Annex A. These recommendations have been consolidated within this Roadmap, leading to a number of specific recommended actions and detailed R&D programmes.

[10] A 20 Year Vision for the UK Contribution to Fusion as an Energy Source, Research Councils UK, February 2010

[11] Significant input from the academic community was obtained at the UK Nuclear Academics Discussion Meeting at the University of Oxford (September 2012)

2. Nuclear Energy R&D Vision

In three of the four scenarios described in the Carbon Plan, nuclear power is seen as delivering increased levels of electricity production. One scenario models 75 GW of nuclear power electricity generating capacity by the year 2050 and is equivalent to approximately seven times[12] the current level of installed nuclear power capacity. This is a substantial increase from current levels and options for achieving this may include:

- Development of advanced reactor designs (either thermal or fast reactors[13]), including Small Modular Reactors (SMRs);
- Consideration of alternative fuels; and
- Consideration of alternative fuel cycles including options for closing the fuel cycle and reprocessing spent fuel.

There is a risk that options, including the above, will not be evaluated in a timely manner, if left to the market. This document outlines R&D programmes which would ensure that these options are not foreclosed and that essential skills are not lost, thus mitigating the risk of market failure.

The vision is that nuclear energy research and development programmes have the capability and capacity to support significant expansion of the nuclear energy sector.

[12] DECC, Table of Past and Present UK **Nuclear** Reactors (Dec 2012). Website (http://www.gov.uk/government/organisations/department-of-energy-climate-change).
[13] See Annex B for definition of thermal and fast reactors.

3. Drivers

Introduction

The two high-level strategic drivers for the development of the objectives and programmes set out in the Roadmap are to:

- Establish R&D programmes to ensure that nuclear power is able to deliver the requirements for tackling climate change and maintaining energy security; and
- Ensure that nuclear R&D can make a positive contribution to delivery of the UK economic growth strategy.

These two 'strategic' drivers are discussed below (Figure 2) together with consideration of supporting 'tactical' drivers which drive optimisation within individual nuclear energy R&D programme areas.

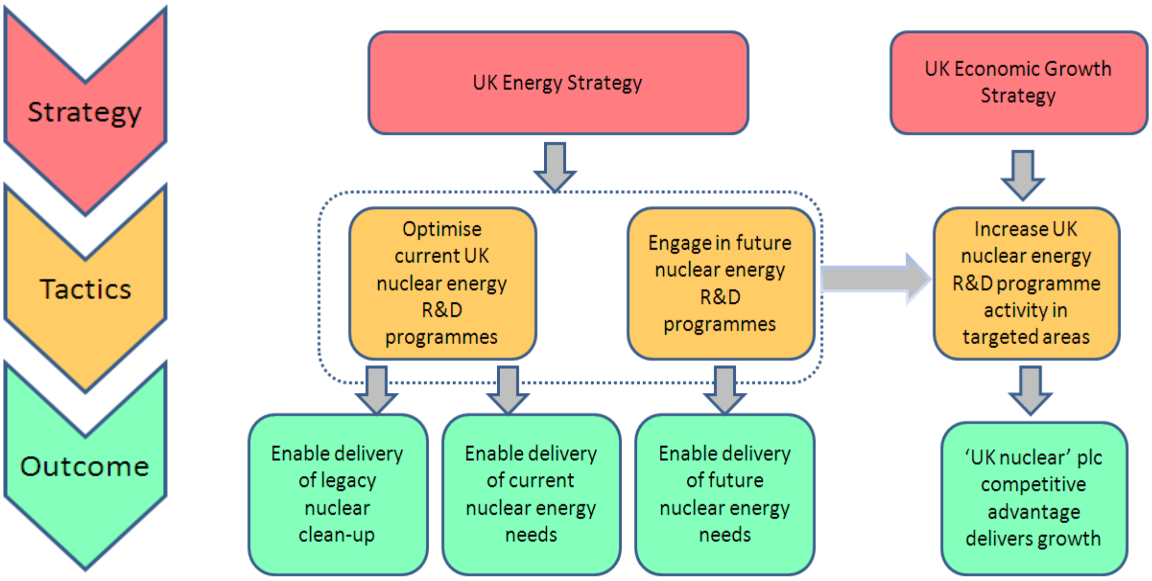


Figure 2: Rationale for nuclear energy R&D

Both energy and growth development strategies for nuclear energy R&D have an international dimension; in some programme areas the UK is either already internationally recognised as a key 'player', or there is a significant capability to achieve this level. National and international opportunities are explored in more detail in Section 7 (R&D programmes).

Delivering the recommended R&D programmes will ensure that a range of options remains accessible, including technical solutions, which are more sustainable, have lower cost, and offer greater energy security. Successful delivery of the R&D

programmes set out in the Roadmap will also demonstrate internationally that the UK is adopting a leadership position on the low carbon economy and on non-proliferation of nuclear material. Conversely, failure to keep options open could limit the UK's ability to adopt advanced technologies, or delay the time at which the nuclear programme could be delivered.

If nuclear technologies are to play an effective role in UK energy markets and industry, there is a need for a core UK nuclear R&D capability (facilities, technologies, skills and knowledge) that can engage fully with the market. Exercising this R&D capability will strengthen UK competence and ensure that UK companies can effectively take the role of intelligent customers, able to identify and select the most appropriate technologies needed and to deploy them in the most effective manner. UK domestic success supported by R&D could also be further used as a springboard for growth in export business, through development of new technologies and exporting products and expertise in a competitive global market (e.g. decommissioning).

An effective R&D programme addresses both strategic drivers and delivers wider economic benefits to the UK, including the domestic nuclear supply chain.

The Roadmap describes a national nuclear energy R&D programme addressing all stages of the nuclear fuel cycle without prematurely focusing attention in particular programme areas. Priority areas for action are identified within each of the individual programmes.

Nuclear R&D to Support the UK Energy Strategy

A number of pathways have been identified, including those in which nuclear fission would generate substantially more power than the current contribution. However, the need for a strategic UK R&D programme is not dependent on a subsequent decision to expand the scale of nuclear power generation.

It is important that the UK continues to have access to the skills and facilities required to meet the existing challenges associated with operating current plant, extending the life of existing stations, waste management and decommissioning.

The following programmes have concluded, or will conclude, in the period 1990 – 2020:

- The UK fast reactor programme concluded in the 1990's;
- The Sellafield Mixed Oxide Fuel (MOX) plant closed in 2011; and
- The Magnox and Thermal Oxide Reprocessing Plant (THORP) reprocessing programmes will both be concluded before 2020.

R&D capability areas associated with these programmes will need to be maintained the UK wishes to maintain the option of realising the full range of potential energy strategies.

Nuclear R&D Contribution to UK Economic Growth Strategy

The absolute minimum requirement for realising ambitious future pathways is that the UK is able to take the role of an intelligent buyer, and to deliver effective and independent regulation of an expanded nuclear power sector. Many of the potential programmes for increased nuclear power generation are only likely to be achievable through collaboration with international R&D programmes. The opportunity therefore exists to make a significant contribution to the UK economic growth strategy if the UK takes an active role in applying nuclear fission skills and expertise within international collaborations and takes a leading role in specific areas, especially as a technology developer and exploiter. In order to do so, it may be necessary to identify one or more areas of science and technology relevant to nuclear fission in which the UK could take a leading role.

One of the means by which a leading role can be established is by volunteering to host facilities for the demonstration of aspects of technology required in the fuel cycle. This has the advantage of creating new jobs, which support the operation of the facility as well as meeting the high technology requirements of the researchers. For example, the Daresbury synchrotron[14] was a hub around which a number of associated high technology companies set up, offering related technologies such as high vacuum technologies. Some of these then spun out diversified businesses such as development and manufacture of mass-spectroscopy equipment.

Tactical Drivers

Within the overall context of providing energy security and de-carbonising the UK economy, many factors influence the optimisation of nuclear energy R&D, including the need to:

Technical and Safety

- Develop ‘cleaner' pathways, minimising the quantity of radioactive waste generated and the technical challenge posed to geological disposal;
- Make optimum use of available nuclear materials (efficient use of fuel resources);
- Deliver lifetime extensions to existing reactors and factor in the learning to future reactors;
- Consider technical and safety factors holistically across the whole fuel cycle;
- Evaluate passive safety and accident-resistant designs; and
- Improve non-proliferation features.

[14] For details, refer to Sci-Tech Daresbury at Science and Technologies Facilities Council website: http://www.stfc.ac.uk/

Economic

- Evaluate the cost of different options;
- Understand the trade-off between cost and ‘sustainability and social factors’ (which value prompt action);
- Understand the impact of considering discounted cost (which can favour delay);
- Evaluate the economic downside risks of allowing options to close;
- Develop pathways which increase confidence in (cap)ability to deliver;
- Diversify the marketplace, particularly low capital cost and/or operating cost offerings; and
- Evaluate a wider choice of thermal and electrical power options, including improved load following[15].

Social

- Understand public perceptions of nuclear energy technology development, and factors which inform public acceptability; and
- Understand public engagement processes on nuclear R&D, and their effectiveness.

Timing

- Develop a clear view of which options should be kept open and which should be closed off, and when.

[15] Adjusting power output as demand for electricity fluctuates.

4. Nuclear Energy R&D Pathways

A range of possible nuclear energy R&D pathways is postulated. The highest dependency on nuclear energy would require an increase in nuclear generating capacity (further to the current plans for 16 GW of new nuclear build capacity by 2025) of up to 75 GW by the middle of the 21st century, spanning the range of plausible scenarios for nuclear and other electricity generation technologies set out in the Government's 2011 Carbon Plan.

A wide range of technical solutions could deliver such an output. These vary from the construction of a large number of Light Water Reactors (LWRs) operating an open fuel cycle, through to a mix of LWR and fast reactors designed to maximise the utilisation of nuclear materials (and hence minimises the demand for fresh nuclear material). Innovative concepts, such as SMRs, may also find a role in a future nuclear energy programme (refer to Annexes B, C and D for details of reactor, fuel and fuel cycle technologies). This document sets out the R&D that would need to be carried out to ensure that the UK could select from these different technologies to deliver the required outcome.

At a high level, there are three high level R&D pathways:

- An R&D baseline without new nuclear build and with the completion of current fuel recycling operations;
- R&D to support 16 - 75 GW on an open fuel cycle basis (uranium and plutonium fuels); and
- R&D to support 16 - 75 GW on the basis of a transition from an open to a future closed fuel cycle (uranium and plutonium fuels).

There are significant R&D challenges associated with all three pathways considered in the Roadmap. The salient characteristics of the pathways are as follows:

Baseline Pathway

The Baseline Pathway involves operating the existing reactor fleet for the remainder of its life, the justification of lifetime extensions (where appropriate), the decommissioning and clean-up of all of the civil nuclear licensed sites in the UK and the implementation of geological disposal of higher activity radioactive wastes.

A significant programme of R&D will be required to deliver this pathway. The accountabilities for completing the decommissioning, clean-up and geological disposal programmes are already clear, but the associated research programmes will be challenging to complete.

The Baseline Pathway represents the current status quo, and *excludes* delivery of the current plans for 16 GW of new nuclear build capacity by 2025.

The delivery of the current fusion R&D programme is present in the Baseline Pathway.

Open Fuel Cycle Pathway

An open fuel cycle is one in which fuel is fabricated, loaded into a reactor to generate power and subsequently stored, possibly for many decades, pending geological disposal. A proportion of the fissile material remains in the spent fuel at the point of discharge from the reactor. An open fuel cycle has a relatively high demand for fresh supplies of fissile material.

This pathway *includes* delivery of the current plans for 16 GW of new nuclear build capacity by 2025. In practice the bounding case for this pathway involves the construction of a series of reactor units with a combined installed capacity of up to 75 GW by the middle of the 21st century.

This pathway includes the elements of the Baseline Pathway.

(Transition to) Closed Fuel Cycle Pathway

In a closed fuel cycle the spent nuclear fuel is treated to recover and recycle fissile material to generate further power. In some fuel cycles, options also exist to incorporate some of the long lived actinides into fuel, thus reducing the disposal challenge. Closing the fuel cycle beyond the middle of the 21st century reduces the requirement for fresh fissile material. The transition to a closed fuel cycle would not be immediate and would need to be phased in accordance with the development of advanced technologies e.g. fast reactors and advanced reprocessing methods.

This pathway *includes* delivery of the current plans for 16 GW of new nuclear build capacity on an open fuel cycle basis by 2025. In practice the bounding case for this pathway involves the construction of a series of reactor units with a combined installed capacity of up to 75 GW by the middle of the 21st century.

This pathway includes the elements of the Baseline Pathway.

Other Fuel Cycles: Thorium

Most of the world's nuclear power reactors run on uranium fuel, are cooled by water and, in order to sustain the heat-giving nuclear reaction in the reactor core, must slow down the neutrons emitted by the fuel. However, there are a range of reactor designs in various stages of development which differ from these and which may offer advantages over currently available reactor systems. Some of these also offer the possibility of using thorium, rather than uranium, as a fuel, which may offer desirable characteristics.

Thorium is a fertile[16] material that is used to breed uranium fuel in reactors. This fuel cycle requires a fissile[17] fuel (e.g. uranium or plutonium) seed in order to start up reactor operations. Thorium reactors are, therefore, expected to be subject to the same fuelling limitations in roll-out as fast reactors, in which the rate of commissioning is constrained by the rate of production of start-up fuel from the existing reactor fleet.

Thorium-fuelled variations of current reactor designs, as well as novel thorium-fuelled reactors, may allow different fuel breeding ratios from their uranium-fuelled counterparts. Assessing thorium-fuelled reactors and understanding the implications for the attainable rates of expansion of nuclear capacity will be important for understanding the potential role of thorium in a UK fuel cycle.

Thorium fuels are also likely to differ from uranium fuels in their waste characteristics, including their radiological properties and the amounts of heat they generate. These waste characteristics will vary with the type of reactor in which thorium fuels are used and individual systems may offer significant advantages or barriers to the waste's management and final disposal. Again, further analysis and fuel cycle modelling will be necessary to understand the implications on waste management and disposal of using thorium fuels.

[16] Fertile Material - Nuclear material that can be converted to fissile material through the capture of a neutron. An example of a fertile material is uranium-238.
[17] Fissile Material - Fissile materials are capable of undergoing nuclear fission (splitting of the nucleus of an atom) by slow neutrons. Examples of fissile materials are uranium-235 and plutonium-239.

5. Fuel Cycle Modelling

ORION is a fuel cycle simulation code able to simulate a wide range of nuclear related facilities (storage buffers, fabrication and enrichment plants, reprocessing facilities, waste conditioning plants and reactors) that can be linked together to allow different fuel cycle scenarios to be investigated. ORION has been used in the development of this document to analyse a number of scenarios incorporating different fuels, reactor technologies and recycling/reprocessing options, to explore the range of potential UK open and closed fuel cycles.

ORION models and tracks the transfer of material with time throughout the different stages of the fuel cycle, starting from a mine through to final disposal in a geological disposal facility. ORION tracks the demand for raw materials and reflects the availability with time of materials such as spent fuel, separated plutonium and uranium. The code manages the availability of materials and, for reactors, will automatically vary the amounts of each fuel type loaded depending on the feedstock available. During each stage of the fuel cycle, decay and transmutation of the material is modelled, as well as other chemical and physical changes such as uranium enrichment, reprocessing and partitioning.

Results from ORION include the activity of each nuclide being transferred between different components (facilities) of the fuel cycle and the activity of each nuclide within storage buffers. Other measures, including radiotoxicity, decay heat and spontaneous neutron emission, can also be calculated from the nuclide inventories and used to identify modifications to fuel-cycle operation. Some results on economics and proliferation risk measures can also be determined. Since the simulations defined in ORION are time-dependent (i.e. systems can evolve over time), time-evolution profiles of the different model outputs are determined.

Examples of information that can be provided from simulations using ORION include:

- The variation in time of the amount of electricity generated;
- The variation in time of the quantities of nuclear materials (e.g. plutonium, uranium tails[18]) available and/or required to fuel different reactor fleets (e.g. for use in fast reactors);
- Uranium ore requirements for different fuel cycle scenarios;
- Decay heat of wastes sent to a geological repository; and
- Volumes and nuclide activity of solid, liquid and gaseous discharges;
- Volumes of wastes requiring disposal (in the categories of Low Level Waste (LLW), Intermediate Level Waste (ILW) and High Level Waste (HLW)) and spent fuel.

[18] By-product of the uranium enrichment process.

These measures enable the impact of a fuel cycle to be estimated in terms of the implications for fuel fabrication and handling, the reprocessing of spent fuel, the suitability of separated plutonium for recycling, waste management requirements, and final disposal in a repository. For example, the amount of plutonium required to fuel a fast reactor fleet has implications for the timing and magnitude of spent fuel reprocessing to generate nuclear materials, whilst the size of a geological disposal facility for heat-generating wastes is dependent on decay heat production from the wastes.

ORION has been used to model several potential future UK nuclear fuel cycle scenarios. These scenarios simulate the Magnox and Advanced Gas-cooled Reactor (AGR) fleets, the fabrication and enrichment of uranium dioxide (UO_2) fuel for the Sizewell B reactor and a future LWR (Pressurised Water Reactor (PWR) modelled) reactor fleet, as well as the continual recycling of neptunium, plutonium and americium through a fast reactor fleet. Spent UO_2, Enriched Reprocessed Uranium (ERU) and MOX fuel from the LWR fleets and spent MOX fuel from the fast reactor fleet are cooled before being reprocessed. The separated plutonium and uranium are used to fabricate MOX and ERU fuel for the LWR and fast reactor fleets, and the fission product and un-recycled minor actinide inventory immobilised, stored, cooled and eventually consigned for geological disposal.

The scenarios analysed using ORION fall into two main categories: ‘open’ and ‘closed’ fuel cycles.

Open Fuel Cycles

A range of open fuel cycle scenarios can be envisaged. The main variables are the number and type of reactors that are built. The scenarios modelled include power outputs from 16 GW (about the level envisaged in the current plans for a new generation of nuclear power reactors) to 75 GW. All of these scenarios assume the construction of LWR reactors.

Closed Fuel Cycles

A wider range of closed fuel cycles is possible, when compared to the open fuel cycle. More variables need to be considered in developing a closed fuel cycle. Some of the main variables are:

- The extent to which nuclear material is recycled into fuel. The reprocessing currently carried out in the UK extracts uranium and plutonium from irradiated fuel. These are separated from each other and either uranium, plutonium, or both, can be recycled into fuel. It is also possible to recycle minor actinides such as americium and neptunium into fuel, which has the effect of reducing the radiological hazard of waste requiring disposal.
- The type of reactor. The current generation of reactors operating in the UK are all thermal reactors. However a number of fast reactor concepts have been

developed which permit a much higher degree of recycling and can, if operated to do so, generate additional fissile material, thus enabling much more energy to be generated from the same raw material.

- The number of reactors.

A range of closed fuel cycles has been modelled which vary from 16 GW of thermal reactors burning MOX fuel to a 75 GW bounding case including both thermal and fast reactors and in which uranium, plutonium, americium and neptunium are recycled in fast reactors. The closed fuel cycle scenarios that have been modelled include scenarios in which uranium and plutonium are recycled in LWR thermal reactors, as well as scenarios in which a mixture of LWR thermal reactors and fast reactors are constructed.

Comparison of Open and Closed Fuel Cycles

In comparing the output from modelling of a range of fuel cycles, a number of observations can be made.

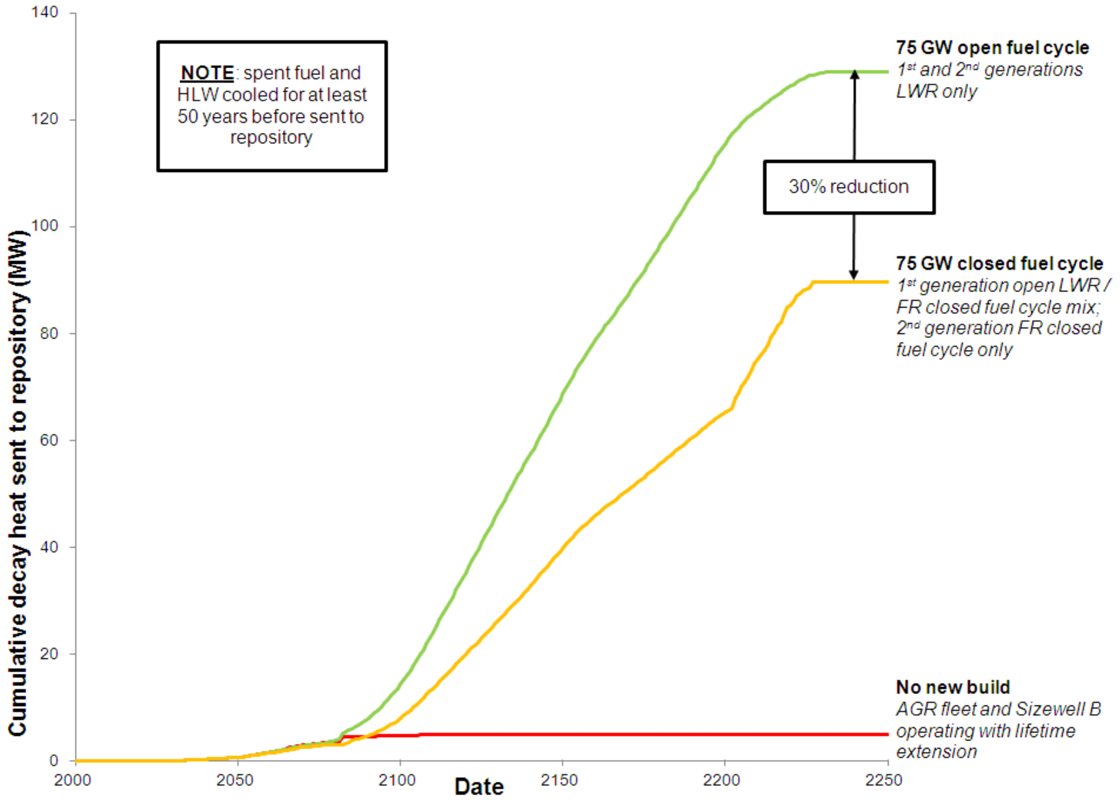


Figure 3: Comparison of heat output from two generations of reactors delivering 75 GW of power on open and closed fuel cycles

Figure 3 illustrates that the cumulative decay heat output from the spent fuel and HLW, from two generations of reactors (LWR only, or LWR and Fast Reactors (FR)) operating under a closed fuel cycle (each generating 75 GW), will be approximately 30% less than the same output from an open fuel cycle.

Figure 4 plots the uranium ore required to fuel the same two generations of reactors (75 GW open and closed scenarios). The ore demand for the closed fuel cycle, which includes fast reactors, is substantially lower than that for LWRs operating in an open fuel cycle. However, since a closed fuel cycle requires separated plutonium initially, a future fast reactor fleet has to be preceded by a similar sized LWR fleet and the reprocessing of the LWR spent fuel. Therefore, the ore demand from 2020 to 2100 is dominated by the fuel required for the LWR fleet. The ore requirement for the period from 2100 to 2220 is reduced as the fast reactors are fuelled by recycled nuclear material and breed all future fissile material during operation.

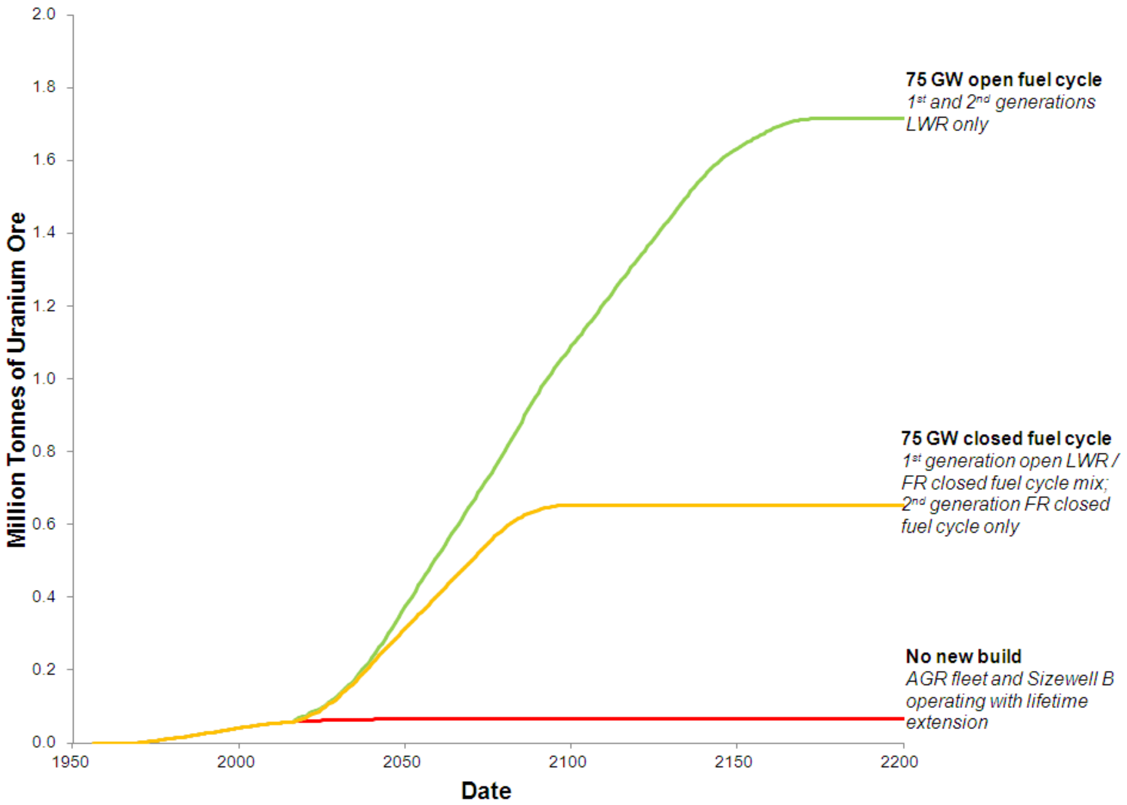


Figure 4: Comparison of uranium ore required to power two generations of reactors delivering 75 GW of power on open and closed fuel cycles

The 75 GW closed fuel cycle scenario models two generations of reactors, each generating 75 GW and operating for 60 years. Figure 5 shows the level of power generated over time and the type of reactors contributing to that power. The fuel from the LWRs is recycled to produce fuel for fast reactors. In this scenario, the second generation of reactors contains only fast reactors.

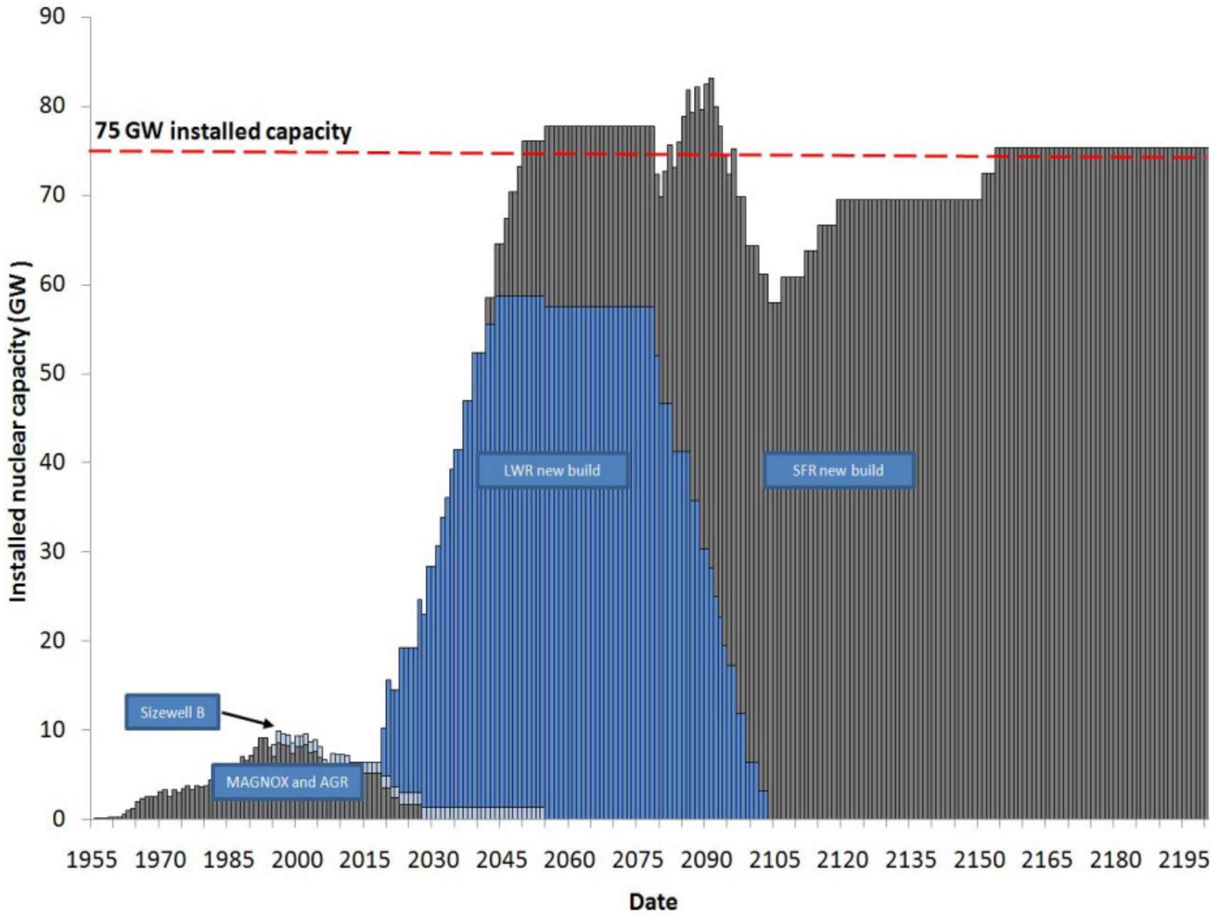


Figure 5: The source of power generated against time for a 75 GW closed fuel cycle[19]

General Observations

In the absence of spent fuel reuse or recycling, the quantity of spent fuel requiring disposal in a geological disposal facility (i.e. GDF) would increase with the increased number of reactor cores. The spent fuel may need to be stored for many decades prior to disposal.

One of the factors constraining geological disposal of spent fuel is the rate of heat generation. Current geological disposal concepts require heat generating wastes to be distributed in a manner that limits the temperature rise in the surrounding rock. An increased scale of a new build programme will increase the total heat output of fuel for disposal and (unless the fuel is processed further) increase the footprint of the GDF.

An open fuel cycle operating thermal reactors requires increased levels of uranium ore to be made available for fuel fabrication when compared to the same size of

[19] The fuel cycle modelling has assumed new reactor build contributions from (i) The UK European Pressurized Reactor (EPR) design developed by AREVA and Electricité de France (EDF) and (ii) The AP1000 design developed by Westinghouse Electric Company (WEC).

power generating programme operating a fuel cycle in which plutonium and uranium are recycled as MOX fuel. Therefore, for any given power output the recycling of plutonium reduces the requirement for fresh uranium ore supplies.

The current stock of separated plutonium would not be sufficient to sustain a 75 GW fleet of fast reactors. Any plan to build a fleet of fast reactors of this scale (fuelled by uranium and plutonium) would need to incorporate a means of generating the plutonium required (e.g. via a fleet of thermal reactors and a spent fuel recycling facility). In this scenario, a future fast reactor fleet would be limited by the size of a preceding uranium-oxide-fuelled thermal reactor fleet.

Using the existing stock of plutonium to manufacture MOX fuel for LWR reactors would reduce the quantity and quality of plutonium available to fuel a fast reactor fleet, even if the LWR fuel is recycled.

Observations on a 75 GW Nuclear Programme

The ORION scenarios both assume that nuclear power in the UK expands to a total installed capacity of 75 GW by the year 2050. This corresponds to the most ambitious scenario identified in the Carbon Plan and represents very substantial growth to approximately seven times the current level of installed nuclear power capacity.

Construction of more than 50 new reactors would be required (assuming units of approximately 1 GW capacity). In order to achieve this, new reactor sites may have to be identified and licensed, or existing sites extended, and new reactors would have to be completed at a rate of around 3 units per year – similar to historic peak levels of new build in France.

6. Pathway Timelines

Illustrative timelines and their significant milestones have been developed for each pathway up to 2050, in order to highlight where nuclear R&D could be key to the credibility of the pathways and their associated activities. The timelines have been prepared using existing UK decommissioning and waste management strategies, the ERP Roadmap[20] and pathway analysis undertaken for this Roadmap.

Additionally, an international example of national steps taken to achieve a nuclear fuel cycle outcome is presented: the French programme for developing a prototype fast reactor.

Reading the Timelines

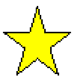
Pathway activities are shown as coloured bars, segmented where appropriate to show supporting steps, e.g. design, build, operation.

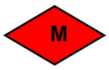
denotes a milestone or stage gate relevant to the success of a pathway

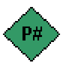
denotes a decision relevant to the success of a pathway (ASTRID Timeline)

denotes a time point at which public acceptability is significant to the success of a pathway

denotes a technology insertion point (ASTRID Timeline)


denotes an outcome relevant to the pathway

Pathway-related R&D programmes are shown as coloured bars and linked to specific


or


points on the timeline.

Details of these programmes can be found in the following section.

[20] Energy Research Partnership, UK Nuclear Fission Technology Roadmap: Preliminary Report, February 2012

Outline Timeline for ASTRID Deployment

The French Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID) programme began in 2010 and the course is set for a target date of 2023 for the prototype fast reactor to commence operations, with a final decision to give the go-ahead for construction expected in 2017. Notable aspects of this include:

- It is anticipated that the operation of ASTRID and European and international collaboration would lead to the deployment of a commercial sodium-cooled fast reactor by 2040.
- The timeline presented in Figure 6 includes the associated fuel cycle development activities in support of ASTRID (i.e. fuel fabrication and fuel recycling).
- The French continue to research and develop gas-cooled fast reactor technology via the ESNII collaborative ALLEGRO project.

Illustrative Timeline for Baseline Pathway

The timeline for the Baseline Pathway (Figure 7 & Figure 8) illustrates indicative timings for delivery of the UK GDF and decommissioning and clean-up activities up to 2050. It also shows potential immobilisation activities for UK plutonium and uranium stocks. Notable aspects of this include:

- The timeline assumes that lifetime extensions are granted for the AGR fleet and Sizewell B leading to the end of nuclear fission power generation by 2055.
- Nuclear fusion energy development and demonstration activities are mapped out up to 2050, but it is not yet certain at which point industrial deployment could be expected.
- R&D in relevant areas has been linked to key stages in the Baseline Pathway.

Illustrative Timeline for Open Fuel Cycle (75 GW) Pathway

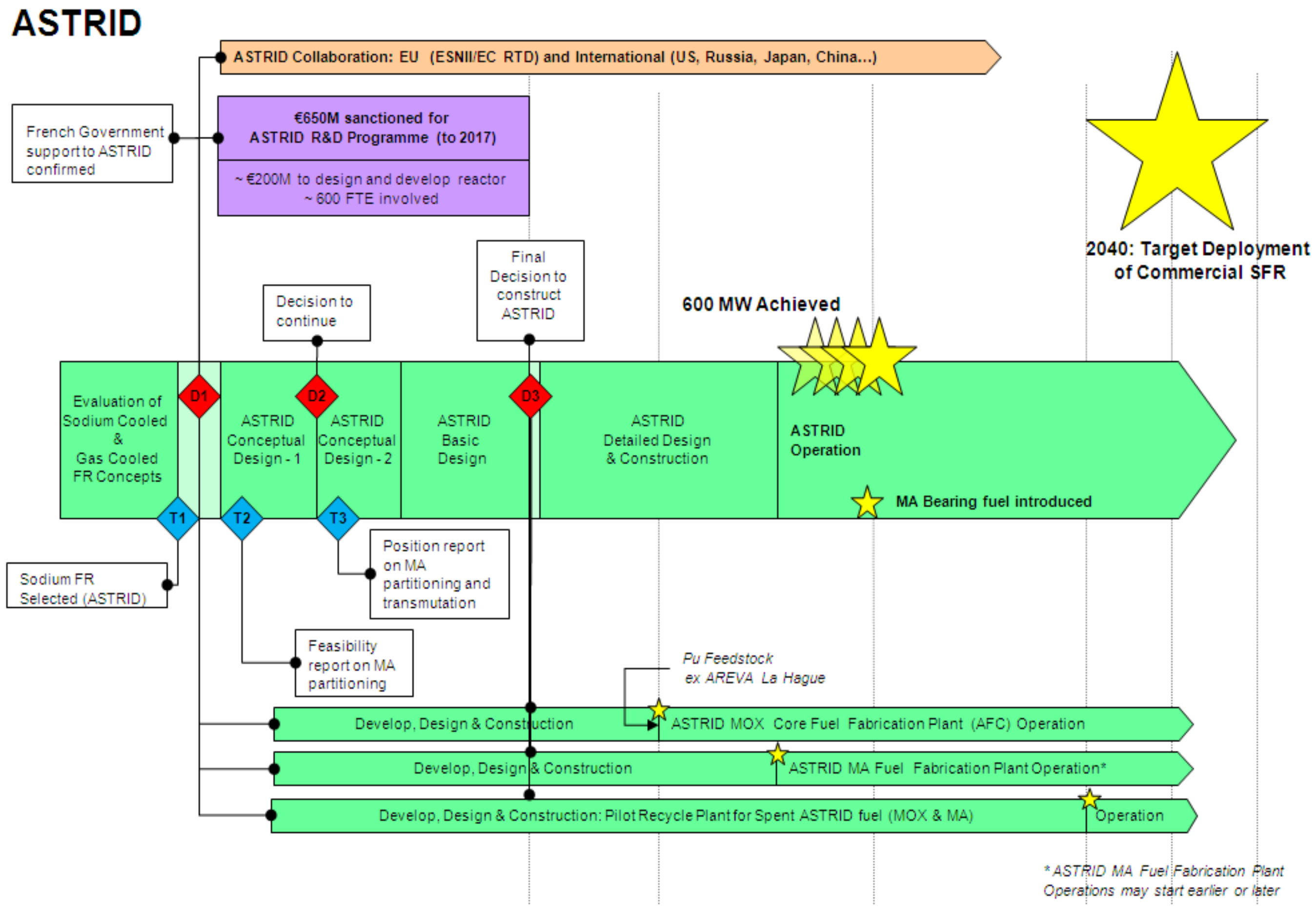
The timeline for the Open Fuel Cycle Pathway (Figure 9 & Figure 10) illustrates the anticipated timings for activities associated with the delivery of 75 GW of nuclear fission energy by 2050. It includes the assumption that UK plutonium would be used within the new LWR fleet and that advanced thermal reactor technology, in this case small modular reactors (SMRs) would be assessed for assisting with a mission for 75 GW by the middle of the 21st century. Notable aspects of this include:

- Recognising the greatly increased demands on a GDF from a 75 GW programme, repetition of the volunteer community led process for site selection has been assumed.
- GDF, decommissioning and clean-up activities are part of the pathway but have not been included on the timeline to minimise complexity of the image.
- R&D in relevant areas has been linked to key stages in the Open Fuel Cycle Pathway.

Illustrative Timeline for Transition from Open to Closed Fuel Cycle (75 GW) Pathway

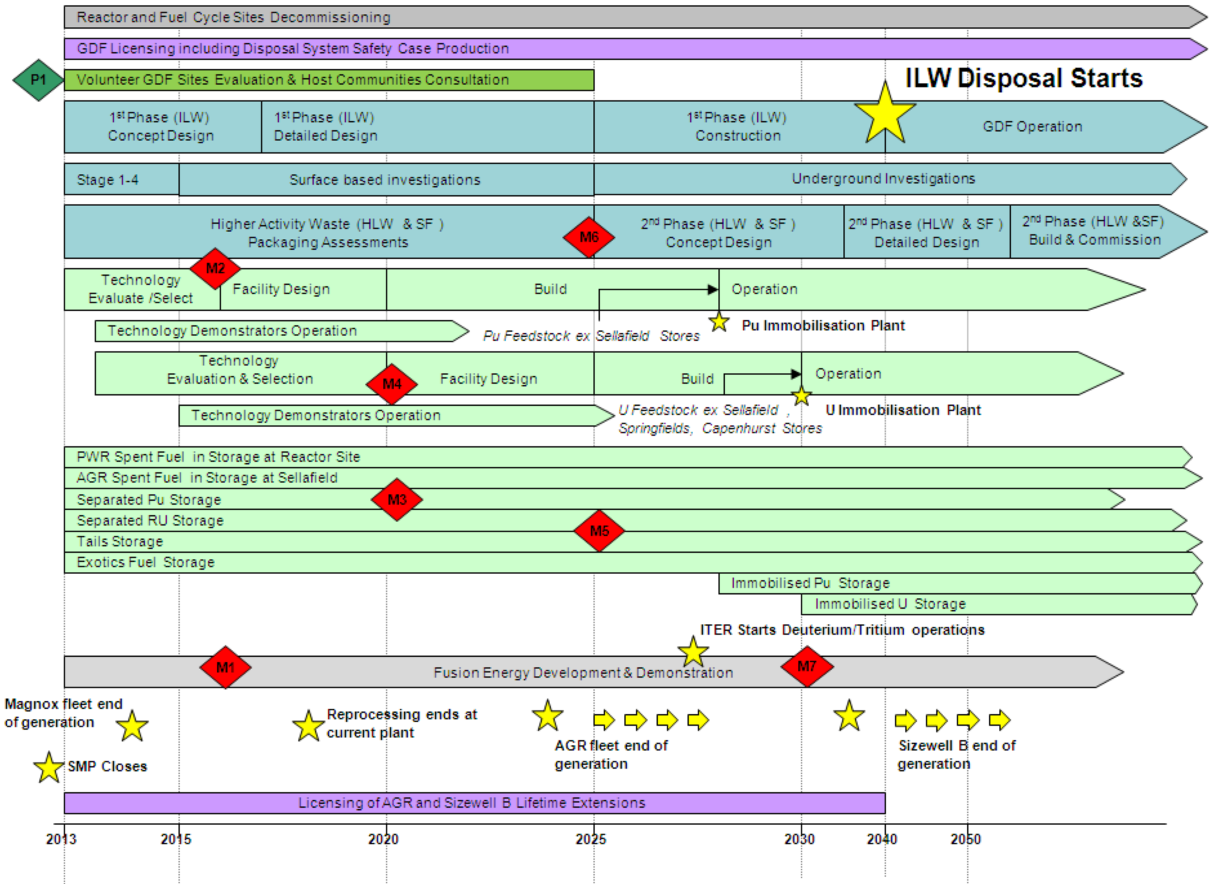
The timeline for the transition from Open to Closed Fuel Cycle Pathway (Figure 11 & Figure 12) illustrates the anticipated timings for activities associated with the delivery of 75 GW of nuclear fission energy by 2050. It includes the key assumption that the UK would be actively involved in international advanced fuel cycle initiatives and have access to international technology demonstrators, with an option of hosting demonstrators in the UK. Notable aspects of this include:

- GDF, decommissioning and clean-up activities are part of the pathway but have not been included on the timeline to minimise complexity of the image.
- R&D in relevant areas has been linked to key stages in the transition from Open to Closed Fuel Cycle Pathway.



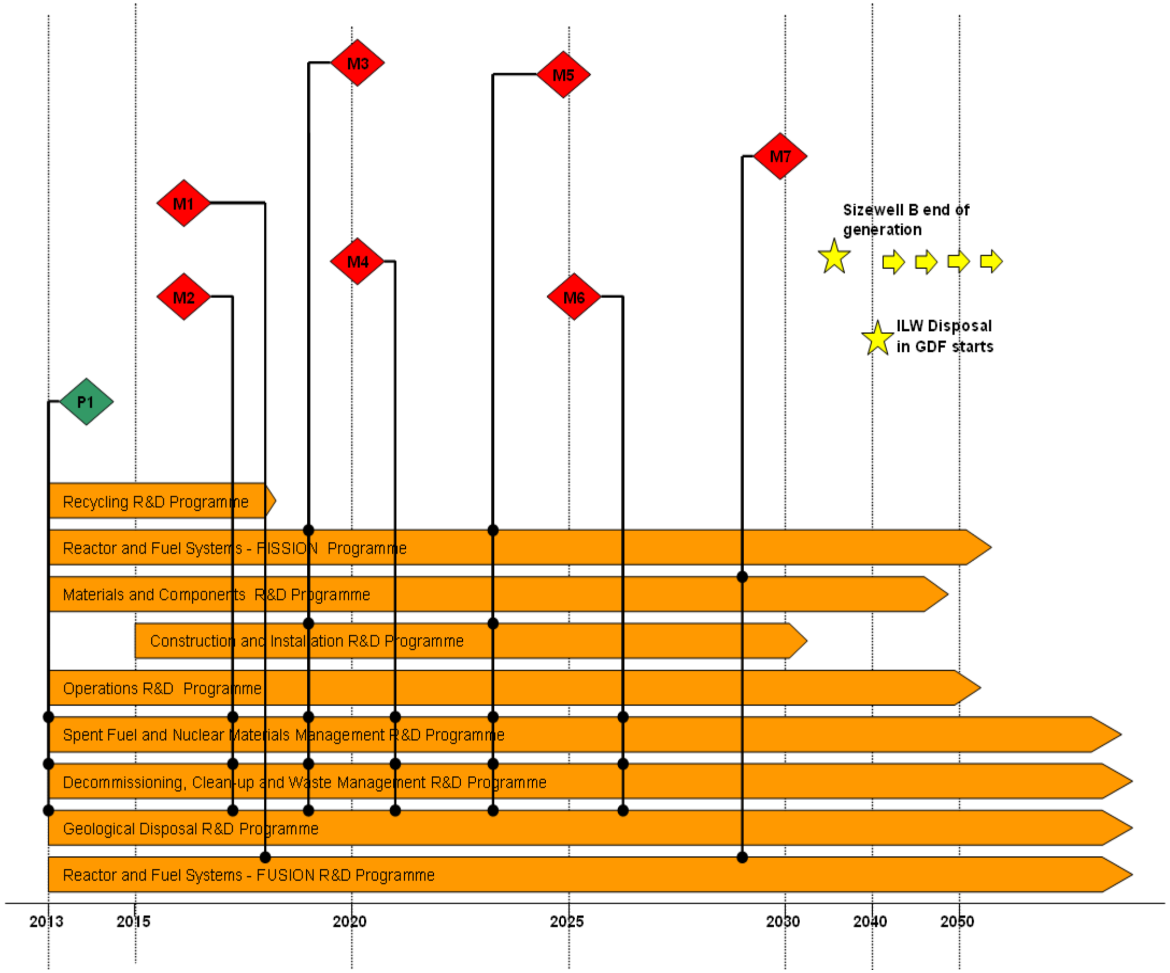
KEY TO FIGURE 7:	
AFC	ASTRID Core Fabrication Workshop
ASTRID	Advanced Sodium Technological Reactor for Industrial Demonstration
ECRTD	European Commission Research and Technological Development
ESNII	European Sustainable Nuclear Industrial Initiative
EU	European Union
FTE	Full Time Equivalent
FR	Fast Reactor
MA	Minor Actinide
MW	Megawatt
MOX	Mixed Oxide Fuel
SFR	Sodium-cooled Fast Reactor

Figure 6: Illustrative timeline for ASTRID deployment in France



KEY TO FIGURES 7 AND 8:	
AGR	Advanced Gas-cooled Reactor
GDF	Geological Disposal Facility
HLW	High Level Waste
ILW	Intermediate Level Waste
ITER	International Thermonuclear Experimental Reactor project
Pu	Plutonium
PWR	Pressurised Water Reactor
RU	Reprocessed Uranium
SF	Spent Fuel
SMP	Sellafield MOX Plant
U	Uranium
M1	Continuation of funding of Fusion R&D at end of current EPSRC funding
M2	Select technology for Pu immobilisation
M3	Decision on immobilisation of civil separated Pu stocks
M4	Select technology for U immobilisation
M5	Decision on immobilisation of separated U, tails
M6	HAW packaging concepts confirmed
M7	Update of UK Fusion Energy Vision
P1	Host community acceptance or otherwise of geological disposal
Note	Indicative timelines are shown in those cases where decisions are taken to immobilise U and Pu, and to proceed with geological disposal programme beyond Stages 1 - 4

Figure 7: Illustrative timeline for baseline pathway



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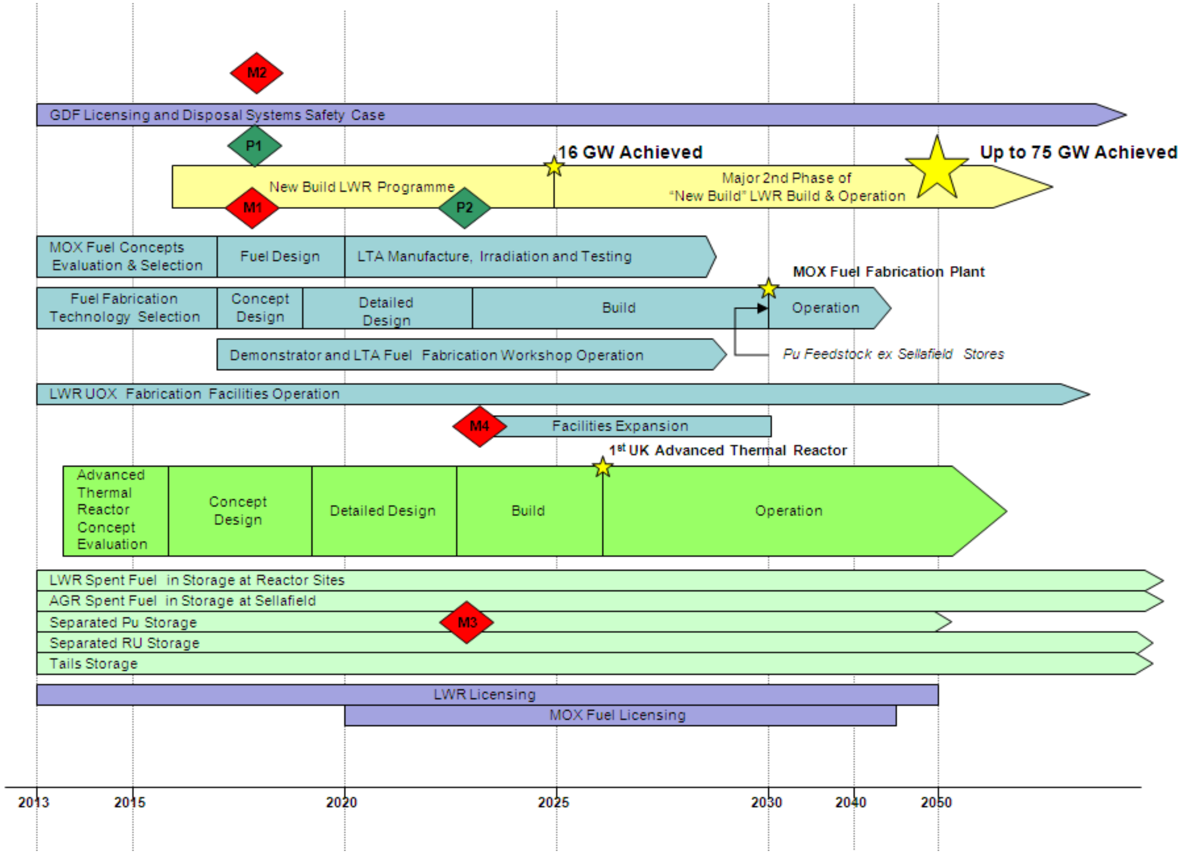
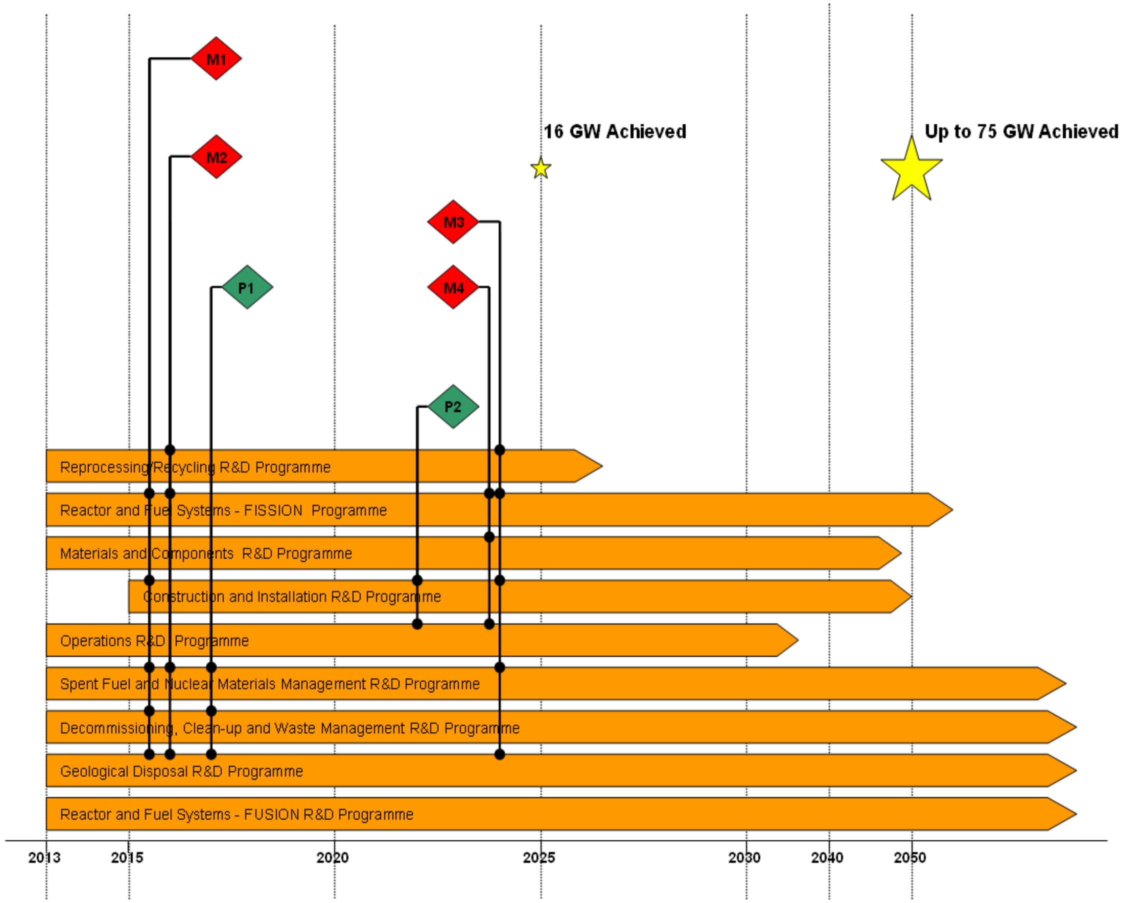
M7	Update of UK Fusion Energy Vision
P1	Host community acceptance or otherwise of geological disposal
Note	Indicative timelines are shown in those cases where decisions are taken to immobilise U and Pu, and to proceed with geological disposal programme beyond Stages 1 - 4

Figure 8: Illustrative timeline of research areas for baseline pathway



KEY TO FIGURES 9 AND 10:	
AGR	Advanced Gas-cooled Reactor
GDF	Geological Disposal Facility
GW	Gigawatt
LTA	Lead Test Assembly
LWR	Light Water Reactor
MOX	Mixed Oxide Fuel
UOX	Uranium OXide
M1	Proceed with second phase of LWR fleet
M2	Revision to scope of GDF in light of second phase of LWR fleet
M3	Decision on re-use of Pu in LWR MOX
M4	Decision on expand UOX fabrication facilities in light of second phase of LWR fleet
P1	Host community acceptance or otherwise of geological disposal of spent fuel for a 75 GW open fuel cycle programme
P2	Additional sites/further site expansion
Note	Indicative timelines are shown in cases where decisions are taken on second phase of LWR fleet, Pu re-use, UOX facilities expansion and host community acceptance or otherwise of geological disposal of irradiated fuel

Figure 9: Illustrative timeline for open fuel cycle pathway



KEY TO FIGURES 9 AND 10:	
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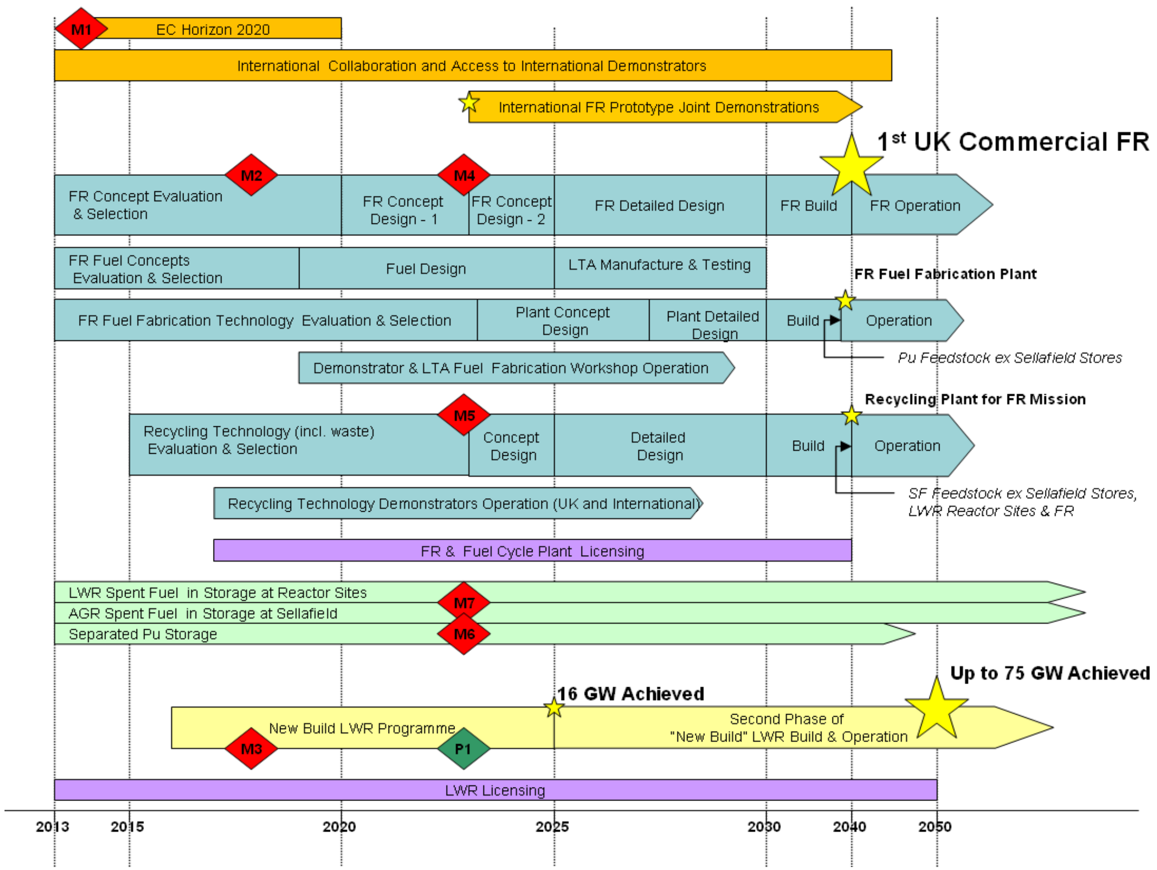
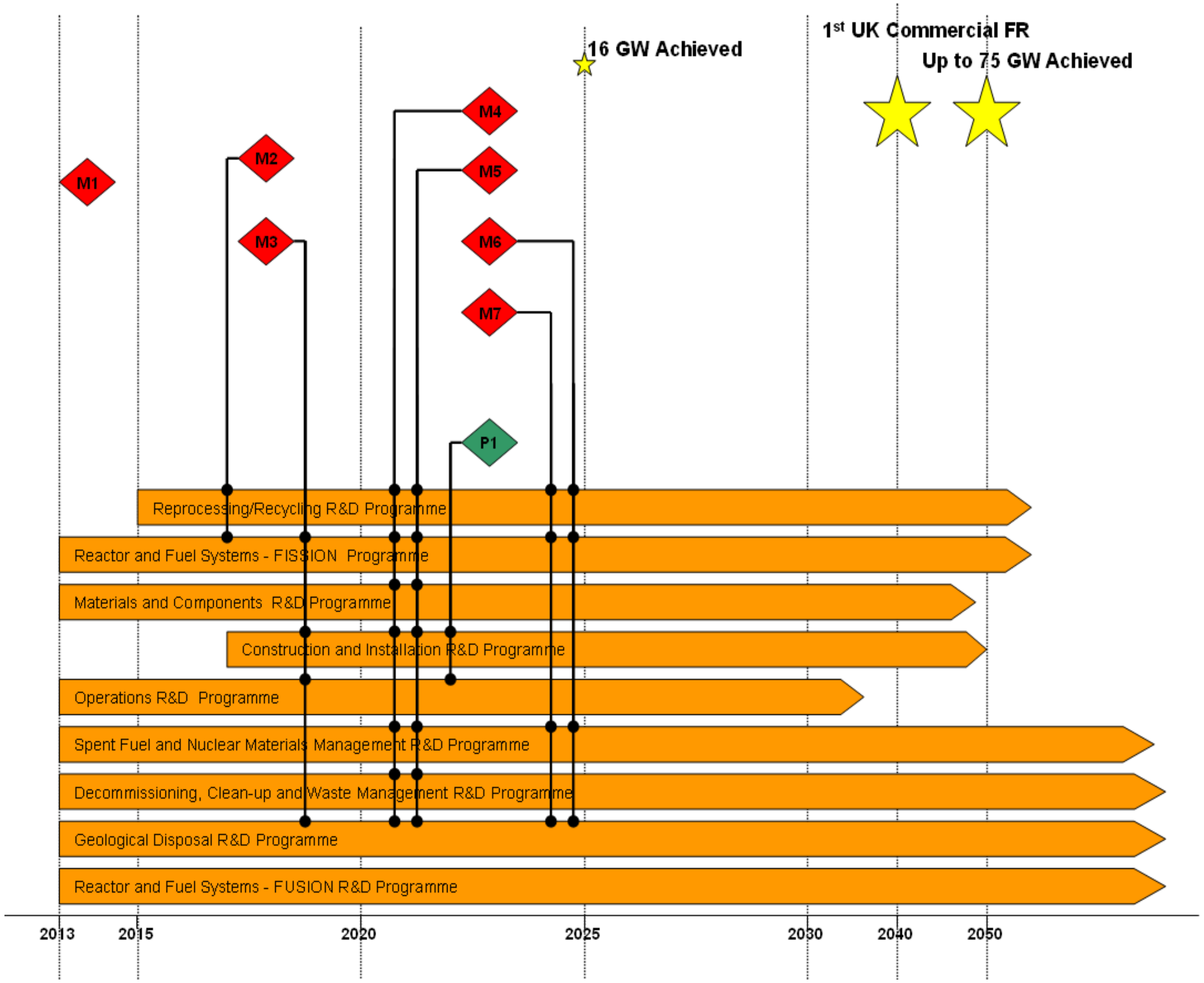
M3	Decision on re-use of Pu in LWR MOX
M4	Decision on expand UOX fabrication facilities in light of second phase of LWR fleet
P1	Host community acceptance or otherwise of geological disposal of spent fuel for a 75 GW open fuel cycle programme
P2	Additional sites/further site expansion
Note	Indicative timelines are shown in cases where decisions are taken on second phase of LWR fleet, Pu re-use, UOX facilities expansion and host community acceptance or otherwise of geological disposal of irradiated fuel

Figure 10: Illustrative timeline of research areas for open fuel cycle pathway



KEY TO FIGURES 11 AND 12:	
AGR	Advanced Gas-cooled Reactor
EC	European Commission
FR	Fast Reactor
LTA	Lead Test Assembly
LWR	Light Water Reactor
Pu	Plutonium
SF	Spent Fuel
M1	Commit to EC Horizon 2020 for leverage
M2	Develop commercial FR through international demonstrator project participation
M3	Proceed with second phase of LWR build
M4	Proceed with design of UK commercial FR
M5	Proceed with design of UK recycle plant
M6	Decision on possible retention of Pu (and potentially RU) for re-use in FR
M7	Recycle of AGR and LWR spent fuel into FR
P1	Additional sites/further site expansion agreed
Note	Indicative timelines are shown in cases where decisions are taken on second phase of LWR fleet, development of FR and fuel recycle

Figure 11: Illustrative timeline for transition from open to closed fuel cycle pathway



KEY TO FIGURES 11 AND 12:	
AGR	Advanced Gas-cooled Reactor
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FR	Fast Reactor
LTA	Lead Test Assembly
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SF	Spent Fuel
M1	Commit to EC Horizon 2020 for leverage
M2	Develop commercial FR through international demonstrator project participation
M3	Proceed with second phase of LWR build
M4	Proceed with design of UK commercial FR
M5	Proceed with design of UK recycle plant
M6	Decision on possible retention of Pu (and potentially RU) for re-use in FR
M7	Recycle of AGR and LWR spent fuel into FR
P1	Additional sites/further site expansion agreed
Note	Indicative timelines are shown in cases where decisions are taken on second phase of LWR fleet, development of FR and fuel recycle

Figure 12: Illustrative timeline of research areas for transition from open to closed fuel cycle pathway

7. R&D Programmes

Introduction

Current research programmes are being carried out under a clear set of accountabilities, including support to operating reactors and the delivery of lifetime extensions (EdF Energy), clean-up of civil nuclear sites (NDA), the implementation of geological disposal (NDA Radioactive Waste Management Directorate (RWMD)), and regulator-led programmes (Office for Nuclear Regulation, Environment Agency, Scottish Environment Protection Agency). There is currently no long-term research programme in place to support the development of an increased contribution from nuclear fission to UK power generation.

A structured R&D programme will need to be developed and implemented if the UK wishes to retain the option to expand the contribution of nuclear fission to deliver a low carbon source of energy. A long-term national R&D programme will need to build on existing research programmes, as illustrated in Figure 13. A small number of issues (interface issues) will be of interest to both programmes requiring some dialogue and exchange of information. One such example may be the issue of plutonium disposition. Government's preferred policy is that the vast majority of the existing stockpile of separated plutonium should be reused as MOX. The NDA is currently exploring the means of implementing this policy. Under the closed fuel cycle pathway, involving the construction of fast reactors, this material could be deployed as fuel for the fast reactor fleet.

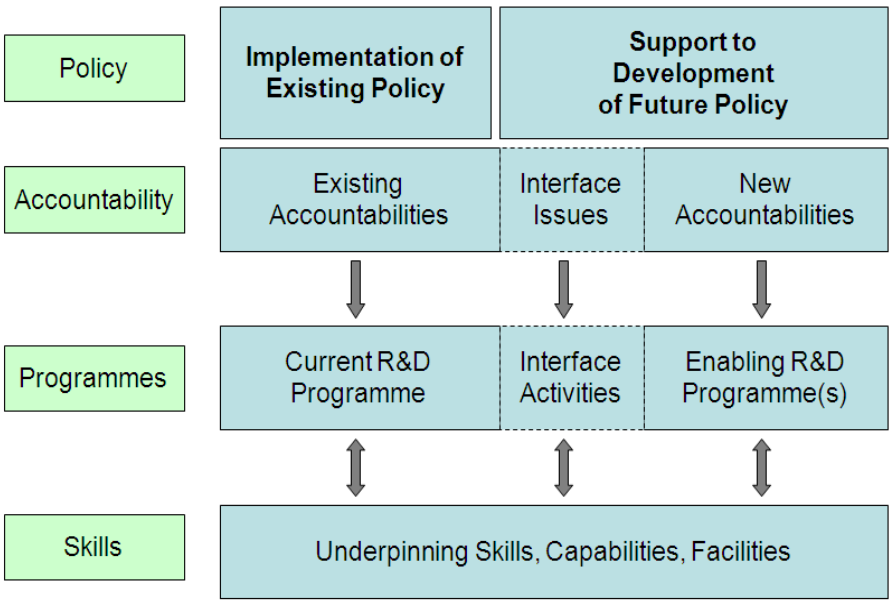


Figure 13: Existing and future R&D programmes and accountabilities

The additional, enabling R&D programme would need to address the issues associated with a range of possible pathways and would need to include the following activities:

Identifying priority R&D needs across programme areas;

- Developing an integrated R&D programme, from research through development to deployment to meet those needs;
- Generating subject matter experts;
- Supporting the nuclear R&D skills pipeline;
- Ensuring that the appropriate data is generated at the right time to inform energy strategy and policy decisions;
- Establishing mechanisms to ensure effective communication and sharing of learning between programme areas;
- Identifying and acting upon the synergies that exist between different programme areas, to accelerate technology development;
- Establishing a mechanism which enables UK nuclear businesses to realise growth opportunities in overseas markets by acting with one voice as ‘UK nuclear’;
- Aligning the nuclear R&D community to meet the needs of the full range of potential future programmes; and
- Establishing a mechanism that ensures the nuclear manufacturing businesses have programmes of activities, in terms of facilities, equipment, skills and capabilities, to deliver the nuclear energy R&D strategies in a cost effective manner that enables growth, both in the UK and globally.

This document identifies the R&D that would be needed to realise a baseline R&D programme and additionally considers the implications of a significant expansion (up to 75 GW installed capacity) in nuclear power generation. If a decision is made to expand significantly, further decisions will be required to select an appropriate fuel cycle and reactor design or designs from the wide range of options that currently exist. These include fuel cycles based on uranium, thorium and combinations of fissile materials, construction of large reactors only, or a mixture of large reactors with SMRs, and the use of only thermal reactors or a combination of thermal and fast reactors. The R&D identified would provide information that informs these decisions, and should include programme elements to support these decisions. No options are ruled out at this stage.

National R&D Programme

There is currently no national integration of nuclear energy R&D in the UK. A number of organisations sponsor R&D to address particular nuclear issues, mostly focused on short to medium term issues, and a larger number of organisations perform R&D, including academia, national laboratories and industry. A list of organisations co-ordinating aspects of nuclear energy R&D is included in Annex E.

The fragmented nature of programmes means that the UK nuclear R&D community is not currently optimised to undertake a national programme of the scale or ambition required to deliver the future nuclear energy pathways, particularly those predicated on large future nuclear build. Coordination of, and interchange between, programme elements could greatly enhance R&D output and economic impact, and strengthen the UK offering internationally (see Figure 14). A high-level description of the nine R&D programme areas is shown in Table 1.

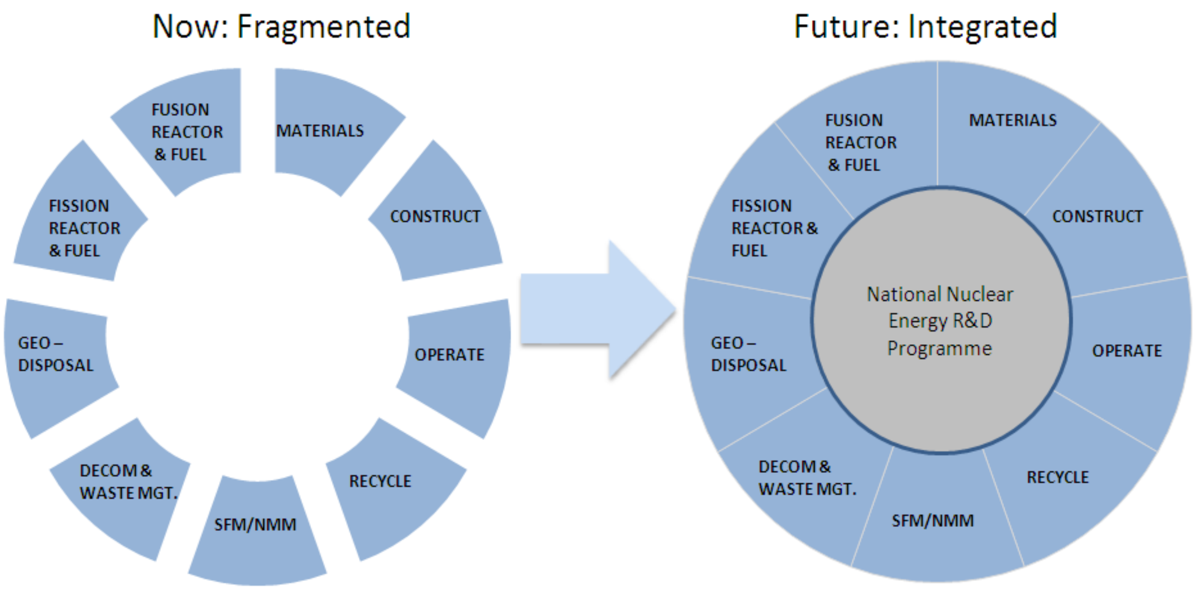


Figure 14: Present and future coordination of nuclear R&D

There is a need to develop an integrated R&D programme to support the life extension of the existing reactor fleet, and the supply chain needs in delivering the new build programme, in addition to delivering the decommissioning and clean-up and geological disposal R&D programmes.

Table 1: High level description of the R&D programme areas

R&D Programme Area	Short Title (Figure 14)	Description
Reactor and Fuel Systems – Fission	Fission Reactor & Fuel	R&D skills and capabilities for the design and manufacture of potential future advanced reactor system technologies, including Generation IV systems and LWRs such as SMRs. This area also includes the design, manufacture and supply of fuel (including enrichment).
Materials and Components	Materials	Design, manufacture and supply of nuclear components. This includes R&D on the materials state of critical components in the reactor core to enable delivery of life extensions for existing reactors and the design and R&D to inform development of and manufacturing technologies for new and optimised materials for new build and future reactor systems.
Construction and Installation	Construct	Nuclear (and non-nuclear) island technology and construction, installation and commissioning. This includes R&D for development in modular construction and design for new build and decommissioning, and engagement with the supply chain for optimised delivery of new build and fuel cycle plants, including skills (regulatory, project management).
Operations	Operate	R&D to support existing plant operations, maintenance, testing and inspection – supporting life extensions and ensuring the UK's operational plants (both reactors and fuel cycle facilities) can be safely and efficiently operated through to the end of their life.
Reprocessing / Recycling	Recycle	Includes current fuel processing and advanced reprocessing for future pathways that involve a high generating capacity, and which are likely to rely on recycling nuclear materials and potentially the concept of burning minor actinides in fast reactors; the "closed fuel cycle".
Spent Fuel and Nuclear Materials Management	SFM/NMM	R&D on the treatment, packaging, storage and transport of Higher Activity Wastes (HAW), spent fuels and nuclear materials both to continue to meet existing requirements and for the future.

R&D Programme Area	Short Title (Figure 14)	Description
Decommissioning, Clean-up and Waste Management	Decom. & Waste Mgt.	Decommissioning and clean-up R&D will continue to be driven primarily by the current legacy clean-up mission for which NDA is responsible. A significant expansion in nuclear power generation would result in an increase in the scale of the decommissioning task, but may not create new technical challenges. This area includes decontamination technology, radioactive waste treatment and storage, and radioactive waste retrieval including remote handling. LLW disposal at the LLWR is discussed within the Roadmap under this programme area.
Geological Disposal	Geo-disposal	NDA RWMD is responsible for implementation of geological disposal of the UK's higher activity wastes. This includes delivery of research work to refine facility design and construction, improving understanding of chemical and physical properties and interactions of emplaced waste, addressing specific issues raised by regulators, and supporting development of site specific safety cases.
Reactor and Fuel Systems – Fusion	Fusion Reactor & Fuel	The main fusion research challenges have been i) achieving the conditions needed for fusion, ii) developing materials suitable for use in a fusion environment, and iii) addressing the major technological challenges associated with large scale fusion power production. The first is largely solved and the emphasis globally is shifting towards the materials and technology issues.

A significant R&D programme would be needed to support the implementation of either of the pathways involving the expansion of nuclear power generating capacity. The Closed Fuel Cycle pathway will not be met solely through private sector investment and aspects of the Open Fuel Cycle pathway (e.g. geological disposal) are also outside the private sector's remit. The creation of an environment which stimulates a nuclear R&D programme will ensure that the UK is able to adopt a closed fuel cycle as part of the strategy for delivering a low carbon economy.

Successful completion of R&D capable of supporting the implementation of a large nuclear programme will require research across the Technology Readiness Level (TRL)[21] spectrum. Although the UK has a strong history of nuclear R&D and still has world leading skills in particular sectors, the UK no longer has the strength in depth required to deliver a large programme effectively. The age profile of UK nuclear expertise is such that a substantial proportion of the remaining skills and internationally renowned experts will be lost to retirement within the next 10 years.

[21] NASA website: http://www.nasa.gov/topics/aeronautics/features/trl_demystified.html

One of the immediate priorities of a national nuclear R&D programme therefore must be to create the next generation of subject matter experts, a process which will take at least a decade. This needs to be supported by an increase in the number of students achieving PhD qualifications in relevant subjects, or equivalent experience, to ensure that a sustainable high-level skills pipeline is achieved and maintained. Action particularly needs to be taken in skills areas that lie outside those where clear accountabilities have already been set, such as the NDA mission to deliver clean-up and decommissioning.

In addition to a skilled population of researchers an organisational infrastructure is required which may expand the range and number of nuclear R&D facilities/equipment, both at national laboratory and university level. This includes, for example, facilities in which highly active materials such as irradiated fuels can be examined, or which can be used to take microscopic samples that can be exported to other (non-active) research facilities, including university laboratories, for testing and examination. One of the ways of meeting this requirement is through the formation of a facility/equipment 'cluster' called the National Nuclear User Facility (NNUF), which would establish a multi-user, multi-purpose national capability able to support a number of strands of nuclear R&D including optimising facilities for the irradiation, machining and examination of materials at the National Nuclear Laboratory (NNL), Culham Centre for Fusion Energy (CCFE), and the University of Manchester’s Dalton Cumbrian Facility (DCF). One component of the NNUF proposal centres on creating leading edge facilities for the receipt, size reduction and detailed examination of highly irradiated materials, thus facilitating new insights into material properties and structures to support the development of advanced fission technologies. To be successful, such facilities will need to be accessible to the whole research community. Further work will therefore be required to devise and implement access arrangements.

International collaboration will be essential to the development of advanced reactors and the associated fuel cycle facilities. Several countries are active in these fields, including the US, France, Japan and South Korea. The UK will need to develop credible national R&D programme where it wishes to participate in international R&D collaboration.

Although the UK may have the ambition to be a leader in low carbon energy generation, it is neither desirable nor realistic to be the leaders in all aspects of the nuclear fuel cycle. A strategic decision will need to be taken on the areas in which the UK should take a leading role. A leading role can be established by hosting facilities for the demonstration of aspects of technology required in the fuel cycle. As well as establishing an internationally recognised centre of excellence, this has the additional advantage of creating new jobs which support the operation of the facility, as well as meeting the high technology requirements of the researchers.

An early priority for a national nuclear R&D programme should be to identify the demonstration facilities that could be hosted in the UK, playing particularly to the UK’s strengths. For example the UK could choose to exploit its expertise in various aspects of nuclear fuel by hosting demonstrators for advanced fuel fabrication and/or spent fuel recycling technology.

The UK is already a significant participant in spent fuel management projects co-funded by the European Commission (for example ACSEPT, ASGARD and SACSESS[22]), so it would be a relatively modest step to develop and demonstrate proliferation resistant flowsheets for recycling spent thermal and fast reactor fuels. The NNL Central Laboratory Phase 3 hot cells are designed to be a facility for undertaking the recycling R&D necessary to underpin the chemistry and flowsheet development programmes. The Nuclear Advanced Manufacturing Research Centre (NAMRC) has already been established to develop technologies to manufacture structural components for reactors. A complementary Advanced Fuel Cycle R&D facility, incorporating high-temperature materials testing relevant to high-temperature gas reactors, would build on the UK's capability in nuclear fuel technologies to create new jobs and build long-term economic impact in a growth area critical to national and international nuclear energy programmes. This could include possible involvement in an international high-temperature gas-cooled reactor demonstrator under the Generation IV International Forum (GIF) programme.

The European Fusion Development Agreement (EFDA) vision for the Fusion programme was updated in early 2013[23]. UK funding will be essential to supplement the EU funding of CCFE activities. The UK participates in fusion energy research in a major role globally, and is well placed to secure benefits of the fusion energy programme post 2050.

A series of R&D programme areas and the needs which they should address are identified in Annex F. It is important that each area is implemented appropriately to ensure that the UK is able to evaluate its options objectively. An early priority should be to establish a rational basis for identifying those areas in which the UK wishes to establish a world leading capability, or to take a leading role in international collaborations.

The consolidated findings derived from Annex F, in terms of the capability, research output and technology that are delivered, are shown in Table 2.

[22] Actinide reCycling by SEParation and Transmutation (ACSEPT), Advanced fuelS for Generation IV reActors: Reprocessing and Dissolution (ASGARD), Safety of ACtinide SEparation proceSSes (SACSESS).
[23] European Fusion Development Agreement (EFDA), Fusion Electricity: A roadmap to the realisation of fusion energy, November 2012, www.efda.org

Table 2: Summary of national R&D programme capability, research output and technology delivered

R&D Programme Theme	Capability Delivered	Research Output	Technology Delivered
Manufacture and Construction (including components and materials, construction and installation).	Advanced manufacturing capability for components, high temperature materials and construction techniques. Sufficient skilled scientists and engineers to support implementation, if required. Continuity of subject matter experts.	Advanced and high temperature materials. Methods for achieving safety certification of embedded firmware (software embedded within hardware). Advanced instrumentation and control methods. Methods for incorporating technological developments into operating systems.	Advanced construction, installation and commissioning technologies and techniques. Fabrication technologies.
Front End of Fuel Cycle (including fuel fabrication, reactor design, reactor operations and materials behaviour).	Establish research programme to investigate fuel fabrication technologies. Complete commissioning of Phase 2 of the NNL Central laboratory to include fuel pin and lead test assembly manufacturing capability. Access to materials test reactor. Advanced reactor development and assessment. Sufficient skilled scientists and engineers to support implementation, if required. Continuity of subject matter experts.	Analysis of fuel and reactor options to inform strategic decisions. Fuel fabrication methodologies. Fuel cycle modelling of a range of reactors and fuels. Fuel performance assessments. Formal capture of knowledge from historic UK fast reactor programme. Licensing and regulatory framework for advanced reactors.	Accident resistant or inherently safe fuel designs. Design and evaluation of reactor concepts. Monitoring and assessment technologies. Preferred advanced reactor designs/concepts. Case for lifetime extension of existing reactors accepted. Advanced materials.

R&D Programme Theme	Capability Delivered	Research Output	Technology Delivered
Back End of Fuel Cycle (including spent fuel storage, fuel recycling, nuclear materials management, waste management and decommissioning).	Active facilities able to handle highly active materials. Establish and implement research programmes to investigate: • proliferation resistant technology options for recycling spent fuel. • safe storage of spent fuel. Access arrangements in place to enable access to active laboratories. Sufficient skilled scientists and engineers to support implementation, if required. Continuity of subject matter experts.	Flow sheets for spent fuel recycling processes. Small/medium scale demonstration of spent fuel dissolution, separation and product finishing. Demonstration of the practicability of closing the fuel cycle. Evaluation of the overall consequences of closing the fuel cycle (for example, quantifying the impact on raw material supply and geological disposal). Develop and demonstrate processes for treating waste streams arising from the back end of alternative fuel cycles which are compatible with geological disposal. Demonstrate the compatibility of the products of spent fuel recycling for reuse in advanced reactors. Demonstrate the ability to store spent fuel, wastes and nuclear materials safely and securely. Safety case for the long term storage of spent fuel. National archive of materials.	Sustainable recycling route for UK spent fuel. Safe, secure interim storage of spent fuel, nuclear materials and wastes. Waste treatment, packaging and immobilisation technologies. Waste characterisation and segregation technologies. Decontamination technologies. Remediation technologies for contaminated land.

R&D Programme Theme	Capability Delivered	Research Output	Technology Delivered
Geological Disposal	Application of social sciences to geological disposal and the communication of science. Access to sufficient geoscientists to support site selection and the implementation of geological disposal. Regulator driven research to support scrutiny of implementer plans. Access to underground research facilities for short and long term experiments. Access to facilities to work on highly active materials. Sufficient skilled scientists and engineers to support implementation, if required. Continuity of subject matter experts.	Evaluation of the impact of possible future nuclear power programmes on the implementation of geological disposal. Assessment of the impact of disposal options for surplus uranium and plutonium. Characterisation of candidate disposal sites. Assessment of the post closure performance of candidate disposal sites. Transport, operational and post closure safety cases for a geological disposal facility.	Host community acceptance of geological disposal.
Fusion	Manufacturing process for first fusion wall. Secure access to a National Nuclear User Facility. Sufficient skilled scientists and engineers to support implementation, if required. Continuity of subject matter experts.	Computer simulations of fusion reactors. Hot isostatic pressing. Performance data for tritium breeding. Transient and accident analysis for safety studies. Non-destructive examination and testing technologies.	Next generation structural materials. High temperature materials. Hot isostatic pressing for bonding of beryllium, copper, chromium and zinc. Demonstration of power production from fusion by 2050. Magnetic fusion.

Cross-Cutting Capabilities

Several technical topics, for example safeguards and security, cut across the individual R&D programme areas and, in addition to these, R&D in a wide range of complementary disciplines are required such as social factors, risk perception, human factors, safety analysis and socio-economics. A high-level description of cross-cutting capabilities is shown in Table 3. These cross-cutting capabilities are common to nuclear fission, fusion and, in many cases, wider industry.

Table 3: High level description of cross-cutting capabilities

Area	Capability	Description
Assessment	Safety and Environmental	Delivery of nuclear safety requirements and expectations to ensure protection of workers, the public and the environment from the hazards associated with nuclear operations.
	Safeguards/ Security	Protection of special nuclear material, Government property, and information from theft, diversion, sabotage, espionage, unauthorised access, compromise and other hostile acts.
	Proliferation Resistance	Development of proliferation resistant fuel cycles and research on securing, detection, assay and characterisation of nuclear material.
	Socio-economic	Consideration of the socio-economic impacts of nuclear energy. For instance, the principle of volunteerism, which applies to the siting of a geological disposal facility, means that the social, political and economic aspects merit specific attention within the R&D programme.
Engineering Support	Systems Design	Design concepts for complete integrated nuclear energy concepts used to understand the impact of introducing various innovative and advanced systems and components on the performance, safety and the feasibility of the design.
	Engineering Simulation/ Modelling	Engineering, simulation and modelling for R&D, design and construction of nuclear energy systems.
	Training/ Virtual Reality	3D visualisation and simulation to assist decommissioning, manufacture and maintenance of new build plant.

Area	Capability	Description
Knowledge Management	Knowledge Management/ Transfer	Preservation and transfer of existing experience and knowledge acquired over many decades by the UK nuclear workforce (now reaching or beyond retirement) and to facilitate the efficient acquisition of this knowledge by the next generation of nuclear workforce.
Financial Risk Management	Finance/Contract mechanisms	Innovative approaches to financing new build of nuclear power stations addressing the unique risk allocation and procurement issues.
Regulatory Frameworks	Regulatory and Licensing Frameworks	Laws and regulations that outline the legal requirements to be met. They may also be complemented by policies, standards, directives and guidelines.
Generic Capabilities	High Performance Computing	Developing and applying computational methods and software in order to support the design and safety of nuclear facilities, improve reactor core designs and nuclear fuel performance, ensure the safety of nuclear materials, such as spent nuclear fuel, and support development of geological disposal safety cases.
	Operational Research	Employing techniques from other mathematical sciences, such as mathematical modelling, statistical analysis, and mathematical optimisation, to arrive at optimal solutions to complex nuclear energy decision-making problems.

8. Nuclear Energy R&D Skills

A substantial expansion of nuclear fission in electricity generation represents a major challenge to the UK. Successful delivery will depend critically on the ability to regenerate an experienced, expert R&D community. Such a community is essential to provide a trained workforce for the nuclear programme, create innovative solutions to the many technical challenges presented by a future nuclear programme, and ensure the UK can deploy, operate and regulate the necessary technologies. An immediate, concerted effort, without which future nuclear programmes cannot be delivered, is therefore needed to meet this skills challenge.

The vision for regeneration of the UK's high level (experienced and expert) nuclear fission R&D skills is that the UK will be able to deliver the large future nuclear energy programmes envisaged in the Roadmap pathways.

The development of skilled R&D personnel for the nuclear industry requires around five to ten years of experience. The development of nationally or internationally renowned subject matter experts takes longer: a minimum of ten to fifteen years, and this requires that they are engaged in leading edge R&D for this period. The availability of skilled R&D personnel and subject matter experts is critical not only for the experience required to build robust safety cases for nuclear operating plant, but also to provide the leadership and expertise necessary to implement the longer-term R&D that is needed to inform future nuclear pathways and to provide strategic advice on emerging nuclear issues.

Applied R&D has historically proved to be a training ground for staff across the nuclear industry. It was common practice to spend a few years in an R&D department and then move to other areas such as operations, design and strategy or to one of the nuclear regulators. Many of the senior leaders of the nuclear industry have a background that includes R&D.

Universities provide a prime source of high-level skills for industry, including the R&D sector, generally at the high end of the skills pyramid. However expertise in the applied nuclear R&D/industrial environment is predominantly developed by experience over a number of years and does not necessarily require formal training or previous nuclear research experience upon entry to the industry, although this is clearly beneficial. In practice, R&D in the nuclear industry requires capabilities across a broad range of scientific and engineering disciplines.

A comprehensive evaluation of the skills needs to support up to 16 GW of nuclear new build using LWRs operating an open fuel cycle is already being carried out. A substantially larger nuclear programme, further in the future and possibly including novel reactor technologies and a closed fuel cycle, will be much more demanding and will need to be underpinned by extensive R&D and associated R&D skills. Immediate action to address future skills needs is required because the lead time for skills development of subject matter experts is 10-15 years. This action will enable exploitation of all of the UK's capabilities in order to meet a critical skills shortage by fostering the next generation of suitably qualified and experienced persons and subject matter experts, or equivalent, in academia, industry, national laboratories and regulators.

Whilst at overview level there are common capabilities required across a range of technical areas, at a detailed level, more detailed analysis shows that gaps can and do exist. Annex G shows the core applied R&D capabilities as a matrix against UK strategically important (or potentially important) programme areas; the capabilities are either highlighted as being leading or supporting. The table in Annex G refers to the position following the closure of THORP and Magnox reprocessing around 2018 (and with Sellafield MOX Plant closure) and reflects the position in the absence of any new programmes commissioned to ensure capabilities are maintained.

The analysis in Annex G highlights that there are a number of specific technical capabilities that will shortly fall below critical level either in numbers or due to the expertise being lost. This will be due to programmes being closed, as in the case of reprocessing and fuel technology development, or due to the age profile of staff in areas where there are insufficient programmes to support successors to the current experts.

As well as tackling the next generation of subject matter experts, it is recognised that other mechanisms for developing and retaining these personnel are also part of the R&D skills activity, especially in the short term. These include:

- Maintaining and developing the next generation of suitably qualified and experienced persons and subject matter experts from early/mid-career R&D practitioners;
- Retraining experienced staff attracted into the nuclear industry from other sectors; and
- Retaining as far as possible senior staff with the high-level skills and knowledge gained over extended careers in the nuclear industry.

9. Prioritisation, Actions and Metrics

R&D Programme Prioritisation

Decisions on nuclear policy in the near future range from broad policy decisions to specific choices of technologies. These will include, but will not be limited to:

- Should there be an increasing level of power generation from nuclear fission?
- Should an open fuel cycle be adopted, or would a closed fuel cycle be more appropriate?
- What should the mix of power generation from thermal power reactors and fast reactors be?
- Does a thorium fuel cycle offer strategic benefits to the UK?
- How and when could nuclear fusion technology be commercially deployed?

Evidence needs to be produced before decisions on future technologies (e.g. open vs. closed fuel cycles) can be made on an informed basis, and at the appropriate time, to ensure that nuclear energy pathway options are not inadvertently foreclosed. This Roadmap sets out the R&D programmes necessary to provide the required evidence base.

There are a number of ways in which an increase in nuclear power generation could be realised, including the use of either an open fuel cycle or a closed fuel cycle and the adoption of a wide range of reactor types. It is not clear at this time how to decide between pursuing an open fuel cycle over a closed fuel. For example, there is currently a broad global resurgence of interest in power generated by nuclear fission and ambitious construction programmes are planned. In light of this, some studies conclude that world uranium reserves are sufficient and that the mining capacity can be expanded to meet the demand from these programmes, yet other studies question the rate at which uranium could be supplied at a reasonable cost, in both financial and environmental terms[24], and note that decarbonising the world electricity supply by 2050 would consume all the currently known uranium resources[25].

The lack of consensus indicates that, in order to keep options open, it may be necessary to research closed fuel cycles and associated reactor designs that minimise the reliance on fresh supplies of uranium ore for fuel fabrication, in parallel with research in support of an open fuel cycle pathway.

Additionally, there are currently a number of claimed benefits of the thorium fuel cycle over the uranium fuel cycle. Although the principles are well understood, the

[24] Joint economic and physical constraints on nuclear power: how much uranium would be needed to decarbonise electricity supply, D Liu, G Butler, P Johnson, P Duck, G Evatt, and S Howell, Proc. IMechE Vol. 226 Part A: Journal of Power and Energy
[25] Towards a low carbon pathway for the UK, Smith School of Enterprise and the Environment, University of Oxford, March 2012

evidence base for the thorium fuel cycle is much smaller in the UK than that for uranium fuels, and more research is needed to provide the evidence to support any future decision.

Therefore, in order to retain the ability to pursue any of these options at an appropriate time, the UK must ensure that it has access to a full and agile R&D capability, until such time as a firm, well founded strategy decision is made.

The UK's decommissioning, waste management and geological disposal programmes that are currently under way are a necessary component of all the pathways discussed in the Roadmap, and will also benefit from such a strengthened R&D skills base and improved access to facilities and international fora.

Through consultation with industry and academia, nine national R&D programme topic areas have been recognised and described in the Roadmap, which would support delivery of the Baseline Pathway and also an increase in nuclear power generation in the UK.

Research objectives have been identified for each of the programme areas which need to be addressed in the short and longer term. These can be grouped into three common categories, as follows:

- **Skills and Knowledge** - The need to fund research programmes to protect and develop the nuclear fission skills base in general and to develop a framework within which subject matter experts can be developed and sustained, as well as generating underpinning data to support strategic and technical decision making.
- **Organisational Infrastructure** - Development of a National Nuclear User Facility which ensures that both academic and applied researchers have access to facilities able to handle the full range of radioactive materials, up to and including irradiated nuclear fuel.
- **International Collaboration** - Active re-engagement with international collaborative programmes, such as the Generation IV International Forum.

The research objectives have been prioritised to identify those which need to be addressed within a period of two to three years in order to secure the UK's R&D capability needs, to ensure that the UK's strategic energy options are not limited prematurely, and to provide data to underpin future strategy and policy decisions. The priority objectives are set out in Table 4.

Table 4: Roadmap priority R&D objectives

Category	Roadmap Priority R&D Objectives
Skills and Knowledge	Safeguard skills and capabilities at risk and introduce procedures for generation of subject matter experts. Deploy Knowledge Management to ensure retention of key information and data and, importantly, capture earlier UK fast reactor programme knowledge. Develop a rational basis (data bank and analysis) for selecting a preferred UK future nuclear contribution to UK power generation. Develop a rational basis (data bank and analysis) for selecting a preferred recycling technology, if a closed fuel cycle is to be adopted. Develop and demonstrate recycling flowsheet science and technology for a possible UK future closed fuel cycle. Develop and demonstrate flowsheet science and technology for managing the wastes which may be generated by a future fuel cycle. Develop a rational basis for selecting a preferred UK future nuclear energy fuel cycle.
Organisational Infrastructure	Deploy the UK's extensive and world leading nuclear fuel cycle R&D facilities, which exist across a variety of institutions, to deliver national and internationally focused R&D programmes, as well as commercial R&D for overseas clients.
International Collaboration	Build on existing, and develop new, multilateral and bilateral international nuclear energy links to develop complementary goals and symbiotic relationships.

This document does not aim to set out the detailed scope of work required to deliver the priority research objectives and to deliver the programmes themselves. This would be a significant piece of work requiring the input of a wide range of technical specialists and should be one of the first tasks carried out within the programmes themselves under a new UK nuclear R&D coordinating mechanism.

Recommended Actions

It is recommended that Government should lead on delivery of the following actions (Table 5) for improved nuclear energy R&D coordination, optimised national capability, skills development and international collaboration to meet the needs of the Baseline and future nuclear energy pathways. The timescale for completion of all these actions is prior to the end of 2014.

Table 5: Roadmap recommended actions

Issue	Roadmap Recommended Action	Metric
Coordination	1. Establish a new UK nuclear energy R&D coordinating mechanism to: a. Detail the specific R&D needs associated with the bounding nuclear energy pathways; b. Serve national interests in the area of R&D across the full nuclear lifecycle; c. 'Horizon scan' domestically and internationally for upstream requirements; and d. Represent the UK internationally.	UK nuclear energy R&D co-ordinating mechanism established
	2. Implement a start-up project for the national nuclear energy R&D programmes with targets of establishing the details of the programmes' scope and objectives, and delivering the priority objectives that have been identified in this Roadmap, once they too have been detailed.	Project commenced
National R&D Capability – Organisational Infrastructure	1. Define a longer-term mission for the NNL, coupled with changes to its remit to ensure responsiveness to the new nuclear strategy. In addition: a. Provide investment in existing facilities, where refurbishment is necessary, and fully actively commission new ones to realise their full benefit to the UK; and b. Enable access by both industry and academia to NNL facilities to allow the UK to have a commercial advantage in the domestic and global marketplace.	Mission defined
	2. Establish organisational infrastructure to ensure access to key active research facilities, equipment and materials for the wider nuclear research community.	National Nuclear User Facility (NNUF) established

Issue	Roadmap Recommended Action	Metric
	3. Continued HM Government support through existing initiatives (such as the NAMRC) to enable industry and research entities to exploit successful mid TRL technology development activities.	None
National R&D Capability – Skills and Knowledge	1. Establish an integrating body to oversee a national nuclear R&D skills strategy to be delivered by NNL, academia and the National Skills Academy for Nuclear (NSAN). The body would be tasked with: a. Defining future national R&D skills needs, particularly development of next generation subject matter experts, and an implementation plan to ensure their sustainability. b. Working with academia and NSAN members to develop the approach for establishing an integrated R&D skills pipeline from R&D to industry.	Body established
	2. Implement a feasibility study to develop an industry wide Knowledge Management system, building on the NDA's Knowledge Hub, which will be the 'single point of knowledge' providing access to nuclear information, subject matter experts, peer-to-peer collaboration tools, communities of practice, inter-project learning, subject matter fora, and the national nuclear archive.	Study completed
National R&D Capability - International Collaboration	1. Department for Business, Innovation and Skills/Foreign and Commonwealth Office networks (Science Innovation Network (SIN) and UK Trade and Investment (UKTI)) to implement the strategy overseas with clear UK objectives.	Objectives established
	2. Increase UK involvement in Generation IV technology development through sustained domestic programmes and international fora such as the Generation IV International Forum (GIF).	Increased activity
	3. Develop plan for optimal influence over and participation in the Euratom R&D programmes; including identification of key demonstrator facilities the UK could host.	Plan developed

Issue	Roadmap Recommended Action	Metric
	4. Continue involvement in the International Thermonuclear Experimental Reactor (ITER) project through R&D contributions, to position UK industry for a substantial share of the future fusion economy.	Project involvement continues
	5. Define clear objectives for bilateral relationships with, for example: a. The US - for SMR and advanced fuel cycles opportunities and decommissioning. b. France - for its ASTRID sodium fast reactor and the Jules Horowitz Reactor (JHR) materials test reactor consortium; future fuel cycles, decommissioning and geological disposal. c. South Korea – for Generation IV fast reactors and advanced reprocessing; predominantly a business/economic opportunity. d. Saudi Arabia, Malaysia – examples of emerging nuclear markets with business opportunities. e. Japan – potential links on decommissioning, new build, Generation IV, and advanced fuel cycles.	Objectives defined

Impact of Decisions Made in the Period 2013 – 2016 to Retain Technology Options

Associated with the above enabling actions, a suite of early decisions has been identified, which is likely to be necessary to ensure that all nuclear pathway options remain available to the UK. Details of these decisions and their impact are shown in Table 6 below. The outcome of these decisions will not commit the UK to a particular strategy for power generation by nuclear fission. The aim is to generate the information needed to inform strategic decisions. The research programme will need to be modified in the light of such decisions and can be focused on the needs of any of a range of energy strategies. Decisions have been identified within the following thematic areas: reactor systems, fuel fabrication, and spent fuel recycling.

Table 6: Impact of decisions (2013 – 2016) to retain technology options

Decision	Date	Theme	Fuel Cycle Closed	Fuel Cycle Open	Assumption	Potential Consequence (of not making decision)	Opportunity
UK to resume active participation in the Generation IV International Forum.	2014	Next Generation Reactors, including Fast Reactor	✓	✓	First commercial UK next generation reactor could be operational in 2040.	Delay in international collaboration leading to delays in eventual implementation. Pursuing next generation reactors without collaboration could have cost implications. Not pursuing fast reactors could constrain future energy options.	Collaboration will give influence on international programmes. Opportunity to create and exploit IP. Builds on existing expertise. Hosting a demonstrator could bring revenue into the UK.
Extend capability to independently and authoritatively evaluate and regulate additional Gen III / III+ and advanced thermal reactors.	2013	Thermal Reactors - general	✓	✓	Advanced thermal reactors could be deployed in the UK.	Greater dependence on vendors / utilities. UK becomes a passive receiver of technology.	Ability to leverage industrial sector support.

Decision	Date	Theme	Fuel Cycle Closed	Fuel Cycle Open	Assumption	Potential Consequence (of not making decision)	Opportunity
Join US Dept. of Energy Small Modular Reactor (SMR) programme.	2013	Thermal Reactors – SMRs.	✓	✓	UK may wish to deploy SMR as part of the energy mix. UK industry is in a position to join a consortium that is successful in obtaining US Dept. of Energy funding.	Not participating in the US programme could increase costs. Failure to join could result in a lost opportunity for UK involvement in deployment.	Leverage UK capability to create and exploit IP. Share costs with US.
Invest in UK fuel fabrication capability and infrastructure.	2014	Fuel Fabrication	✓	✓	Lead test fuel assemblies would need to be manufactured for all future reactors.	Risk of loss of UK capability following Sellafield MOX Plant (SMP) closure. Difficult to enact current policy to use plutonium in MOX fuel manufacture.	Generate revenue by supplying fuel pins and lead test assemblies to the international market. Create wider opportunities for UK industry. Create revenue by hosting an international demonstration facility.

Decision	Date	Theme	Fuel Cycle Closed	Fuel Cycle Open	Assumption	Potential Consequence (of not making decision)	Opportunity
Invest in spent fuel recycling capability through R&D using EU and national programme.	2013	Spent Fuel Recycling	✓		A technology decision may need to be made in about 10 years' time if the UK is to adopt a closed fuel cycle.	UK loses leading technical and industrial positions when THORP (Thermal Oxide Reprocessing Plant) closes. Reduced ability to host international fuel recycling demonstration facilities.	Participation in international collaborations could enable the UK to influence those programmes. Enables UK to host an international demonstration facility to create revenue for the UK.
Invest in integration of recycling R&D programme with next generation (including fast) reactors, fuel fabrication and disposal R&D programmes to create a complete fuel cycle capability.	2016	Spent Fuel Recycling	✓		As above.	Credibility of next generation (including fast reactor) development programme weakened.	A complete capability which could extend the capacity to generate revenue for the UK. Commission laboratories that are able to handle highly active materials.

Annex A - NRDAB Sub Group Recommendations Relating to Nuclear R&D

Members of the Ad Hoc Nuclear R&D Advisory Board (NRDAB) included representatives of academic institutions, industrial organisations, regulators and applied research organisations. Five sub-groups were established to address aspects of nuclear R&D in the UK and worldwide. Each reported formally to the NRDAB and all of the sub-groups made recommendations relating to R&D, which have been summarised as follows:

Industrial Sub-Group

- The UK's extensive and world leading nuclear fuel cycle R&D facilities exist across a variety of institutions and will be fundamental in the delivery of national and internationally focused R&D programmes, as well as commercial R&D for overseas clients.
- A national R&D body is required to act to serve national interests and represent industry internationally.
- Government will need to support investment in existing R&D facilities with national relevance where refurbishment is necessary, and ensure new facilities are fully commissioned to realise their commercial potential.
- The remit of the existing Government owned bodies such as the NDA and the NNL will need to be changed to enable the most strategic use of the UK's active R&D facilities.
- Some aspects of R&D should be led by industry, including, but not limited to, advanced manufacturing, depleted uranium management, transfer of AGR life extension knowledge to future reactor designs and fuel supply and servicing.
- However, some aspects of R&D will only happen if they are led by Government. These include, but are not limited to, advanced reactor technologies, Small Modular Reactors, fusion, geological disposal and public acceptance.

Academic Sub-Group

- All nuclear research requires a range of specialist facilities and expertise to support work with radioactive and nuclear materials, and with ionising radiation. The UK already has significant capability to support such research but it is fragmented and not well focused on the needs of UK business.
- Developing the broad nuclear energy research agenda and ensuring economic growth will necessitate a new coordinated and integrated approach to the delivery of nuclear R&D that is focused, timely and translates innovation into impact.

- The UK can optimise and network its nuclear research facilities by creating a National Nuclear User Facility (NNUF) that facilitates academic and industrial access.
- The expertise of the wider research community should also be engaged by creating a Nuclear Researchers' Network with the National Nuclear User Facility at its heart.
- An industrial strategy is needed to establish a pipeline of nuclear R&D across the Technology Readiness Levels to enhance business growth. This will ensure that new innovation, knowledge and skills are effectively targeted to maximise economic impact.
- A nuclear skills strategy is needed to address the developing gap in high-level research skills and subject matter experts to ensure the UK increases its tacit and explicit nuclear knowledge and builds momentum in developing and applying research innovation to enhance economic growth.
- The socio-economic benefit of the emerging nuclear R&D programme and the role of nuclear energy within a low carbon economy should be communicated effectively and clearly to the wider public.

Skills Sub-Group

- Establish a national nuclear R&D skills strategy, which will define future national R&D skills (particularly development of next generation subject matter experts) and an implementation plan to ensure their sustainability.
- Implement national R&D programmes to maintain strategically important key capabilities including in future reactor systems and advanced fuel cycle and disposal.
- Implement a strategic approach to procurement to ensure key capabilities are maintained.
- Create a coherent (multi-site) National Nuclear User Facility that incorporates academic access to internationally leading large-scale experimental facilities including the NNL Central Laboratory (including Phase 3), Culham Centre for Fusion Energy (CCFE), and the Dalton Cumbrian Facility (DCF) to underpin R&D skills.
- Develop an integrated skills pipeline to create a clear R&D and subject matter expert career pathway across academia, NNL, industry and regulators, including a range of entry routes including via Higher Level Apprenticeships as well as traditional graduate routes.
- Implement a feasibility study to develop an industry wide Knowledge Management system building on the NDA's Knowledge Hub which will be the 'single point of knowledge' providing access to nuclear information, subject matter experts, peer-to-peer collaboration tools, communities of practice, inter-project learning, subject matter fora, and the national nuclear archive. An area of focus for Knowledge Management activities would be on advanced fuel cycle/reactors.

- Establish an R&D Working Group under the Nuclear Energy Skills Alliance (NESA) comprising of the National Skills Academy for Nuclear, NNL, Sellafield and the Dalton Nuclear Institute to oversee how the above can be taken forward.

International Sub-Group

- The Government should clarify its nuclear policy goals and, in the light of associated market opportunities, determine adequately the appropriate levels of investment in R&D resources and infrastructure (potentially > £30M /yr).
- Simplify the existing frameworks which fund and coordinate nuclear R&D in the UK.
- Identify and provide sustained support for key UK R&D institutions.
- Identify and prioritise R&D target areas which support the UK's nuclear energy and decommissioning strategy e.g. delivery of new build, supporting existing facilities, geological disposal facility, Small Modular Reactors, advanced reactors and fuel cycle technology.
- Identify new, and evaluate existing, multilateral and bilateral links to develop complementary goals and symbiotic relationships.

Geological Disposal Sub-Group

- Geological disposal R&D must support the implementation, as soon as practicable, of geological disposal for the full range of wastes and spent fuels which currently exist, or are committed to be produced. The R&D must meet the needs of implementers, regulators, potential host communities and Research Councils. It must also support the Government in selecting an appropriate site for a geological disposal facility.
- The geological disposal R&D programme or programmes must provide a basis for evaluating the consequences of possible future nuclear energy programmes on geological disposal plans.
- Greater engagement between scientists, engineers, bio-scientists and social scientists should be facilitated to ensure that social issues are addressed and the science and research results relevant to geological disposal are communicated in the most effective manner.

Annex B - Nuclear Fission Reactor Technology

Nuclear power plant technology has evolved as distinct design generations:

- Generation I: prototypes, and first realisations (~1950-1970)
- Generation II: current operating plants (~1970-2030)
- Generation III: deployable improvements to current reactors (~2000 and on)
- Generation IV: advanced and new reactor systems (2030 and beyond)

Generation III

Generation III reactors are mainly evolutions of the Generation II systems, with enhanced safety systems, reliabilities and efficiencies. Described below (adapted from NEA 2010[26]) are the leading designs presently being offered by the major nuclear power plant suppliers worldwide, which are expected to provide the great majority of new nuclear capacity at least until 2020.

- The **AP-1000** is the flagship design from Westinghouse. The AP-1000 is an advanced pressurised water reactor (PWR) with a capacity of about 1,200 megawatts (MW). Although majority owned by Toshiba of Japan, Westinghouse is headquartered in the United States.
- The **EPR** is the main offering from AREVA, the main European nuclear industry group which is majority owned by the French state. Also an advanced PWR, it will have an output of 1,600 to 1,700 MW.
- The **ABWR** (Advanced Boiling Water Reactor) units have outputs in the 1,300 MW range, but up to 1,600 MW versions are offered. The basic design was developed jointly by General Electric (GE) of the United States and Toshiba and Hitachi of Japan. GE and Hitachi subsequently merged their nuclear businesses.
- The **ESBWR** (Economic Simplified Boiling Water Reactor), a further development of the ABWR concept, is the latest offering from GE-Hitachi. Its output will be in the region of 1,600 MW.
- The **APWR** (Advanced PWR) has been developed for the Japanese market by Mitsubishi Heavy Industries (MHI). Output will be around 1,500 MW per unit.
- The **VVER-1200** (also known as AES-2006) is the most advanced version of the VVER series of PWR designs produced by the Russian nuclear industry, now organised under state-owned nuclear holding group Rosatom. The units have a capacity of 1,100 MW.

[26] NEA / IEA (2010), Nuclear Energy Technology Roadmap.

- The **ACR** (Advanced Canada Deuterium-Uranium (CANDU) Reactor) is the newest design from Atomic Energy of Canada Ltd. (AECL), owned by the Canadian Government. Most CANDUs use heavy water to moderate (or slow) neutrons, making it possible to use natural uranium fuel. However, the 1,200 MW ACR will use enriched fuel, the first CANDU design to do so. AECL also offers the Enhanced CANDU 6, a 700 MW unit using natural uranium.
- The **APR-1400** is the latest 1,340 MW Korean PWR design. It is based on original technology now owned by Westinghouse. This has been further developed by Korean industry in a series of more advanced designs.
- The **CPR-1000** is currently the main design being built in China. This 1,000 MW design is an updated version of a 1980s AREVA Generation II design, the technology for which was transferred to China.
- India's **PHWR** (Pressurised Heavy Water Reactor) designs are based on an early CANDU design exported from Canada in the 1960s. The latest units have a capacity of 540 MW, and 700 MW units are planned. Although further developed since the original design, these are less advanced than Generation III designs.

Generation IV

The Generation IV International Forum (GIF) and the International Atomic Energy Agency (IAEA) International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) research collaborations have identified key areas where advanced reactor systems would be expected to demonstrate significantly improved performance compared with current reactors: sustainability; economics; safety and reliability; proliferation resistance and physical protection and waste management.

The Generation IV Technology Roadmap (2002)[27] prepared by GIF member countries, identified six promising reactor system and fuel cycle concepts (see Table 7), along with the research required to study these concepts in view of potential deployment and/or commercialisation.

[27] GIF (2002), A Technology Roadmap for Generation IV Nuclear Energy Systems. Generation IV International Forum.

Table 7: Overview of the six Generation IV systems

System	Neutron Spectrum	Coolant	Temperature (°C)	Fuel Cycle	Size (MW)
VHTR (very-high temperature reactor)	Thermal	Helium	900-1000	Open	250-300
SFR (sodium-cooled fast reactor)	Fast	Sodium	550	Closed	30-150 300-1500 1000-2000
SCWR (supercritical water-cooled reactor)	Fast / Thermal	Water	510-625	Open / Closed	300-700 1000-1500
GFR (gas-cooled fast reactor)	Fast	Helium	850	Closed	1200
LFR (lead-cooled fast reactor)	Fast	Lead	480-800	Closed	20-180 300-1200 600-1000
MSR (molten salt reactor)	Fast / Thermal	Fluoride salts	700-800	Closed	1000

The six selected systems employ a variety of reactor, energy conversion and fuel cycle technologies. Their designs feature thermal and fast neutron spectra, closed and open fuel cycles and a wide range of reactor sizes. The European roadmap for nuclear technology development is shown in Figure 15.

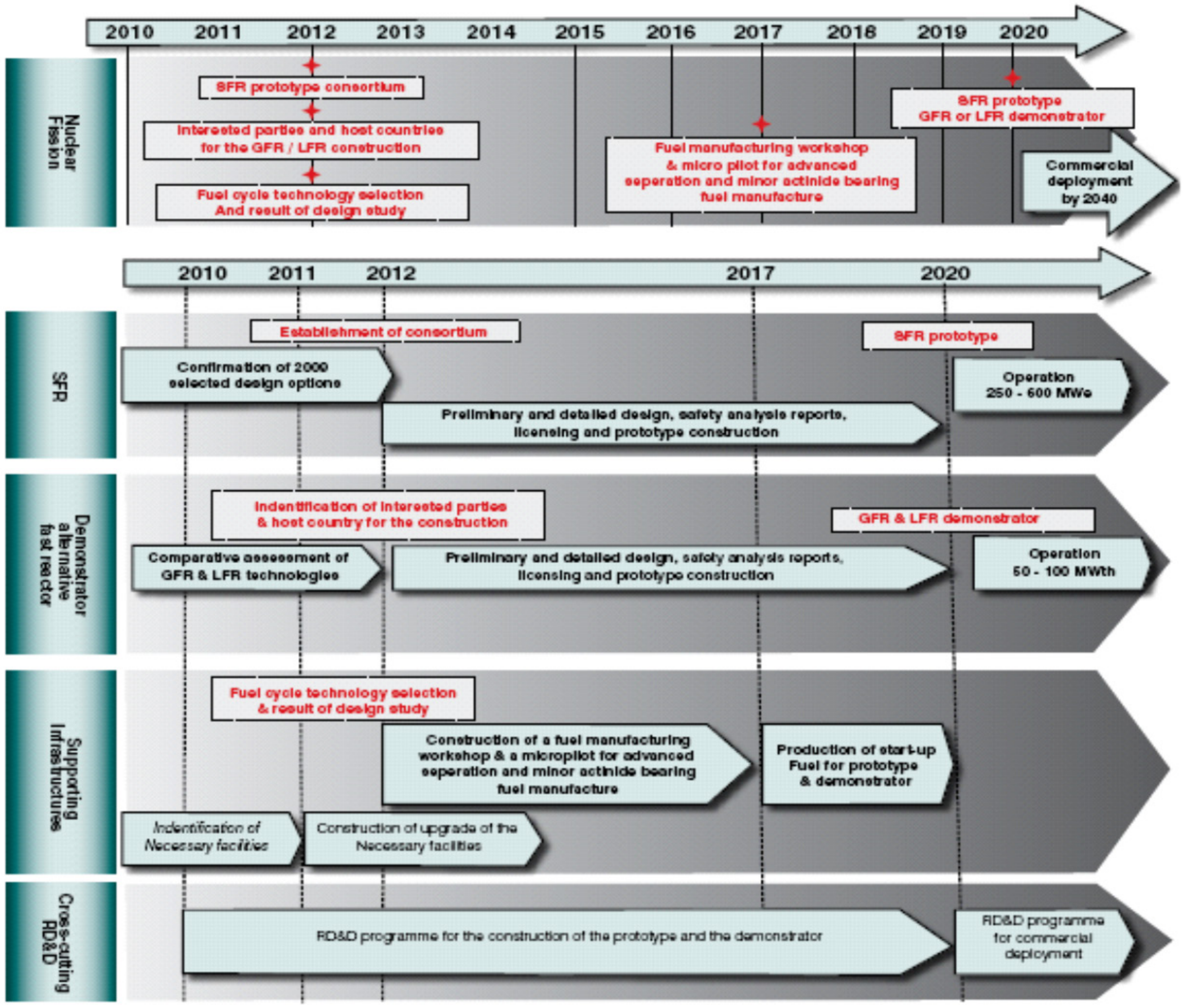


Figure 15: European roadmap for nuclear technology development[28]

[28] EC (2009), Investing in the Development of Low Carbon Technologies (SET-Plan) - A Technology Roadmap. European Commission.

The six types of reactor being considered by GIF can be divided into two main types: (A) thermal reactors; and (B) fast reactors, with breeding potential. Details of these are listed below (adapted from NEA 2010[29]).

(A) Thermal Reactors

Thermal reactors in the Generation IV category are developments of Generation III, but operate at notably higher temperatures. Development of high temperature reactors is also driven by the potential to use the high-grade heat for industrial processes (oil, chemical and metal industry, synfuels and hydrogen production, seawater desalination, etc.) with the potential to be co-located close to industrial centres. Very High Temperature (VHT) reactors also have the potential to produce hydrogen directly from water without electrolysis.

Very-High Temperature Reactor (VHTR) - A graphite-moderated, helium cooled reactor with a once-through uranium fuel cycle.

The chief attraction of the VHTR concept is its ability to produce the higher temperatures (up to 1,000 ºC) needed for hydrogen production and some process heat applications. However, VHTRs would not permit use of a closed fuel cycle. Reference designs are for around 250 MW of electricity, or 600 MW of heat, with a helium coolant and a graphite-moderated thermal neutron spectrum. Fuel would be in the form of coated particles, formed either into blocks or pebbles according to the core design adopted. VHTR designs are based on prototype high-temperature gas-cooled reactors, including examples built in the United States and Germany, and much R&D has been completed. Remaining challenges include developing improved temperature-resistant materials, and the fuel design and manufacture.

Supercritical Water-Cooled Reactor (SCWR) - A high-temperature, high-pressure water-cooled reactor that operates above the thermodynamic critical point of water.

Of the Generation IV designs, the SCWR is most closely related to existing LWR technology. SCWRs would operate at higher temperatures and pressures, above the thermodynamic critical point of water, allowing design simplification and greatly improved thermal efficiencies. Reference designs provide up to 1,500 MW, use uranium or mixed oxide fuel, and have outlet temperatures up to 625ºC. SCWRs could have either a thermal or a fast neutron spectrum; the latter would use a closed fuel cycle based on centralised fuel facilities. Major R&D challenges involve overcoming safety-related core design issues, as well as developing corrosion-resistant materials.

(B) Fast Reactors

The technology for fast reactors has been around for many years and a number of pilot plants and larger scale plants have been built in France, Russia, China, Japan, India and the UK (demonstration and prototype fast breeder reactors at Dounreay).

[29] NEA/IEA (2010), Nuclear Energy Technology Roadmap.

Sodium-Cooled Fast Reactor (SFR) - A sodium-cooled reactor with a closed fuel cycle for efficient management of actinides and conversion of fertile uranium.

Several prototype SFRs have already been built and operated in a few countries, making it one of the best established Generation IV technologies. SFRs feature a fast neutron spectrum, liquid sodium coolant, and a closed fuel cycle. Full-sized designs (up to 1,500 MW) use mixed uranium plutonium oxide fuel, with centralised recycling facilities. Small designs in the 100 MW range, using metallic fuel and co-located recycling facilities, are also being considered. SFRs have a relatively low (550ºC) outlet temperature, limiting their use for high-temperature applications. Reducing capital costs and increasing passive safety are important R&D aims, together with the development of advanced fuel reprocessing technologies. Examples of the SFR technologies include:

- ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration): a SFR led by the French Commissariat à l'Énergie Atomique et aux Énergies Alternatives (CEA), involving EdF and Areva.
- PRISM (Power Reactor Innovative Small Module): a SFR designed by GE-Hitachi.

Lead-Cooled Fast Reactor (LFR) - A liquid-metal-cooled reactor using lead/bismuth with a closed fuel cycle for efficient conversion of fertile uranium and management of actinides.

The LFR system would feature a fast-spectrum liquid metal-cooled reactor and a closed fuel cycle. Molten lead is a relatively inert coolant, offering safety advantages as well as being abundant. Designs being investigated to date include both small (20 MW) and mid-sized (600 MW) designs. The former would be a factory-fabricated plant with a very long refuelling interval (15-20 years). Initially, LFRs would be developed for electricity production, but high temperature versions could allow hydrogen production. Major R&D needs are in fuels, materials and corrosion control. An example of this technology is the Multi-purpose Hybrid Research Reactor for High-tech Applications (MYRRHA) LFR technology pilot proposed by Belgium.

Gas-Cooled Fast Reactor (GFR) - A fast-neutron-spectrum, helium-cooled reactor and closed fuel cycle.

The GFR system reference design includes a 1,200 MW helium-cooled reactor with a fast neutron spectrum and a closed fuel cycle with an on-site spent fuel treatment and re-fabrication plant. It features a high thermal efficiency direct-cycle helium turbine for electricity generation. The high outlet temperature (850ºC) could also be suitable for hydrogen production or process heat. Key R&D challenges include the development of new fuels (such as ceramic-clad fuels or fuel particles) and materials, as well as the core design and the helium turbine. An example of this technology is the ALLEGRO GFR supported by Central and Eastern Europe.

Molten Salt Fast Reactor (MSR) - In MSRs, fuel materials are dissolved in a circulating molten fluoride salt coolant.

The liquid fuel avoids the need for fuel fabrication and allows continuous adjustment of the fuel mixture. The current concept is for a 1,000 MW fast neutron reactor with a closed fuel cycle. This could be used for breeding with fertile thorium or for burning plutonium and other actinides. An Advanced HTR with liquid fluoride salt coolant is also being studied. Molten salt chemistry, handling and corrosion resistance, as well as materials and the fuel cycle, are the main R&D challenges.

Small Modular Reactors (SMR)

Designs for SMRs, with generating capacities ranging from tens to a few hundred megawatts, are being developed in several countries, often through cooperation between Government and industry. Countries involved include Argentina, China, Japan, Korea, Russia, South Africa and the United States. SMR designs encompass a range of technologies, some being variants of the six Generation IV systems selected by GIF, while others are based on established Gen III LWR technology. Such reactors could be deployed as single or double units in remote areas without strong grid systems, or to provide small capacity increments on multi-unit sites in larger grids.

Annex C - Advanced Fuels

The development of advanced fuels is an essential component of the framework for developing advanced fuel cycles and taking into account new fuel processing technologies. Fuels used in current commercial reactors are oxide based, for example, uranium oxide fuels and uranium-plutonium oxide fuels (e.g. MOX fuel). For fast reactors, fuels need a high density of fissile material and high thermal conductivity since the reactors operate at higher heat generation rates than those of thermal reactors. Alternatives to oxide fuels that offer improvements in terms of these factors have been under consideration, including metallic fuels, nitrides and carbides. Some of the main advanced fuel types under investigation are listed below (largely based upon IAEA, 2003)[30].

Advanced uranium dioxide fuels – These are aimed at achieving higher burn-up in reactors for the same volume of fuel compared with current fuels. Methods to achieve this include using doped fuels, for example with beryllium oxide or silicon carbide, or ‘duplex’ fuels, in which fuel pellets have an inner core at a different enrichment to the remainder of the pellets. Additionally, ‘dual-cooled fuels’ are being investigated, where additional cooling can be achieved via a central cladding tube, which could be enabled through the use of annular pellets.

Advanced uranium-plutonium oxide fuels – These contain recycled/recovered plutonium.

Advanced metallic fuels – These are normally alloys with uranium (e.g. uranium - zirconium), plutonium or other actinides. For example, uranium alloys such as uranium silicide have been considered for thermal reactors, whilst uranium-plutonium-zirconium alloys have been investigated for fast reactors due to their higher density and thermal conductivity compared with oxide fuels.

Carbide fuels – These have a greater thermal conductivity than oxide fuels, a high breeding ratio and high heavy-metal density, making them attractive for use in fast reactors. Examples include uranium monocarbide, mixed uranium-plutonium carbides and carbides of transuranic elements.

Nitride fuels – As for carbide fuels, nitride fuels (e.g. uranium mononitride) have a high thermal conductivity, high breeding ratio and high heavy metal density.

Inert matrix fuels – These can be applied to utilise and dispose of plutonium (e.g. by forming solid solutions of plutonium) and minor actinides in a once-through cycle. Examples of potential ceramic inert matrices include yttria-stabilised zirconia, zirconium carbide and silicon carbide.

[30] IAEA, 2003. Development status of metallic, dispersion and non-oxide advanced and alternative fuels for power and research reactors. IAEA-TECDOC-1374. International Atomic Energy Agency.

Dispersion fuels – As for inert matrix fuels, dispersion fuels can utilise plutonium and minor actinides in a once-through cycle. Proposed dispersion fuels include pelletised particle or prismatic fuels. For example, TRISO (tristructural-isotropic) fuel, which is a type of micro fuel particle that is designed for use in high temperature reactors (e.g. the pebble bed reactor) can be pressed into pellets and used in standard fuel pins rather than in graphite pebble beds.

Molten salt fuels – These are liquid fuels in which nuclear fuel is dissolved in the molten salt coolant for use in thermal reactors or molten salt fast reactors. Liquid fluoride salt coolants containing uranium and thorium fluorides have been under investigation as part of uranium-plutonium and thorium fuel cycles.

Fuels containing thorium – Examples include thorium dioxide and thorium-based molten salt fuels for use within the thorium fuel cycle.

Fuels containing minor actinides – These fuels utilise the minor actinides (e.g. americium, neptunium) that can be extracted from spent nuclear fuel. Minor actinide fuels include alloys and oxides.

Annex D - Advanced Fuel Cycles

In addition to conducting R&D to improve current fuel cycle technologies, significant effort is being devoted to the development of advanced fuel cycle technologies. For many countries, R&D on advanced fuel cycles and nuclear systems is being undertaken within co-operative programmes (e.g. the Generation IV International Forum (GIF), the IAEA International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), the International Framework of Nuclear Energy Cooperation (IFNEC) and European Commission's Framework 7 Programme projects - Actinide Recycling by Separation and Transmutation (ACSEPT) project and the Advanced Fuels for Generation IV Reactors: Reprocessing and Dissolution (ASGARD) project). The objectives of the longer term advanced fuel cycle concepts under investigation include reducing the mass and radiotoxicity of wastes for final disposal, optimising the use of natural resources and enhancing proliferation resistance features, by not separating out plutonium in isolation.

Alongside the development of fast neutron reactors and advanced fuels, advanced processing methods are being developed to close the fuel cycle and recycle the actinides. Current reprocessing and recycling methods involve the removal of uranium and plutonium from the spent fuel, with minor actinides (e.g. neptunium, americium and curium) and fission products remaining in the waste stream. Advanced processing techniques are being developed for the selective separation (partitioning) of the long-lived radioisotopes within the spent fuel, including minor actinides and possibly some fission products. These radioisotopes may then be transformed into shorter-lived radioisotopes (transmutation), either in fast reactors or in accelerator-driven systems[31]. Alternatively, the separated isotopes can be vitrified as waste and disposed of separately.

There are two main categories of advanced fuel cycles. In the first, the separated minor actinides may be mixed directly with the fuel (homogeneous transmutation) or incorporated into dedicated targets (heterogeneous transmutation), with the fuel cycle combining the use of, typically, LWR reactors and low conversion ratio fast reactors or accelerator driven systems. The second category comprises a fully closed fuel cycle with the combined treatment of transuranics (including minor actinides) and plutonium as fuel in fast reactors, with the ability to multi-recycle plutonium and uranium.

[31] Accelerator driven systems have been designed to burn minor actinides produced during the reprocessing of fuel, resulting in a reduction in the radiotoxicity and heat load of the wastes for disposal.

Separation – Advanced Processing Technologies

Key to the development of advanced fuel cycles is advanced processing technologies. There are two main advanced processing technologies being considered:

- Hydrometallurgical processes (aqueous processes); and
- Pyrochemical processes (dry processes).

Current reprocessing techniques are based on the hydrometallurgical PUREX (plutonium-uranium recovery by extraction) method, in which uranium and plutonium are separated from the minor actinides and fission products. The uranium and plutonium can be recycled as fuel, while the minor actinides and fission products are vitrified as high level waste. There are a range of advanced separation methods under consideration, including modifications to the PUREX process, alternative hydrometallurgical processes to recover the minor actinides, hydrometallurgical processes to remove fission products for waste management purposes and pyrochemical methods. Some of the main advanced processing techniques that are being developed are listed below (largely based upon NEA, 2011)[32].

UREX (Uranium Extraction) process – This is a modified version of the PUREX process that does not involve the isolation of a plutonium stream. The uranium product can be utilised in the fabrication of new fuels, whilst the plutonium and other transuranics remain with the fission products and may be removed for transmutation. This process can be supplemented to recover the fission products iodine, by volatilisation, and technetium, by electrolysis.

UREX+ processes – Only uranium and technetium are recovered initially for recycling and the residual material is treated to recover plutonium with other transuranics. The fission products then comprise most of the high level waste.

NUEX process – This is another modified version of the PUREX process in which uranium is initially separated and then all transuranics (including plutonium) together, with fission products separately.

COEX (Co-Extraction) process – This is based on co-extraction and co-precipitation of uranium and plutonium (and usually neptunium) together, as well as a pure uranium stream, eliminating any separation of plutonium on its own. The ratio of uranium and plutonium can be adjusted and the product converted to oxides for use in new fuels.

SANEX (Selective Actinide Extraction) process – This process allows for the separation of the trivalent minor actinides from the trivalent lanthanides in the PUREX raffinate. The SANEX process has been combined or extended with other processes.

[32] NEA, 2011. Trends towards Sustainability in the Nuclear Fuel Cycle. NEA No. 6980. ISBN 978-92-64-16810-7. Nuclear Energy Agency, Organisation for Economic Co-operation and Development.

DIAMEX-SANEX (Diamide Extraction-SANEX) process – This process involve the selective separation of long-lived radionuclides (focusing on americium and curium) from short-lived fission products. The process uses a malonomide extractant in place of the tributyl phosphate (TBP) extractant used in the PUREX process, which simplifies disposal of the solvent. This process can be implemented with COEX, following separation of uranium, plutonium and neptunium. Uranium, plutonium and minor actinides can be recycled separately in Generation IV fast neutron reactors.

i-SANEX (innovative SANEX) process – Trivalent actinides and lanthanides are co-extracted in a DIAMEX-type process followed by several selective stripping steps for actinides and lanthanides.

GANEX (Group Actinide Extraction) process – This process co-precipitates some uranium with the plutonium (as with COEX), but then separates minor actinides and some lanthanides from the short-lived fission products. The uranium, plutonium and minor actinides together become fuel in Generation IV fast neutron reactors, whilst the lanthanides become waste.

TRUEX (transuranium extraction) process – This is a process used alongside NUEX to extract americium, curium and lanthanide fission products. The remaining fission products in the aqueous phase can then be vitrified for disposal.

TALSPEAK (trivalent actinide lanthanide separation by phosphorus extractants and aqueous complexants) process – This process separates the americium and curium from the lanthanide fission products resulting from the TRUEX process. The lanthanides are then added to the fission product waste from the TRUEX process, before vitrification.

Pyroprocessing – This comprises several dry separation methods for the recovery of uranium and also transuranic elements. Stages in the process include electrochemical separation from molten salts, molten salt/liquid metal extraction, volatilisation and fractional crystallisation. The processes are generally based on the use of either fused salts, such as chlorides or fluorides, or fused metals such as cadmium, bismuth or aluminium. Application is more suited to metal fuels rather than oxide fuels, however oxide fuels can be treated once having undergone reduction step.

Alternative Fuel Cycles – Thorium

Uranium and uranium-plutonium are the primary fuel cycles currently being applied and developed. Alternative fuel cycles are also under consideration, such as the thorium fuel cycle. Thorium is more abundant than uranium in the earth's crust and naturally occurring thorium consists of fertile thorium-232. Through neutron capture and subsequent decay, thorium-232 is transformed into fissile uranium-233. Thorium-based fuels can be used in closed fuel cycles. The characteristics of the spent thorium fuel (including lower quantities of plutonium production than for the uranium fuel cycle) are often stated as a benefit in terms of providing enhanced proliferation resistance. Although thorium-fuelled reactors have previously been demonstrated, the potential future use of thorium requires considerable research and development effort on reactors, alternative fuel cycles and recycling technologies. In addition, studies are necessary to determine the economic and commercial viability of the thorium fuel cycle.

Annex E - Organisations Coordinating UK Nuclear R&D

Coordination Mechanism	Organisation	Role
National	Research Councils UK (RCUK)	The research councils, including the Engineering and Physical Sciences Research Council (EPSRC)-led Energy Programme, play a key role in funding consortia of R&D organisations across a wide range of subjects related to both nuclear fission and fusion.
	Nuclear Research Coordinating Group (NRCG)	NRCG is an informal strategy group convened by EPSRC with the aim of supporting the development of the UK university sector nuclear R&D programme.
	Nuclear Decommissioning Authority (NDA) Research Board	This is an independently chaired board that takes an overview of UK decommissioning R&D including NDA R&D and Radioactive Waste Management Directorate (RWMD) R&D. Representatives are from industry, regulators, academia and international representatives.
	Nuclear Waste Research Forum (NWRF)	NWRF is an advisory body to the NDA Research board. It has a broad membership of NDA, Site license company representatives, regulators and wider industry. The main focus of its work is identifying common R&D needs and opportunities to support integrated waste management and site restoration, with working groups in characterisation, waste packaging, decommissioning and land quality.
	RWMD Technical Advisory Panel (TAP)	The panel is an external group established in 2012, providing strategic advice to RWMD Executive on the delivery of its technical programme and advising the NDA Research Board on research to support geological disposal.
	Office for Nuclear Regulation (ONR)	ONR is the national regulator and maintains a Nuclear Research Index (NRI). The NRI provides guidance on research priorities and the current direction of research, with the aim of encouraging industry to align its research to the current trends.

Coordination Mechanism	Organisation	Role
	Nuclear Advanced Manufacturing Research Centre (NAMRC)	NAMRC works to combine the experience of industry with the capability of universities. Its three work programmes, manufacturing process R&D, quality requirements, and training and skills development, aim to help UK business collaborate and compete internationally.
Skills	National Skills Academy for Nuclear (NSAN)	NSAN is an employer led membership organisation established to ensure that the UK Nuclear Industry and its Supply Chain has the skilled, competent and safe workforce it needs to deal with the current and future UK nuclear programme.
	Nuclear Energy Skills Alliance (NESA)	NESA is a grouping of the key strategic skills bodies and organisations with an interest in nuclear skills, and Government.

Annex F – R&D Programmes

Programme Descriptions

The following tables provide details for each of the programme areas:

Applicability

Applicability to one or more of the three bounding pathways is shown.

Capability and/or Technology Delivered

This shows the outcome of the programmes in terms of the capability and/or technology which will be delivered. These are distinguished between the Baseline (without new build), and Open or Closed (transition from open) Fuel Cycles (up to 75 GW).

Enabling Actions

These are shown for:

- National Facilities (including National Laboratories)
- Skills Maintenance and Development
- Knowledge Management
- Collaboration Action – Bilateral
- Collaboration Action – Multilateral

Entries against each of these are distinguished between those which are under existing accountabilities, and those which relate to new programmes and/or accountabilities.

Programme Activities and Growth Opportunities

The primary programme activities are detailed, together with the economic growth opportunities that these programmes present.

Comments

Comments to support programme table entries.

Programme Area: Reactor and Fuel Systems - Fission		**Programmes: Reactor Design and Technology**	
Applicability	Baseline ✓	Open Cycle ✓	Closed Cycle ✓
Capability and/or Technology Delivered:	Lifetime extensions of Advanced Gas-cooled Reactor (AGR) fleet and Sizewell B achieved.	Advanced Boiling Water Reactor (ABWR) (and other reactor types) licensing and regulatory framework. International collaboration in Gen IV. Prototype Small Modular Reactor (SMR) and Fast Reactor (FR) in operation (through international collaboration). Develop licensing and regulatory framework in parallel.	
Enabling Actions:	**Under Existing Accountabilities**	**New Programmes / New Accountabilities**	
National Facilities	UK nuclear engineering R&D facilities: deliver Nuclear Advanced Manufacturing Research Centre (NAMRC) capability to support reactor design and technology R&D programme.	New nuclear components production facilities. Deliver materials test reactor capability to support current fleet and advanced reactor options through to 2020 onward.	
Skills Maintenance and Development; Knowledge Management	Transfer of technology and skills to civil use. Rolls-Royce has an extensive graduate training scheme, supporting PhD students and post-doctoral researchers and with links to several universities. Introduce scheme to support the creation of the next generation of subject matter experts.	Capture UK fast reactor programme knowledge. Nurture a reactor design community. Safety certification of embedded firmware. Development of advanced control and instrumentation methods. Human factors assessments into the design of control systems which take into account how operators respond in emergency situations. Assess how technological developments can safely be incorporated into extant operating systems.	
Collaboration Action - Bilateral		France – Jules Horowitz Reactor (JHR) & FR programmes. US – FR and SMR development.	

Programme Area: Reactor and Fuel Systems - Fission		**Programmes: Reactor Design and Technology**
Collaboration Action - Multilateral	European Commission Joint Research Centre (EC JRC)- Petten High Flux Reactor (HFR), Halden, Sustainable Nuclear Energy Technology Platform (SNETP), Nugenia, US Department of Energy (USDOE), Electric Power Research Institute (EPRI).	Generation IV International Forum (GIF).
Programme Activities:	Support lifetime extension activities and continued safe operation of existing reactors.	Re-engage with GIF. Develop SMR & FR options within a sustainable fuel cycle in collaboration. Develop licensing arrangements for SMR & FR options.
Growth Opportunities:		Develop niche role for UK on regulatory capability for licensing & operation of SMR & FR. Develop UK contribution to SMR concept. Manufacture of nuclear components/ systems in European region. Provision of safety and regulatory support.
Comments: Seek opportunities for design input to new reactor designs either independently or collaboratively. New reactor type considerations for plutonium disposition.		

Programme Area: Reactor and Fuel Systems - Fission		**Programmes: Fuel Design, Technology and Manufacture**	
Applicability	Baseline ✓	Open Cycle ✓	Closed Cycle ✓
Capability and/or Technology Delivered:	Accident resilient fuel for Gen III Light Water Reactors (LWRs) developed and demonstrated.	Test assembly fabrication facility for LWR Mixed Oxide (MOX) fuel. Remotely handled test assembly fabrication facility for SMR and FR fuels. Demonstrated SMR and FR test assemblies including targets, in conjunction with reactor system development.	
Enabling Actions:	**Under Existing Accountabilities**	**New Programmes / New Accountabilities**	
National Facilities	Deliver NAMRC capability to support current Fuel Design, Technology and Manufacture R&D Programme.	Deliver NAMRC capability to support advanced Fuel Design and Technology R&D Programme. Deliver Fuels Test Reactor Capability through to 2020 onward. Enable university access to facilities for materials and fuel cladding tests. Deliver National Nuclear Laboratory (NNL) Central Laboratory combined Phase 2 and Phase 3 Fuel R&D Programme Capability.	
Skills Maintenance and Development; Knowledge Management	Introduce procedures for generation of subject matter experts.	Capture UK FR programme knowledge. Nurture a fuel design community. Re-engage with GIF.	
Collaboration Action - Bilateral		France – JHR & FR. US – FR and SMR.	
Collaboration Action - Multilateral		GIF, EC JRC- Petten HFR, Halden.	

Programme Area: Reactor and Fuel Systems - Fission		Programmes: Fuel Design, Technology and Manufacture
Programme Activities:	Support lifetime extension activities and continued safe operation of existing reactors.	Re-engage with GIF. Development of remote fuel fabrication technology. Development of SMR and FR fuels, in line with advanced reactor development and advanced recycling development. Development of Post Irradiation Examination (PIE) techniques and predictive and simulation tools for Gen III & Gen IV fuels. In collaboration with others, develop accident tolerant fuels for LWRs. Development of target fuel manufacture and management of irradiated targets via FR development programme. Development of UK fuel manufacturing capability and associated R&D for inherently safe LWR fuel (inc. MOX fuel).
Growth Opportunities:		Develop niche role for UK on design and manufacture of FR and SMR test assembly fuels. Develop niche role for UK on post irradiation examination of FR & SMR fuels. Ensuring appropriate regulatory capability for commissioning and operation.

Programme Area: Design/Manufacture/Supply of Components and Materials		**Programmes: Nuclear Component Manufacture**	
Applicability	Baseline ✓	Open Cycle ✓	Closed Cycle ✓
Capability and/or Technology Delivered:	Nuclear component design, development and manufacturing capability. Materials analysis, assessment and characterisation techniques – understanding and predicting materials performance in reactor systems. Training and skills development – ensuring that the nuclear manufacturing supply chain has the skills required to compete in the global market.	Example advanced materials include Silicon Carbide (SiC) technologies and powder metallurgy.	
Enabling Actions:	**Under Existing Accountabilities**	**New Programmes / New Accountabilities**	
National Facilities	Deliver NAMRC Capability to support forward Nuclear Component Manufacture R&D Programme. Deliver NAMRC Capability to support forward Advanced Materials R&D Programme. University facilities for materials and fuel cladding tests. High temperature facilities and access/develop radiation facilities.	New nuclear components production facilities to be built.	

Programme Area: Design/Manufacture/Supply of Components and Materials		Programmes: Nuclear Component Manufacture
Skills Maintenance and Development; Knowledge Management	Programme for addressing identified gaps in current capability and capacity to ensure that UK manufacturing is able to fully maximise the opportunities presented by nuclear. Rolls-Royce has an extensive graduate training scheme, covering graduates in specifically nuclear disciplines and in more general disciplines appropriate to nuclear industry roles, supporting PhD students and post-doctoral researchers and with links to several universities, especially Manchester University and Imperial College.	
Collaboration Action - Bilateral	Reactor vendors (e.g. flexible response to designs new to the UK).	
Collaboration Action - Multilateral	Office for Nuclear Regulation (ONR), International Atomic Energy Agency (IAEA), US Nuclear Regulatory Commission (US NRC), American Society of Mechanical Engineers (ASME), RCC-M (France: Nuclear Design and Construction Code), World Nuclear Association (WNA) etc. (Design and safety principles for existing and alternative reactor concepts). Some synergies with AGR Plant Life Extension (PLEX) programme and fusion in materials. Nugenia, EPRI, EC JRC-Petten HFR, Halden etc.	Generation IV International Forum.

Programme Area: Design/Manufacture/Supply of Components and Materials		**Programmes: Nuclear Component Manufacture**
Programme Activities:	Nuclear component design, development and manufacturing capability for decommissioning, waste management and new build reactors associated with the open and closed pathways. Continue development of LWR materials and chemistry understanding including mechanistic understanding of the effect of thermal neutron irradiation on materials of construction.	Develop licensing arrangements. Factory capability for welding and finishing Reactor Pressure Vessels (RPVs) and other very large vessels if viable. Develop existing AGR experience in high-temperature materials. Develop synergies with fusion materials. Advanced materials (e.g. SiC technologies and powder metallurgy). Development of materials compatible with fast reactor designs (e.g. molten salts, molten metals, high-temperature gases). Develop mechanistic understanding of the effect of fast neutron irradiation on materials of construction.
Growth Opportunities:	Maximise UK content in national new build construction (technology and skills). Opportunity to establish niche for UK in manufacturing and deployment of UK developed technology in international projects. Development of coding (e.g. ASME) of new reactor components.	Marketing of novel manufacturing technologies. Replacement components and technology transplants for existing reactors. Assembling and finishing large vessels for a wider European and global market if viable.
Comments: Coding of new reactor components is taken to mean development of code cases for new manufacturing methods. New build may lead to ‘build to print’ with reduced design input, placing emphasis on reactor design and technology theme. Obsolescence mitigation: replacement parts and technology transplants for existing reactors also provide design and manufacturing opportunities.		

Programme Area: : Plant Construction, Installation and Commissioning		**Programmes: Construction Technology**	
Applicability	Baseline ✓	Open Cycle ✓	Closed Cycle ✓
Capability and/or Technology Delivered:	Concept and development in modular construction and design for decommissioning.	Modularisation to encourage local build and assembly and engage the UK supply chain. Supply chain for delivery of new build and fuel cycle plants and optimised including skills (regulatory, project management). Advanced construction, installation and commissioning techniques (e.g. heat exchangers, turbines; fuel cycle and waste treatment facilities; combined heat and power installations).	
Enabling Actions:	**Under Existing Accountabilities**	**New Programmes / New Accountabilities**	
National Facilities	Deliver NAMRC Capability to support forward Construction Technology R&D Programme.		
Skills Maintenance and Development; Knowledge Management	Develop construction project management skills for nuclear. Develop regulatory capability to support nuclear construction, installation and commissioning.		
Collaboration Action - Bilateral		US – Small Modular Reactors.	
Collaboration Action - Multilateral		Generation IV International Forum (GIF).	
Programme Activities:	Development of nuclear technology supply chain to construction. Development of modular construction research programme on manufacturing technology and performance.	Development of advanced reactor research programme on construction materials manufacturing and performance.	

Growth Opportunities:	Develop niche role for UK in modular construction for nuclear and encourage skills development.	

Programme Area: Plant Operations, Maintenance, Testing and Inspection		**Programmes: Plant Operations, Maintenance, Testing and Inspection**	
Applicability	Baseline ✓	Open Cycle ✓	Closed Cycle ✓
Capability and/or Technology Delivered:	Continued AGR life extensions. Facilities, knowledge and skills required to support Plant Operations, Maintenance, Testing and Inspection. Control, detection and monitoring systems – techniques to support lifetime assessment of existing reactor systems, current nuclear fuel cycle facilities and legacy facilities. Characterisation, imaging, mapping, and condition monitoring techniques using in-situ and ex-situ techniques, remote, mobile and non-destructive analysis techniques to supplement laboratory based capabilities for monitoring land, buildings, plant and process, equipment. Develop non-destructive examination and testing techniques to reduce inspection times. Condition monitoring & preventative maintenance to increase safe life and reduce downtime. Maintenance of facilities and plant lifetime extensions. Asset condition and/or capacity restoration.	Develop non-destructive examination and testing techniques to accelerate new build programme.	
Enabling Actions:	**Under Existing Accountabilities**	**New Programmes / New Accountabilities**	

Programme Area: Plant Operations, Maintenance, Testing and Inspection		Programmes: Plant Operations, Maintenance, Testing and Inspection
National Facilities	Deliver Research Centre for Non Destructive Evaluation (RCNDE) Capability to support testing and inspection requirements of new build programme. Support to NAMRC and similar national facilities.	Deliver facilities needed to test non-destructive evaluation technologies of advanced reactor materials and environments. Need to ensure that arrangements and funding are put in place to ensure that all NNUF are accessible to both academic and industrial researchers. Demonstration facilities to support introduction of processes and technologies for academia, Small and Medium Enterprises, national laboratories and other prospective supply chain.
Skills Maintenance and Development; Knowledge Management	Measurement and Analysis, Plant Operations & Maintenance Support, Material and Corrosion Science, Plant Inspection and Deployment etc. Skills maintained automatically through a successful new build programme. Ongoing support to maintain and develop technical capability in schools, universities and nuclear supply chain. Includes key activities such as the Technical Scientific Trainee Scheme and apprenticeship and graduate programmes.	Implementation of national nuclear Knowledge Management. Implementation of enablers to support longer term national demands beyond 2020. Address potential skills gap due to programme of UK decommissioning activities, broad front decommissioning at Sellafield from 2020s into the future, nuclear new build and implication from other sectors.
Collaboration Action - Bilateral	NAMRC, Dalton Nuclear Institute, RCNDE.	
Collaboration Action - Multilateral	NAMRC, Dalton Nuclear Institute.	Generation IV International Forum.
Programme Activities:	Development of remote monitoring and inspection technology (legacy and open cycle pathways). Ongoing R&D support to existing AGR life extension programmes.	Development of concepts for monitoring and inspection of advanced reactor plants.

Programme Area: Plant Operations, Maintenance, Testing and Inspection		Programmes: Plant Operations, Maintenance, Testing and Inspection
Growth Opportunities:	Ensuring appropriate regulatory capability. Extended lifetime of AGRs.	Knowledge transfer from AGR to Gen IV HTGR designs. Development of niche skills in new techniques for UK with advanced reactor programme.

Programme Area: Reprocessing/Recycling		**Programmes: Spent Fuel Processing**	
Applicability	Baseline ✓	Open Cycle ×	Closed Cycle ✓
Capability and/or Technology Delivered:	Facilities, knowledge and skills required through to support Magnox and Thermal Oxide Reprocessing Plant (THORP) reprocessing programmes and the subsequent Post Operational Clean Out of legacy facilities. Development of conditioning techniques to support the disposition of exotic fuels. Development and evaluation of reprocessing/recycling flow sheets for legacy fuels (to support strategy decisions and possible implementation). Retaining and sustaining key knowledge, experience and expertise from current reprocessing programme.	Underpinning for advanced reprocessing technology selection. Transfer of knowledge, experience and expertise into any future reprocessing programme. Computer modelling and simulation capabilities to support planning and execution of future recycling requirements. Implications of new fuel types – science and engineering. Maintenance and development of skills, expertise and experience to support future chemical processing of nuclear materials to support future fuel cycle strategy, future reactor operations and implications for recycling nuclear materials. Key topics will include: • Fuel processing for recycling e.g. dissolution. • Actinide separation e.g. chemical separation. • Plant operations. • Advanced reprocessing options to reflect future strategy of open fuel cycle and maintaining closed fuel cycle option.	

Programme Area: Reprocessing/Recycling		Programmes: Spent Fuel Processing
Enabling Actions:	**Under Existing Accountabilities**	**New Programmes / New Accountabilities**
National Facilities	Continue to deliver NNL Windscale Laboratory Irradiated Fuel PIE Capability. Need to ensure that arrangements and funding are put in place to ensure that National Nuclear User Facilities are accessible to both academic and industrial researchers if required. Deliver NNL Central Laboratory Phase 3 Fuel Reprocessing R&D Programme Capability to support requirements arising from clean-up mission.	Deliver NNL Central Laboratory Phase 3 Fuel Reprocessing R&D Programme Capability to support development for future nuclear strategy. Demonstration facilities to support introduction of processes and technologies for academia, Small and Medium Enterprises, national laboratories and other prospective supply chain if required.
Skills Maintenance and Development; Knowledge Management	Current experts train next generation subject matter experts. Deploy Knowledge Management to ensure retention of key information and data. Nuclear Decommissioning Authority (NDA) strategic R&D portfolio supports long term work to support these skills areas. Ongoing support to maintain and develop technical capability in schools, universities and within Sellafield Ltd as well as nuclear supply chain. Includes key activities such as the Technical Scientific Trainee Scheme and Sellafield Ltd apprenticeship and graduate programmes.	Implementation of enablers to support longer term national demands beyond 2020. Implementation of national nuclear Knowledge Management programme. Address potential skills gap due to programme of UK decommissioning activities, broad front decommissioning at Sellafield from 2020s into the future, nuclear new build and implication from other sectors. Programme for transition of knowledge and skills from current programme to advanced programme.
Collaboration Action - Bilateral	France, USDOE.	
Collaboration Action - Multilateral	France, USDOE, Organisation for Economic Co-operation and Development (OECD)-Nuclear Energy Agency (NEA), IAEA-International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), European Atomic Energy Community (Euratom), GIF.	

Programme Area: Reprocessing/Recycling		Programmes: Spent Fuel Processing
Programme Activities:	Skills maintenance and knowledge management to ensure skills and capabilities sustained beyond end of Magnox and THORP reprocessing programmes. Plant support through operational and post-operational phases. Development and evaluation of conditioning techniques for exotic and legacy fuels.	Develop rational basis (data bank and analysis) for selecting a preferred recycling technology. Development of a proliferation resistant recycling technology which minimises or eliminates the separation of nuclear materials. Development and demonstration of recycling flowsheet for UK future fuel cycle. Development and demonstration of flowsheet for associated waste management and wasteforms from a future fuel cycle.
Growth Opportunities:	Ensuring appropriate regulatory capability for market. Reuse of facilities for reactor new build. Take part in, and receive funding from international sources e.g. EU programmes, international research programmes.	
Comments: Includes both recycling under the current Baseline programme and advanced options for possible application in a future fuel cycle.		

Programme Area: Spent Fuel Management		**Programmes: Spent Fuel Storage and Transport**	
Applicability	Baseline ✓	Open Cycle ✓	Closed Cycle ✓
Capability and/or Technology Delivered:	Facilities, knowledge and skills required to support spent fuel management. Characterisation, imaging, mapping, and condition monitoring techniques and in particular remote fuel condition monitoring. Spent fuel storage and packaging methods for the safe storage and disposal of spent fuel. Safety case for prolonged storage of AGR fuels. Packaging methods developed which mitigate potential cladding corrosion. Contingency for management of irradiated Magnox fuel. Technology for management of failed fuels. Design of storage solutions to manage the heat output from spent fuel. Retaining and sustaining key knowledge, experience and expertise for future treatment options or alternative fuel options. Fuel storage (e.g. dry storage). Safety case for prolonged storage of LWR fuels. Computer modelling and simulation capabilities to support planning and execution of future spent fuel management requirements. Identification and evaluation of the key considerations which will subsequently underpin the safety case for the transport of irradiated AGR fuel which has been in long-term interim storage.	Identification and evaluation of the key considerations which will subsequently form the basis for design, safety case and licensing for advanced thermal and fast reactor fuel transport.	

Programme Area: Spent Fuel Management		Programmes: Spent Fuel Storage and Transport
Enabling Actions:	**Under Existing Accountabilities**	**New Programmes / New Accountabilities**
National Facilities	Need to ensure that arrangements and funding are put in place to ensure that National Nuclear User Facilities are accessible to both academic and industrial researchers. Continue to deliver NNL Windscale Laboratory Irradiated Fuel PIE Capability and maintain links with Transuranic Institute and Studsvik. Ongoing availability of Windscale Laboratory PIE facilities for investigation of AGR fuel clad corrosion.	Deliver NNL Central Laboratory Phase 2 and Phase 3 combined Fuel R&D Programme Capability. Demonstration facilities to support introduction of processes and technologies for academia, Small and Medium Enterprises, national laboratories and other prospective supply chain.
Skills Maintenance and Development; Knowledge Management	Ongoing support to maintain and develop technical capability in schools, universities and within Sellafield Ltd as well as nuclear supply chain. Includes key activities such as the Technical Scientific Trainee Scheme and Sellafield Ltd apprenticeship and graduate programmes. NDA strategic R&D portfolio sponsors strategic work in this area to inform strategy development.	Implementation of enablers to support longer term national demands beyond 2020. Implementation of national nuclear Knowledge Management. Address potential skills gap due to programme of UK decommissioning activities, broad front decommissioning at Sellafield from 2020s into the future, nuclear new build and implication from other sectors. Development of knowledge and skills for irradiated fast reactor fuel as well as thermal oxide fuel storage. Development of knowledge and skills for irradiated fast reactor fuel as well as thermal oxide fuel transport. Establish process to generate subject matter experts.

Programme Area: Spent Fuel Management		**Programmes: Spent Fuel Storage and Transport**
Collaboration Action - Bilateral	Maintain links with the Institute for Transuranium Elements (ITU) and Studsvik. Membership of EPRI. IAEA Coordinated Research Programme (CRP) Work.	France, US, Japan.
Collaboration Action - Multilateral	OECD-NEA, IAEA-INPRO, Euratom, International Framework for Nuclear Energy Cooperation (IFNEC).	Generation IV International Forum.
Programme Activities:	Consider learning from Germany and Switzerland on storage concepts and strategies for MOX fuels with high heat output. Develop mechanistic understanding of AGR fuel cladding corrosion. Understanding of AGR fuel cladding corrosion impact on transport packaging.	R&D on Advanced Fuels storage and transport to develop beyond the current ‘concept’ phase to ‘development/demonstration’.
Growth Opportunities:	None identified.	

Programme Area: Nuclear Materials Management		**Programmes: Management including storage**	
Applicability	Baseline ✓	Open Cycle ✓	Closed Cycle ✓
Capability and/or Technology Delivered:	Facilities, knowledge and skills required to support nuclear materials management. Retaining and sustaining capability is a key feature. Characterisation, imaging, mapping, and condition monitoring techniques and in particular monitoring and accountancy tracking. Ongoing support to the delivery of the immobilisation process for plutonium residues. Development, validation and demonstration of a wasteform for the immobilisation of surplus Pu. Development, validation and demonstration of a wasteform for the immobilisation of surplus uranic materials (including hex tails). Underpinned long term storage of the separated Pu stockpile. Computer modelling and simulation capabilities to support planning and execution of future nuclear materials management.	Optimal use of nuclear material within fast reactor programme. Support re-use of Plutonium (Pu) and Uranium (U) into LWR fuel.	
Enabling Actions:	**Under Existing Accountabilities**	**New Programmes / New Accountabilities**	
National Facilities	Deliver Central Laboratory Phase 2 Capability for Pu management R&D. Springfields Fuels (U Tails conversion process).	Implement arrangements and funding to ensure that National Nuclear User Facilities are accessible to both academic and industrial researchers. Demonstration facilities to support introduction of processes and technologies for academia, Small and Medium Enterprises, national laboratories and other prospective supply chain.	

Programme Area: Nuclear Materials Management		**Programmes: Management including storage**
Skills Maintenance and Development; Knowledge Management	Retention of Pu management skills. Ongoing support to maintain and develop technical capability in schools, universities and nuclear supply chain. Includes key activities such as the Technical Scientific Trainee Scheme and apprenticeship and graduate programmes. NDA strategic R&D portfolio sponsors strategic work in this area to inform strategy development.	Implementation of enablers to support longer term national demands beyond 2020. Implementation of national nuclear Knowledge Management. Address potential skills gap due to programme of UK decommissioning activities, broad front decommissioning at Sellafield from 2020s into the future, nuclear new build and implication from other sectors.
Collaboration Action - Bilateral	France, US, Japan.	
Collaboration Action - Multilateral	OECD-NEA, IAEA-INPRO, Euratom, IFNEC.	Generation IV International Forum.
Programme Activities:	Development of strategies for the full range of Highly Enriched Uranium (HEU)/exotic materials. Development of understanding of Pu storage over long timescales. Development and demonstration of immobilisation of bulk Pu and validation of an immobilised Pu wasteform for geological disposal. Development and demonstration of U tails conversion process. Development and qualification of U tails wasteforms compatible with geological disposal.	Re-engage with Generation IV International Forum.
Growth Opportunities:	Nuclear materials management knowledge, skills and expertise.	
Comments: Work relevant to the existing separated Pu stockpile is currently within NDA remit and therefore R&D into issues such as long term storage, reuse and disposal will be covered under those programmes. Work for fast reactor programme outside NDA remit.		

Programme Area: Decommissioning and Clean-up		**Programmes: Decommissioning and Clean-up**	
Applicability	Baseline ✓	Open Cycle ✓	Closed Cycle ✓
Capability and/or Technology Delivered:	Facilities, knowledge and skills required to support decommissioning. In-situ and ex-situ decommissioning and clean-up strategies. Characterisation, imaging, mapping, and condition monitoring techniques using in-situ and ex-situ techniques, remote, mobile and non-destructive analysis techniques to supplement laboratory based capabilities for characterising land, buildings, plant and process, equipment, in-situ and ex-situ waste to understand asset conditions and support decommissioning. Decommissioning of alpha and beta / gamma facilities. Treatment of bulk materials e.g. concrete, building structures, plant and process equipment. Development of decontamination technologies capable of reducing dose rates to man entry levels or to recategorise wastes (e.g. from Intermediate Level Waste (ILW) to Low Level Waste (LLW)). Waste (e.g. legacy pond wastes) and materials retrieval and post operational clean out processes. Note: waste retrieval is considered further under the Waste Management programme area. Development of technologies for the treatment or remediation of contaminated land. Blend of applications – technology transfer, development through to research – supported by facilities and demonstration facilities. Implications of potential site end states including reuse. Safety, environmental related needs alongside UK regulators. Clean-up of legacy facilities will require the		

Programme Area: Decommissioning and Clean-up		**Programmes: Decommissioning and Clean-up**
	development of remotely operated technologies for dismantling and size reduction, decontamination techniques and associated effluent treatment, radiological segregation capabilities for plant and buildings during decommissioning.	
Enabling Actions:	**Under Existing Accountabilities**	**New Programmes / New Accountabilities**
National Facilities	Demonstration facilities to support introduction of processes and technologies for academia, Small and Medium Enterprises, national laboratories and other prospective supply chain. Characterisation platforms and facilities. Low Active (LA), Medium Active (MA) and Highly Active (HA) capabilities to supplement demonstration facilities. Need to ensure that arrangements and funding are put in place to ensure that all National Nuclear User Facilities are accessible to both academic and industrial researchers.	
Skills Maintenance and Development; Knowledge Management	Ongoing support to maintain and develop technical capability in schools, universities and within nuclear supply chain. Includes key activities such as the Technical Scientific Trainee Scheme and apprenticeship and graduate programmes. Specific maintenance of alpha decommissioning skills capability. Specific maintenance of nuclear decommissioning capability.	Implementation of enablers to support longer term national demands beyond 2020. Implementation of national nuclear Knowledge Management. Address potential skills gap due to programme of UK decommissioning activities, broad front decommissioning at Sellafield from 2020s into the future, nuclear new build and implication from other sectors.
Collaboration Action - Bilateral	Support to Industry-led collaboration through Nuclear Waste Research Forum and other UK collaborative groups.	

Programme Area: Decommissioning and Clean-up		Programmes: Decommissioning and Clean-up
	University collaborations e.g. Dalton Cumbrian Facility (DCF), NAMRC. European opportunities (OECD) supplemented by links with others such as IAEA, IFNEC, International Thermonculear Experimental Reactor (ITER) and national laboratory organisations such as the French Alternative Energies and Atomic Energy Commission (CEA), USDOE, Japan Atomic Energy Agency (JAEA) Regulator programmes NDA and estate to continue work under bilateral agreements with USDOE, CEA and Japan in particular Collaboration with regulators through Multinational Design Evaluation Programme (MDEP).	
Collaboration Action - Multilateral	Opportunity to utilise experiences at Dounreay, Research Sites to support decommissioning delivery at Sellafield and in turn support decommissioning delivery in the reactor sites. Support to Industry-led collaboration through Nuclear Waste Research Forum and other UK collaborative groups. University collaborations e.g. DCF, NAMRC, Dalton Nuclear Institute. European opportunities (OECD) supplemented by links with others such as IAEA, IFNEC, ITER and national laboratory organisations such as CEA, USDOE, JAEA. Regulator programmes. Multilateral agreements with Japan and other countries on Fukushima decommissioning.	
Programme Activities:	Industry-led collaboration through Nuclear Waste Research Forum and other UK collaborative groups. Identification, coordination of regional assets in decommissioning for economic benefit e.g. Britain's Energy Coast (BEC)	

Programme Area: Decommissioning and Clean-up		Programmes: Decommissioning and Clean-up
	and associated R&D Alliance. BEC Blue Print and Sellafield Plan. Set up commercial and government demonstrators for decommissioning. NDA coordination activities supporting national strategies such as. Low Level Waste Strategy, Plutonium Contaminated Waste Strategy, Magnox Operation Plan. Development of remote characterisation and remote handling technologies.	
Growth Opportunities:	Utilise the experiences at Dounreay, Research Sites, Sellafield etc to lead on national and international opportunities given the breadth of demands and challenges. Enable deployment of UK decommissioning experience overseas. Technology development and transfer of cross over technologies into other UK sectors. Reuse and recycling of wastes retrieved from clean-up of nuclear industry. Support to nuclear new build, resilience and other nuclear related activities. Enable further deployment of UK decommissioning experience overseas, in addition to those being currently undertaken in Europe. Deploy technologies developed and demonstrated overseas to UK decommissioning challenges.	
Comments: Decommissioning and clean-up R&D will continue to be driven primarily by the current legacy clean-up mission. A significant expansion in nuclear power generation would result in an increase in the scale of the decommissioning task, but may not create new technical challenges.		

Programme Area: Waste Management (including consideration of LLW disposal at LLWR)		Programmes: Waste retrieval, storage and treatment	
Applicability	Baseline ✓	Open Cycle ✓	Closed Cycle ✓
Capability and/or Technology Delivered:	Facilities, knowledge and skills required to support waste management. Experimental rig design and build capability supported by simulant design capability for experimental rig programs. Modification of conventional technologies for application in radioactive waste management. Characterisation, imaging, mapping, and condition monitoring techniques using in-situ and ex-situ techniques, remote, mobile and non-destructive analysis techniques to supplement laboratory based capabilities for characterising, in-situ and ex-situ waste and conditioned waste in storage. Make available the capability to carry out experimental work on high activity wastes and wasteforms. NDA strategic R&D portfolio sponsors strategic work in this area to inform strategy development. Raw waste behaviour prior to treatment. Application of waste treatment processes for Higher Activity Wastes (HAW) – encapsulation, thermal, containerisation. Conditioned waste form performance and assessment of rework capabilities for HAW. Waste form and packaging options for disposal at the Low Level Waste Repository (LLWR) and the Geological Disposal Facility (GDF).	Develop waste treatment and immobilisation methodologies suitable for managing waste arising from advanced fuel cycles.	

Programme Area: Waste Management (including consideration of LLW disposal at LLWR)		**Programmes: Waste retrieval, storage and treatment**
	R&D to support waste management hierarchy principles such as development of decontamination technologies to recategorise wastes (e.g. from ILW to LLW to Exempt and reuse). Processing and disposal of bulk volume wastes – graphite, metals and demolition wastes. Mobile, modular and/or rapid deployable liquid and aerial effluent treatment capabilities. Manage implications of post operational clean out activities of current production plants on existing waste treatment plants. Treatment of residues (typically small volume with varying physio-chemical compositions) from plant, process, building and site decommissioning.	
Enabling Actions:	**Under Existing Accountabilities**	**New Programmes / New Accountabilities**
National Facilities	Demonstration facilities to support introduction of processes and technologies for academia, Small and Medium Enterprises, national laboratories and other prospective supply chain. Characterisation platforms and facilities. LA, MA and HA capabilities to supplement demonstration facilities. Support infrastructure for current and future facilities. Implement arrangements to put in place funding arrangement to ensure that all National Nuclear User Facilities are accessible to both academic and industrial researchers.	

Programme Area: Waste Management (including consideration of LLW disposal at LLWR)		Programmes: Waste retrieval, storage and treatment
Skills Maintenance and Development; Knowledge Management	Ongoing support to maintain and develop technical capability in schools, universities and within nuclear supply chain. Includes key activities such as the Technical Scientific Trainee Scheme and apprenticeship and graduate programmes. Increase in number of PhD students funded by Research Councils.	Implementation of enablers to support longer term national demands beyond 2020. Implementation of national nuclear Knowledge Management, Long Term information repository, link networks. National archive of reactor-exposed materials and components. Address potential skills gap due to programme of UK decommissioning activities, broad front decommissioning at Sellafield from 2020s into the future, nuclear new build and implication from other sectors.
Collaboration Action - Bilateral	Support to Industry-led collaboration through Nuclear Waste Research Forum and other UK collaborative groups. University collaborations e.g. Dalton Nuclear Institute, DCF, NAMRC. European opportunities (OECD) supplemented by links with others such as IAEA, IFNEC, ITER and national laboratory organisations such as CEA, USDOE, JAEA. Regulator programmes. ITU and Studsvik for HA facilities and capabilities. CEA and US for ongoing programmes.	

Programme Area: Waste Management (including consideration of LLW disposal at LLWR)		**Programmes: Waste retrieval, storage and treatment**
Collaboration Action - Multilateral	Opportunity to utilise experiences at Dounreay, Research Sites to support decommissioning delivery at Sellafield and in turn support decommissioning delivery in the reactor sites. Support to Industry-led collaboration through Nuclear Waste Research Forum and other UK collaborative groups. University collaborations e.g. Dalton Cumbria Facility, NAMRC, Dalton Nuclear Institute. European opportunities (OECD) supplemented by links with others such as IAEA, IFNEC, ITER and national laboratory organisations such as CEA, USDOE, JAEA. Regulator programmes.	GIF - fuel cycle research.
Programme Activities:	Assess waste management issues as part of any assessment of alternative spent fuel recycling technologies. Identification, coordination of regional assets in waste management for economic benefit e.g. Britain's Energy Coast and associated R&D Alliance. BEC Blue Print and Sellafield Plan. LLW Repository Ltd waste management programme. Reactor site waste management programmes. Set up demonstrators for waste management technology. NDA coordination activities supporting national strategies such as. Low Level Waste Strategy, Plutonium Contaminated Waste Strategy, Magnox Operation Plan. Industry-led collaboration through Nuclear Waste Research Forum	Widen the scope of Third Party Access arrangements and funding model to enable access to all National Nuclear User Facilities.

Programme Area: Waste Management (including consideration of LLW disposal at LLWR)		**Programmes: Waste retrieval, storage and treatment**
	and other UK collaborative groups.	
Growth Opportunities:	Utilise the experiences at Dounreay, Research Sites, Sellafield etc to lead on national and international opportunities given the breadth of demands and challenges. Enable deployment of UK waste management experience overseas. Technology development and transfer of cross over technologies into other UK sectors. Reuse and recycling of wastes retrieved from clean-up of nuclear industry. Support to nuclear new build, resilience and other nuclear related activities.	Availability of facilities in which highly active waste treatment experiments can be carried out should enable the UK to attract funding as part of international collaborations.
Comments: Legacy clean-up poses a number of waste management challenges. Experimental facilities will be required to carry out experimental work on highly active wastes. These will also be needed to address waste management aspects of any advanced spent fuel recycling technologies.		

Programme Area: Geological Disposal			
Applicability	Baseline ✓	Open Cycle ✓	Closed Cycle ✓
Capability and/or Technology Delivered: *Research programmes will need to meet the needs of stakeholder groups (Implementation, regulation, siting and hosting and training and education - see comments)*	To develop and expand the heat generating wastes and spent fuel R&D programme to develop generic designs for their disposal and to assess their safety to appropriate levels of confidence, ensuring that appropriate use is made of knowledge obtained from overseas programmes. To support the development of future management strategies for materials such as uranium and plutonium by developing the technical understanding of disposal issues associated with these materials. To address implementation issues by carrying out R&D into topics such as technical aspects of retrievability and the implications of disposing of all types of higher activity waste in a single geological disposal facility. To continue R&D into intermediate level waste disposal, focusing on specific topics that have been identified as important for ensuring safety, or for optimising waste management. To prepare for site characterisation by developing appropriate knowledge, skills, experience and techniques to support development of a geological disposal facility in a range of geological environments. To investigate the social aspects of implementing a geological disposal facility to help the Radioactive Waste Management Directorate (RWMD) work effectively with local communities and to provide a firm basis for evaluating future options. Carry out research to support the preparation and evaluation of	Identify the implications of possible future fuel cycles on geological disposal to ensure that disposability is taken into account at the planning and evaluation stage. Take a holistic, cradle-to-grave, view of potential future fuel cycles to understand the interaction between the transport, interim storage and disposal phases of waste and spent fuel management plans.	

Programme Area: Geological Disposal		
	safety cases for the transport, operational and post-closure phases of a geological disposal facility and develop an understanding of the interactions between these safety cases.	
Enabling Actions:	**Under Existing Accountabilities**	**New Programmes / New Accountabilities**
National Facilities	Sufficient access to suitable underground research facilities for UK-specific short- and long-term experiments that will be required to underpin a safety case for a GDF. Facilitate access to Highly Active facilities.	
Skills Maintenance and Development; Knowledge Management	Development of sufficient geoscientists and other specialists to support implementation of site-specific stage of the programme. Facilitate engagement between scientists, engineers, bioscientists and social scientists in a geodisposal context.	
Collaboration Action - Bilateral	Expand bilateral regulatory collaborations with regulators from other countries pursuing geological disposal.	
Collaboration Action - Multilateral	Development of joint programmes under the EC 7th Framework Programme (FP7) or Horizon 2020 (in conjunction with Implementing Geological Disposal-Technology Platform (IGD-TP)). Expand multi-lateral regulatory collaborations with regulators from other countries pursuing geological disposal.	
Programme	Continue to deliver the RWMD, implementer led, R&D	

Programme Area: Geological Disposal		
Activities:	programme. Application of social sciences to the implementation of geological disposal (including issues relating to the communication of science and site selection). Develop an R&D programme which supports regulatory assessment of the RWMD R&D programme. Assess the disposal implications of possible future nuclear energy pathways. Ensure the capacity and capability exists to ensure that potential host communities can obtain independent advice on, and review of, research programmes and results. Ensure that mechanisms are in place such that communities can be involved in defining research and development needs.	
Growth Opportunities:	Given the range of likely geologies and UK wastes, successful delivery will ensure that the opportunity exists for the supply chain to export skills and technology applicable to other national disposal research programmes.	

Comments:

R&D programmes must meet the following needs:

Implementation HM Government has allocated responsibility for implementation of geological disposal of the UK's higher activity wastes to NDA, RWMD. RWMD responsibilities include delivery of research to refine facility design and construction; improve understanding of chemical and physical properties and interactions of emplaced waste; address specific issues raised by regulators; and support development of site-specific safety cases. It will be essential to secure public and stakeholder confidence that will be required to secure the approval of plans for geological disposal. It is therefore vital that research is carried out, and the results are communicated in such a way that earns such confidence. The principle of volunteerism which applies to the siting of a geological disposal facility means that the social, political and economic aspects merit specific attention within the R&D programme. In order to achieve an appropriate level of public confidence it is necessary to ensure that certain R&D is carried out which is demonstrably independent of the work commissioned by RWMD. Mechanisms are in place to support any independent research through engagement with regulators and community siting partnerships.

Programme Area: Geological Disposal

Regulation The regulators must carry out sufficient research to enable an informed assessment of the proposals and safety cases prepared by the implementers. It is important that potential host communities and the public at large see the evidence presented and challenged in a transparent manner which engenders trust in the outcome.

Siting HM Government has allocated the responsibility for approving the selection of the site for a geological disposal facility to the Department of Energy and Climate Change (DECC). DECC will need to be confident that research results provide a sound basis for a site selection decision to be made, in line with the principle of volunteerism.

Hosting Potential host communities must have access to independent advice which will allow them to make an informed decision on whether to volunteer to host a geological disposal facility. A decision to participate will require that communities have trust in the science supporting geological disposal.

Research Councils The Research Councils are the agencies through which HM Government funds high level training and research. The Research Councils will need to consider how research calls are placed in parallel with, or in support of, implementer- or regulator-led research programmes.

In order to meet the expectations of openness and transparency, research results will need to be made available as either raw data or unprocessed measurements which facilitate Peer Review and alternative analysis.

Programme Area: Fusion	**Programmes: Nuclear Fusion and associated research**		
Applicability	Baseline ✓	Open Cycle ✓	Closed Cycle ✓
Capability and/or Technology Delivered:	Ultimate aim to demonstrate electricity production before 2050. Advanced technology to position UK industry for a substantial share of future fusion economy. Next generation nuclear structural materials - for both fission and fusion. Enhanced integrated computer simulation capability for reactors and blankets. Consolidate the UK's world leading tritium handling capability. Remote handling capability. Design substantiation, modelling and simulation of components operating at high temperatures. Hot Isostatic Pressing (HIP) technology for bonding Beryllium, Copper, Chromium and Zirconium. Tritium breeding.		
Enabling Actions:	**Under Existing Accountabilities**		
National Facilities	Culham Centre for Fusion Energy (CCFE) (magnetic confinement). Rutherford Appleton Laboratory (inertial confinement). Atomic Weapons Establishment (AWE) (inertial confinement - non-military). National Nuclear User Facility (NNUF).		
Skills Maintenance and Development; Knowledge Management	High-temperature materials assessment. Manufacturing. Non-destructive examination and non-destructive testing techniques.		
Collaboration Action - Bilateral	The establishment of the NNUF together with a UK Nuclear Researchers' Network to coordinate its use.		
Collaboration Action - Multilateral	European Union supports UK fusion research through Euratom - both JET and the UK fusion programme.		

Programme Area: Fusion	**Programmes: Nuclear Fusion and associated research**
Programme Activities:	Demonstrate enhanced fusion performance with tritium on the Joint European Torus (JET), to break-even conditions, and demonstrate alternative compact scenarios on the UK's Mega Amp Spherical Tokamak **(**MAST) facility at Culham. Demonstrate scientific feasibility of magnetic fusion on ITER in the 2020s and deliver first fusion electricity before 2050. Keep the UK well placed to benefit from inertial confinement fusion research. Evolution of fusion first wall manufacturing process. Provide performance data on tritium breeding test blanket. Transient and accident analysis for safety studies.
Growth Opportunities:	Advanced materials for fission and fusion. Technology for ITER and demonstration reactors. Tritium handling for fusion and decommissioning of legacy reactors. DEMO (Demonstration fusion power plant) project.

Annex G – Core Nuclear Fission Science, Engineering and Technology Capabilities and Strategic UK Programme Areas

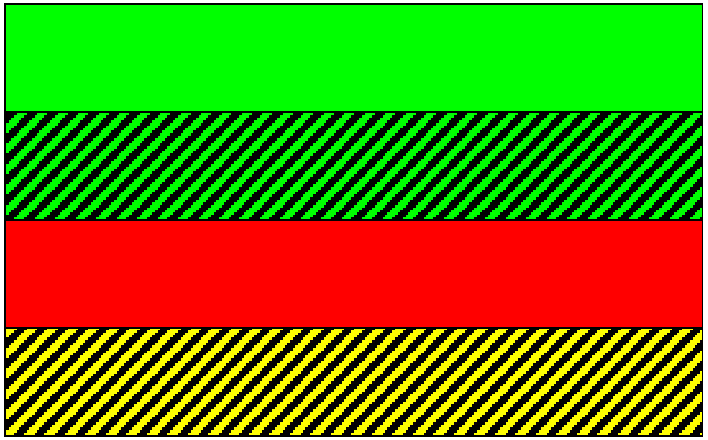
KEY

Leading capability / Programme development

Supporting capability / Existing programmes

Leading capability/ Limited or no programmes

Supporting capability / Limited or no programmes



Foototes:

(1) Vulnerable capability; (2) Position for fuel fabrication programme area after Sellafield MOX Plant moved to ‘Care and Maintenance’

(3) After THORP and Magnox reprocessing end

Core Capability	Strategic Topic in R&D Programme Area (in Italics)								
	Legacy Waste & Decommissioning	Reactor operations / new build (Gen II / III)	Current fuel fabrication (UO_2, MOX)(2)	Current spent fuel reprocessing(3)	Plutonium Disposition	Security & Non-proliferation	Future Reactors (Gen IV)	Future Fuel Cycle	Waste Disposal (including GDF)
	Decommissioning, Clean-up & Waste Management	*Operations*	*Operations*	*Reprocessing / Recycle*	*Spent Fuel & Nuclear Materials Management*	*Cross-cutting*	*Reactor & Fuel Systems – Fission*	*Reactor & Fuel Systems – Fission*	*Geological Disposal*
Reactor & nuclear physics									
Fuel technology(1)									
Radiation & reactor science (1)									
Graphite technology									
Post Irradiation Examination									
Safeguards									
Actinide science & engineering (1)									
Process & waste science									
Chemical & process modelling									

Core Capability	**Strategic Topic in R&D Programme Area (in Italics)**								
	Legacy Waste & Decommissioning	Reactor operations / new build (Gen II / III)	Current fuel fabrication (UO_2, MOX)[2]	Current spent fuel reprocessing[3]	Plutonium Disposition	Security & Non-proliferation	Future Reactors (Gen IV)	Future Fuel Cycle	Waste Disposal (including GDF)
	Decommissioning, Clean-up & Waste Management	*Operations*	*Operations*	*Reprocessing / Recycle*	*Spent Fuel & Nuclear Materials Management*	*Cross-cutting*	*Reactor & Fuel Systems – Fission*	*Reactor & Fuel Systems – Fission*	*Geological Disposal*
Engineering simulation / modelling									
Highly active waste processing									
Materials & corrosion science[1]									
Waste characterisation									
Waste immobilisation									
Plant inspection & deployment									
Systems & front end engineering									
Remote engineering technology									

Core Capability	Strategic Topic in R&D Programme Area (in Italics)								
	Legacy Waste & Decommissioning	Reactor operations / new build (Gen II / III)	Current fuel fabrication (UO_2, MOX)(2)	Current spent fuel reprocessing(3)	Plutonium Disposition	Security & Non-proliferation	Future Reactors (Gen IV)	Future Fuel Cycle	Waste Disposal (including GDF)
	Decommissioning, Clean-up & Waste Management	*Operations*	*Operations*	*Reprocessing / Recycle*	*Spent Fuel & Nuclear Materials Management*	*Cross-cutting*	*Reactor & Fuel Systems – Fission*	*Reactor & Fuel Systems – Fission*	*Geological Disposal*
Safety assessments									
Environmental technology									
Measurement & analysis									
Advanced manufacturing									

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