AFCP
Advanced Fuel Cycle
Programme

Fuelling Net Zero:
Advanced Nuclear Fuel Cycle Roadmaps for a Clean Energy Future

Department for
Business, Energy
& Industrial Strategy

NATIONAL NUCLEAR
LABORATORY

FOREWORD

> **"At the end of 2020, the Government Ten Point Plan and Energy White Paper identified a key role for large, small and advanced nuclear within the UK's evolving clean energy landscape. To uphold this commitment and support the UK's net zero transition, we must strategically elevate these technologies to realise their full potential.**
>
> **Building on the excellent work through the Advanced Fuel Cycle Programme (AFCP), led by the Department for Business, Energy and Industrial Strategy (BEIS) and the UK National Nuclear Laboratory (NNL), this report sets out a view of future research, development and demonstration (RD&D) technology roadmaps for a range of nuclear fission scenarios.**
>
> **Advanced fuel cycles offer significant economic and sustainability benefits, supporting Government's net zero emissions target of 2050. With the UK already at the forefront of advanced fuel cycle innovation, the time has never been better to maximise these benefits through the expansion of capability and capacity. Now is our opportunity to plan for and secure a sustainable future."**

Gareth Headdock
Science and Technology & Government Programmes Director,
National Nuclear Laboratory

EXECUTIVE SUMMARY

The approach to the future UK nuclear fuel cycle will be crucial to support the ambitions for the role of nuclear in delivering a net zero future. As part of the Department for Business, Energy and Industrial Strategy (BEIS) Energy Innovation Programme (EIP), the Advanced Fuel Cycle Programme (AFCP) is delivering world-leading advanced fuel cycle science and technology to contribute to the UK's clean energy commitment. To this end, AFCP has developed research, development and demonstration (RD&D) technology roadmaps. These aim to aid future thinking and investment planning of policy makers and industry over the coming years.

Focusing down

Through an assessment of trends and drivers, applications, technologies and enablers, the programme has produced advanced fuel and fuel cycle RD&D pathways. The focus is on key areas related to the scope of AFCP and cover two fuel cycle components: fuel manufacture and used (irradiated) fuel management.

Essential enablers

Key enablers — including the need for strategic planning, industry collaboration and Government support — are identified in each of the roadmaps. Government support can be characterised by three broad areas: policy, infrastructure and international. The fuel cycle includes elements regarded as national strategic capabilities (related to security and non-proliferation aspects) and will require Government support to maintain UK capability; in addition, due to the long lead times and policy uncertainty, near-term industry investment is unlikely in some areas. Government support to international partnering and access to capabilities is also critical.

Capability and capacity for a sustainable future

Given the right focus on developing capability and capacity, advanced fuels and fuel cycles can deliver significant economic benefit and support a sustainable future in the UK. Maturing key technology areas is crucial to this aim. The roadmaps presented here set out a pathway to support decision makers, within Government and industry, as they continue to develop plans for the future of nuclear in delivering net zero emissions by 2050 – and beyond — in the UK.

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INTRODUCTION

The UK's National Nuclear Laboratory (NNL) has produced this report as part of the Advanced Fuel Cycle Programme (AFCP). AFCP is led by NNL and is part of the Department for Business, Energy and Industrial Strategy (BEIS) £505m[1] Energy Innovation Programme (EIP). Through delivering integrated advanced fuel cycle innovation, the programme supports the UK's commitment to achieve net zero greenhouse gas emissions by 2050. Part of AFCP includes developing research, development and demonstration (RD&D) technology roadmaps; these aim to inform policy makers and industry at a time when the full role that nuclear will play in delivering net zero is still being defined.

Nuclear energy could play an essential role in the drive to decarbonise the economy; this would need to be underpinned by fuel cycle RD&D to ensure technology and knowhow is available at the right time. This report presents fuel cycle RD&D roadmaps, along with the methodology used to produce them, aligned to trends and drivers through to 2050. If implemented, these pathways would enable the UK to build on its world-leading fuel cycle capabilities to support future nuclear ambitions. Through technology roadmapping, the UK can recognise where strong investment can proactively address a range of future needs — including those that may not yet be fully understood.

These roadmaps identify significant opportunities for the UK. This exercise has shown that focus over the coming five years should be on scaling up and progressing technology towards applications, which can be tracked through the technology readiness level (TRL) methodology, Without maturing science and technology it will not be possible to make informed decisions towards future requirements. Several critical enablers — including strategic planning, industry collaboration and Government support — have also been identified and are outlined.

The report is structured as follows:

Section 2: An overview of the UK fuel cycle and AFCP

Section 3: The approach to roadmapping

Section 4: Advanced fuel cycle RD&D roadmaps

- Advanced fuels roadmaps
    - Advanced technology fuels (ATF)
    - Coated particle fuels (CPF)
    - Fast reactor fuels and fuel cycle
- Sustainable advanced fuel cycle roadmaps
    - Advanced recycle of LWR fuel to produce future fuels
    - Advanced recycle technology of ATF for future fuels
    - Pyrochemical (molten salt) recycle technology for future fuels

The roadmaps were produced based on the best available information at the time of publication and with all assumptions outlined. They focus on the drivers, industrial applications, development routes and key enablers for the critical technology components to deliver the applications. Detailed plans underpin the development of each technology component. These should evolve with time based on progress and any changes in the wider operating and policy environments. The information presented in this report provides a detailed view and sets out exciting opportunities for the UK to be leaders in fuel cycle development and deliver its net zero ambitions.

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[1] https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law

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THE UK FUEL CYCLE

The UK has set a world–leading net zero greenhouse gas emissions commitment, becoming the first major economy to do so. The Ten Point Plan[2] and Energy White Paper[3], published by the Government in 2020, set out a clear role for nuclear in the UK's future net zero energy system by its 2050 target and beyond. The nuclear fuel cycle is crucial to the role of nuclear technology in decarbonising the future energy system. Fuel cycle RD&D is hence vital to ensure the technology and knowhow are available when required; advanced fuel and fuel cycle RD&D could underpin the UK's nuclear ambitions and support the delivery and maintenance of net zero.

Over the past five years, through Government investment[4] the UK has started to rebuild capability across the fuel cycle as recommended by the Nuclear Innovation and Research Advisory Board (NIRAB)[5]. However, nuclear energy is a long-term commitment and a continued strategic focus on fuel cycle RD&D will be required to enable the UK to meet future nuclear energy deployment ambitions.

This paper and the roadmaps presented focus on advanced fuels and fuel cycle. Figure 1 shows a schematic representation of a nuclear fuel cycle; the areas of work presented here, which coincide with AFCP's advanced fuels and fuel cycle workstreams, are highlighted by the green boxes. Although not the primary focus of this paper, the other areas of the fuel cycle (blue boxes) are at present the responsibility of the Nuclear Decommissioning Authority (NDA: spent fuel management and plutonium disposition), Urenco (fuel enrichment services), Westinghouse (current uranium oxide fuel supply) and utilities (eg EDF Energy for reactor operation).

Clearly there is significant overlap and interaction required across current and future fuel cycle planning. With the anticipated increase in clean energy required to meet net zero and new reactor technology that may be introduced — for example, as part of the Government's Advanced Modular Reactor (AMR) R&D programme — the associated fuel cycles will require the appropriate consideration.

Possible future fuel cycle deployment scenarios could include:

- The application of new advanced fuels and associated used fuel management in an open, or once-through, cycle
- Fast reactor technology and associated fuel cycles
- Molten salt reactor technologies, including on-line processing
- Future evolution towards partially or fully implementing advanced fuel cycles — aligned with sustainability goals — including options for partitioning and transmutation (P&T)
- Transitions over time from one reactor system and/or fuel cycle to another

The UK has experience across all these fuel cycle areas; however, much of this is becoming historic capability that would need rebuilding so that both capability and capacity are available to support these future applications. AFCP has started to do this.

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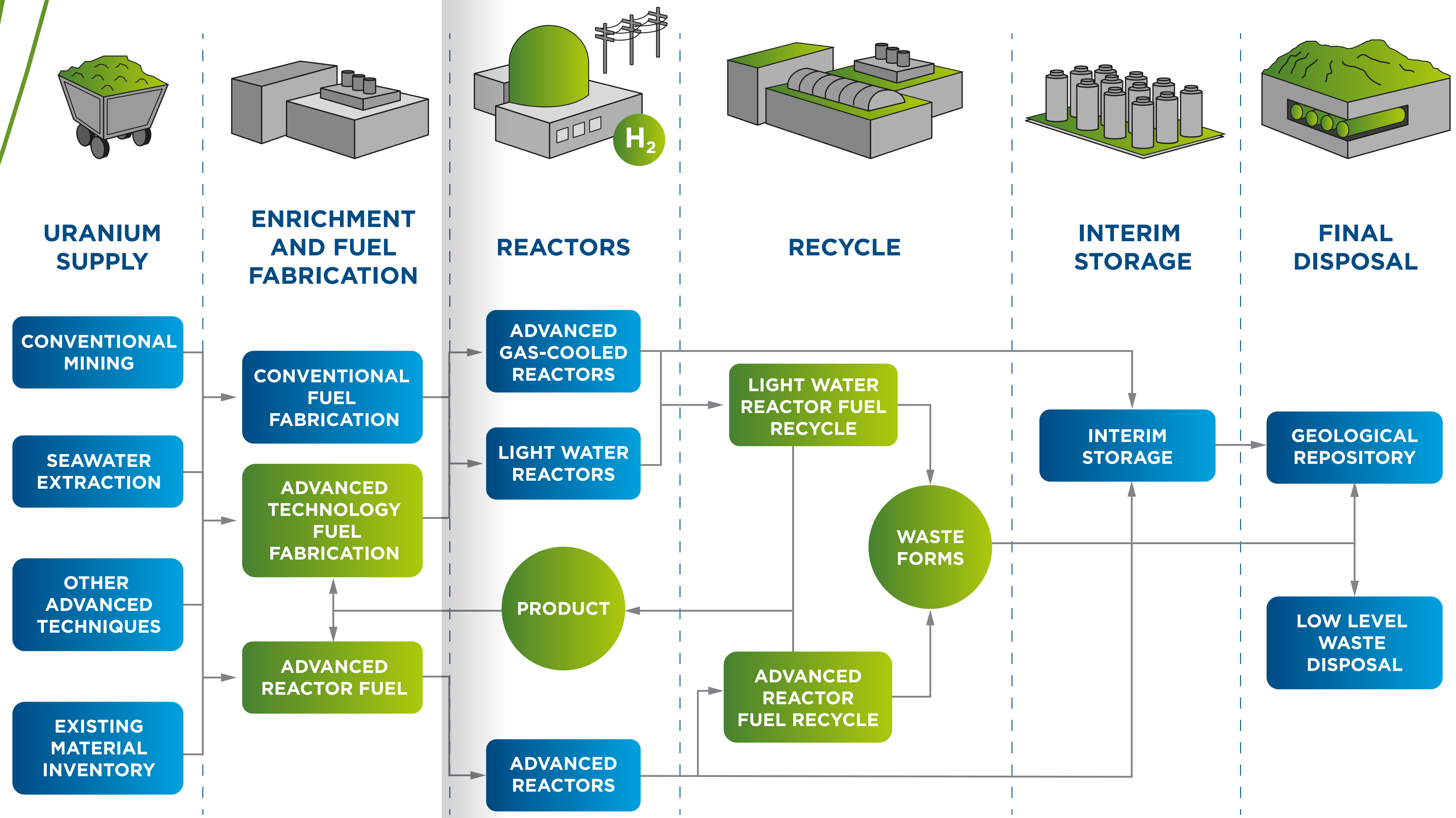
[2] https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution
[3] https://www.gov.uk/government/publications/energy-white-paper-powering-our-net-zero-future
[4] https://www.gov.uk/guidance/energy-innovation
[5] NIRAB, UK Nuclear Innovation and Research Programme Recommendations, March 2016 (https://www.nirab.org.uk/download_file/view/34/202)

The Advanced Fuel Cycle Programme (AFCP)

In 2016, NIRAB recommended to Government to invest in future fuel cycle capability to ensure it could deliver on the ambitions set out in its Nuclear Industrial Strategy (NIS)[6]. Subsequently, there has been public investment in future fuel cycle R&D. Indeed, the BEIS £505 million EIP has provided investment for nuclear innovation between 2016 and 2021.

Focused on eleven specific advanced fuel cycle project areas — spanning advanced fuels and advanced recycle — AFCP has reinvigorated the sector and is building capability. Figure 2 provides a schematic representation of a possible future fuel cycle where different reactor systems are deployed to play a variety of roles and therefore require supporting fuel cycles. The areas related to AFCP are highlighted in the diagram.



green = AFCP fuel cycle themes
rectangles = processes
circles = outputs

Figure 1: Schematic representation of elements of a nuclear fuel cycle

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[6] Nuclear industrial strategy: the UK's nuclear future, 2013 (https://www.gov.uk/government/publications/nuclear-industrial-strategy-the-uks-nuclear-future)

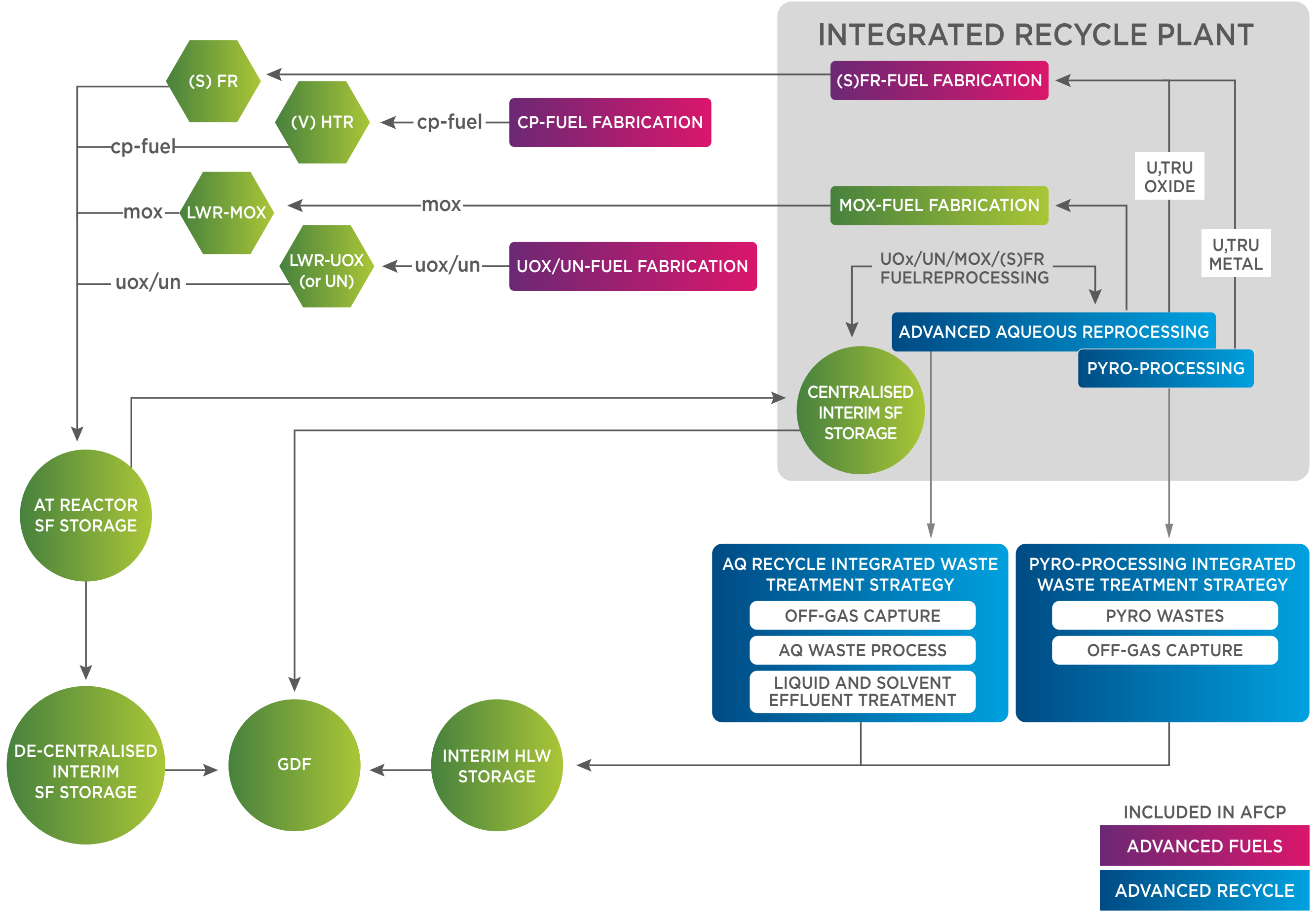

Figure 2: Schematic example of a possible future fuel cycle with AFCP areas highlighted

(S)FR = (sodium) fast reactor, (V)HTR = (very) high temperature reactor, LWR = light water reactor, MOX = mixed oxide fuel, CP-Fuel = coated particle fuel, TRU = transuranic elements, GDF = geological disposal facility, SF = spent fuel, HLW = high level waste

Within AFCP the work on next-generation nuclear fuels looks at improving the economic performance of advanced technology fuels (ATF) for current light water reactors while also delivering R&D on revolutionary coated particle fuels (CPF) and fast reactor fuels (FRF) for advanced reactors. AFCP has enabled the UK to re-engage in future fuel technology development while developing the right tools and resources to safeguard options for the future.

The programme additionally recognises the need for a sustainable[7] fuel cycle to support UK clean energy and environmental goals. Recycle technology is at the heart of AFCP, evolving world-leading science and technology to reuse precious resources.

Within these areas, AFCP is identifying the potential economic benefits both near- and far-term: the programme is helping to position UK organisations to access future markets, enhancing export potential, creating green jobs and targeting solutions to drive down costs across the fuel cycle and ultimately the cost of clean energy generation.

Through this investment in capability, AFCP has grown UK international influence. The programme supports key international partnerships to leverage synergies with bilateral and multilateral programmes, including the US/UK R&D Action Plan[8], Generation IV International Forum (GIF)[9], European Union (EU) Horizon 2020 and OECD Nuclear Energy Agency (OECD NEA). In September 2020, AFCP was instrumental in enabling the UK launch of the first International Atomic Energy Agency (IAEA) Collaborating Centre on the Advanced Fuel Cycle anywhere in the world[10].

The programme has galvanised the sector, ready to deliver a bright future for the UK. There is the opportunity to build on this and continue to develop a world-leading UK RD&D capability that stands ready to address immediate challenges as well as future UK needs that are not yet fully understood. The following roadmaps outlined in this report set out a pathway to continue to build on the platform developed by AFCP.

[7] The United Nations state: Sustainable development has been defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs (https://www.un.org/sustainabledevelopment/development-agenda). The Generation IV International Forum set out in 2009 the following around sustainability: Nuclear energy systems will provide sustainable energy generation that meets clean air objectives and provides long-term availability of systems and effective fuel utilisation for worldwide energy production. They will minimise and manage their nuclear waste and notably reduce the long-term management burden, thereby improving protection for the public health and the environment (https://www.gen-4.org/gif/jcms/c_9502/generation-iv-goals)

[8] In September 2018, the US Department of Energy (DOE) and the Department for Business, Energy, and Industrial Strategy (BEIS) signed the Civil Nuclear Energy Research and Development (R&D) Action Plan (https://www.energy.gov/ne/articles/doe-s-office-nuclear-energy-agrees-nuclear-action-plan-united-kingdom)

[9] In November 2018, the UK ratified the Generation IV International Forum framework agreement for international collaboration on research and development of Generation IV nuclear energy systems. Becoming a party to the agreement allows the UK to 'actively engage' in research and development projects related to Generation IV (advanced nuclear) systems; participation began in 2019.

[10] https://www.nnl.co.uk/blog/2020/09/23/nnl-designated-as-the-uks-first-iaea-collaborating-centre/

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ROADMAPPING

Setting a pathway

Roadmapping approaches are now widely used at company, sector and national levels to align R&D with goals and strategy[11]. A roadmap sets a pathway from current capability towards a future vision and identifies key opportunity areas. It allows a course to be plotted through the development of capability and technology through to exploitation of applications in the opportunity areas aligned to market trends and drivers. Roadmapping can support innovation and build consensus — within industry and policy making — on priorities and actions required to move forward.

Approach and process

AFCP has undertaken technology roadmapping as part of its strategic delivery. Figure 3 shows the programme's high-level approach to roadmapping. The following sections add further detail to this approach. The process involves starting by establishing a vision, understanding what the future may look like, assessing current capability and being clear on the opportunities. These evaluations are then used as a basis to develop future roadmaps.

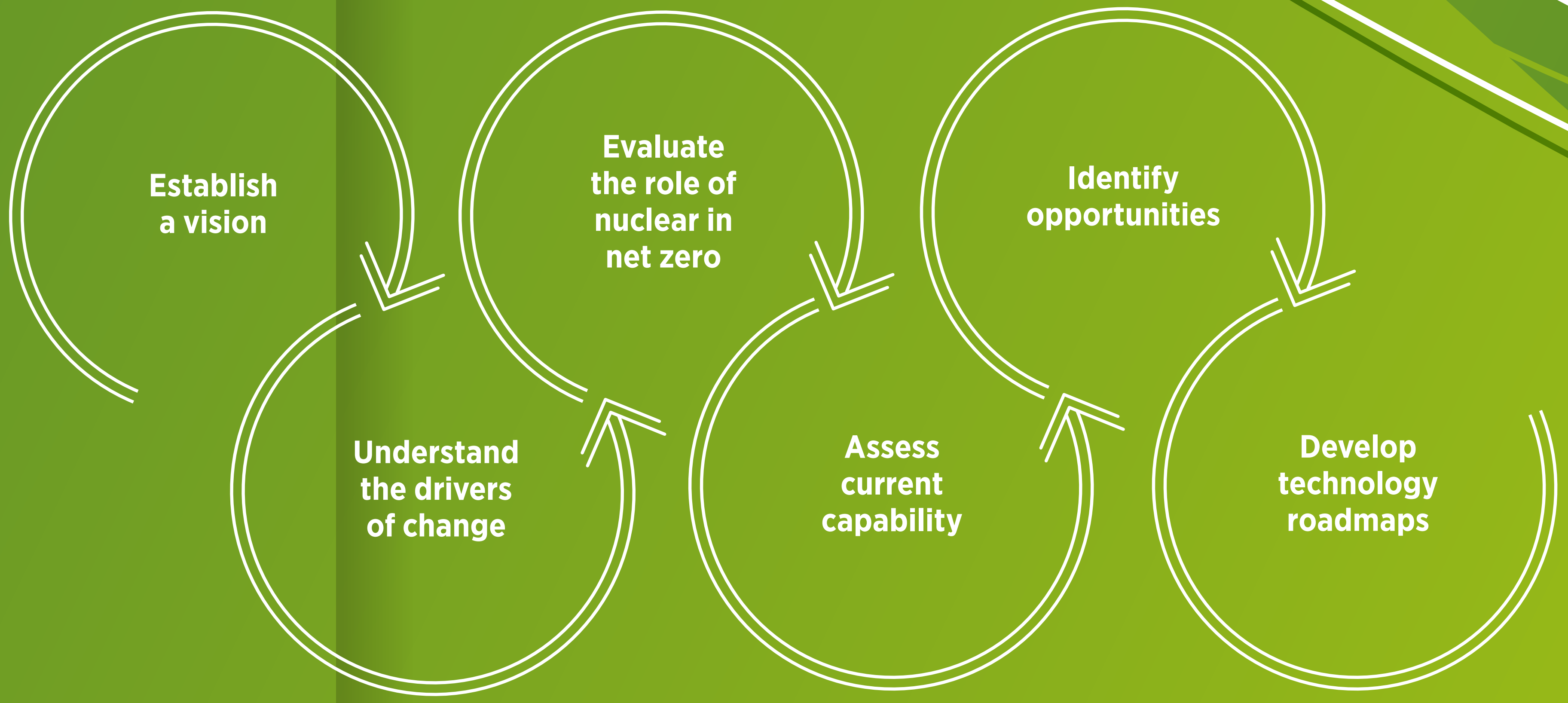

Figure 3 Overview of roadmapping process

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[11] Robert Phaal, Roadmapping for strategy and innovation, 13 January 2020. Centre for Technology Management, Institute for Manufacturing Department of Engineering, University of Cambridge. https://www.ifm.eng.cam.ac.uk/uploads/Resources/roadmapping_overview.pdf

Establishing the vision

A future vision for a 2050 UK fuel cycle capability was set out in detail by UK Government in the NIS[6] and the supporting Nuclear Energy Research and Development Roadmap[12] in 2013. The NIS included the following statements relevant to a 2050 vision:

- UK supplying the fuel needs of Gen III+ and any Gen IV and small modular reactors (SMRs)
- UK industry will have a strong domestic capability from fuel enrichment and manufacture, reactor technology, operations to recycling and waste minimisation, storage and disposal

NIRAB has published ambitions for UK fuel cycle research in their recommendations to Government from 2014 to present[13]. Goals have also been set as part of the BEIS EIP for the work on fuels and recycle[14]. In addition, the 2020 Energy White Paper[3] has set out a potential role for large, small and advanced nuclear in delivering net zero.

Building on the NIS and subsequent NIRAB and Government publications, AFCP has produced the following 2050 vision statements for UK fuel cycle capability:

- **UK supplying the fuel cycle needs of Gen III(+) and advanced nuclear technologies (ANTs)[15], enabling a significant nuclear contribution to achieving net zero in the UK and a sustainable future**
- **UK industry will have a strong domestic capability from fuel enrichment and manufacture through to recycling and waste minimisation, storage and disposal**

This sets out a requirement to develop UK capabilities to deliver the fuel cycle needs of current and future systems in a net zero world.

Understanding the drivers of change

Crucial to achieving the vision is understanding the environment in which advanced fuel cycle RD&D will be operating. Figure 4 presents some of the key 'drivers of change' identified by AFCP that will have an impact on decisions concerning future advanced fuel cycle RD&D needs. These will require close monitoring as the environment changes and technology development progresses, and roadmaps will need to be modified accordingly. The roadmaps produced so far are based on the best understanding of the current circumstances.

Drivers of Change

Social
- Alternate uses of nuclear
- Climate change awareness
- Public understanding of nuclear as low-carbon energy

Technological
- Delivery of new nuclear technology
- The rate of technological maturity of advanced reactors
- Innovation and delivery of other low-carbon technologies (low cost, rapid deployment)

Economic
- New nuclear build cost and schedule certainty
- Economics of advanced reactors (Gen IV) and fuel cycle
- Competitiveness of nuclear vs other low-carbon technology
- Cost to consumer bills driving demand
- Economic recovery as key focus following COVID-19

Environmental
- Net zero by 2050
- Sustainability through drive to reduce waste associated with energy production

Political
- Government policy position
- Clean growth policy to decarbonise while benefiting economy
- Net zero in legislation
- Energy security through support for homegrown energy

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[12] https://www.gov.uk/government/publications/nuclear-energy-research-and-development-roadmap-future-pathways
[13] http://www.nirab.org.uk/
[14] https://www.gov.uk/guidance/funding-for-nuclear-innovation
[15] Advanced Nuclear Technologies (ANTs) include Light Water Small Modular Reactor (SMR) technology and Advanced Modular Reactor (AMR) – non-light water – technology.

Evaluating the role of nuclear in net zero

To develop advanced fuel and fuel cycle technology roadmaps, it is necessary to develop future nuclear deployment scenarios to understand potential fuel cycle demands. Through working with the Energy Systems Catapult (ESC), AFCP examined a few exemplar full UK energy system scenarios to achieve net zero by 2050[16] and then subsequently performed modelling using the NNL fuel cycle modelling tool ORION. The roadmaps in this report were produced based on this information. The key conclusions for nuclear deployment were:

- A range of nuclear deployment pathways are possible from no new nuclear to over 60 GWe installed capacity
- Deployment scenarios tested the roles of large, small and advanced reactor systems; all could play a part in reaching net zero by 2050

The 2020 Government Ten Point Plan and Energy White Paper have set out a possible role for large, small and advanced reactor technologies in delivering net zero by 2050 — including up to 40 GWe nuclear contribution to electricity generating capacity in 2050[3]. As such, the fuel cycle implications for deployment of a range of systems will require assessment. In addition, investing in innovation in the fuel cycle could enhance exports, create jobs and drive down the cost of clean energy. For the front end of the fuel cycle, the BEIS Energy Innovation Needs Assessment (EINA)[17] showed the potential for a £400m addition to gross value added (GVA) per annum and 4500 jobs by 2050. Prior to this, the 2016 Technology Innovation Needs Assessment (TINA)[18] set out the potential for advanced fuel innovation to deliver 41–53% front end cost savings by 2050, supporting an overall potential for 25-29% cost savings for generation IV systems through innovation.

Based on the scenarios considered, two points are key:

- A range of technologies could mean that a range of new and existing fuel types — along with their associated used fuel management — will be needed in the UK
- Advanced reactors and possible large deployment of nuclear (eg over 20 GWe) make assessment of the requirement for recycle technologies — and thus advanced fuel cycles — a logical path to sustainability

The roadmaps presented here therefore include advanced fuels for a range of reactor applications and the consideration of fuel recycle technology.

[16] UK Energy System Modelling: Net Zero 2050 Deployment Scenarios to Support Assessment of Future Fuel Cycles, 2021
https://www.nnl.co.uk/wp-content/uploads/2021/06/NNL-UK-Energy-System-Modelling-for-Net-Zero.pdf

[17] BEIS Energy Innovation Needs Assessment (EINA) 2019,
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/845660/energy-innovation-needs-assessment-nuclear-fission.pdf

[18] Technology Innovation Needs Assessment (TINA), 2016,
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/593463/Refreshed_Nuclear_Fission_TINA_Summary_Report_February2016.pdf

Assessing current capability

Advanced fuels and fuel cycles

The sustainability of nuclear energy is partly determined by the choice of nuclear fuel cycle. The typical light water reactor ‘once-through’ or ‘open’ cycle sees less than 1% of the extracted uranium converted into energy. Although uranium availability is not expected to be a limiting factor in this century, sustainability demands the best use of resources. Any transition away from a once-through cycle — where all the used fuel is disposed of — could instead include recycling of the fuel alongside the optimisation and separation of wastes (eg minor actinides) so that each fraction can be effectively managed to maximise benefit. This concept defines ‘advanced fuel cycles’.

Advanced fuels have the potential to improve the economic performance of future nuclear systems. In addition, the development of advanced fuels is an essential component for developing advanced fuel cycles and considering new fuel processing technologies. Fuels used in current commercial reactors are oxide-based, for example, uranium oxide fuels and uranium-plutonium mixed oxide fuels (ie MOX fuel). For AMRs, fuels may need higher density fissile materials and higher thermal conductivity since the reactors tend to operate at higher heat generation rates. They may also use recycled fuel as part of an integrated fuel cycle, requiring the development of recycling technologies that can produce the required fuels for future applications.

For many countries, RD&D on advanced fuel cycles and nuclear systems is being undertaken within co-operative programmes (eg GIF, IAEA and OECD NEA). The objectives of the longer term advanced fuel cycle concepts under investigation include optimising product streams, maximising the use of natural resources, reducing wastes for final disposal and enhancing proliferation resistance features — all of which work to increase sustainability.

Current UK capability in fuel cycle RD&D

The latest UK civil nuclear R&D landscape survey[19] provided a detailed overview and snapshot of UK capability in 2018/19. It highlighted that the number of researchers engaged in areas related to advanced fuel cycles (fuel fabrication, advanced reactors and used fuel handling) was low compared to other areas in the UK.

Although the relative numbers remain low, the UK is internationally recognised as having world-leading capability across the fuel cycle. The UK has enrichment capabilities at Capenhurst and indigenous fuel manufacturing capability at Springfields; in addition, the UK has previously reprocessed and recycled light water reactor (LWR) fuels, manufactured mixed oxide fuel (MOX) and coated particle fuel (CPF) and had a significant fast reactor programme operating over many decades. The UK continues to play an active part in international fuel cycle programmes, including chairing several international working groups in the OECD NEA and hosting the Advanced Fuel Cycle Collaborating Centre for the IAEA. The UK is also a respected partner in EU Horizon 2020 fuel cycle projects.

Recent public investment, through AFCP and broader UK Research Council-funded programmes in academia, has helped to further improve capability. If the UK continues to invest in advanced fuels and fuel cycle RD&D it can maintain and develop these strategically important capabilities. The AFCP investment has also added to the UK R&D facility landscape for fuel cycle RD&D (Figure 5), strengthening the UK’s world-leading infrastructure to support future programmes as a global hub for fuel cycle RD&D.

To build capability and capacity, the UK will need to invest in programmes that make use of its world-leading infrastructure and continue to develop a significant skill base. This will require a focus on mid- to high-TRL applications to ensure the UK is developing and maintaining cutting-edge skills and capabilities, while also ensuring the UK stays at the ‘top tier’ of nuclear nations and provides significant economic opportunities for the national industry. A broad base RD&D and skills programme enables the UK to be agile in responding to policy, industry and environment changes; it provides the platform so that, when ready, technologies can be developed and accelerated for deployment.

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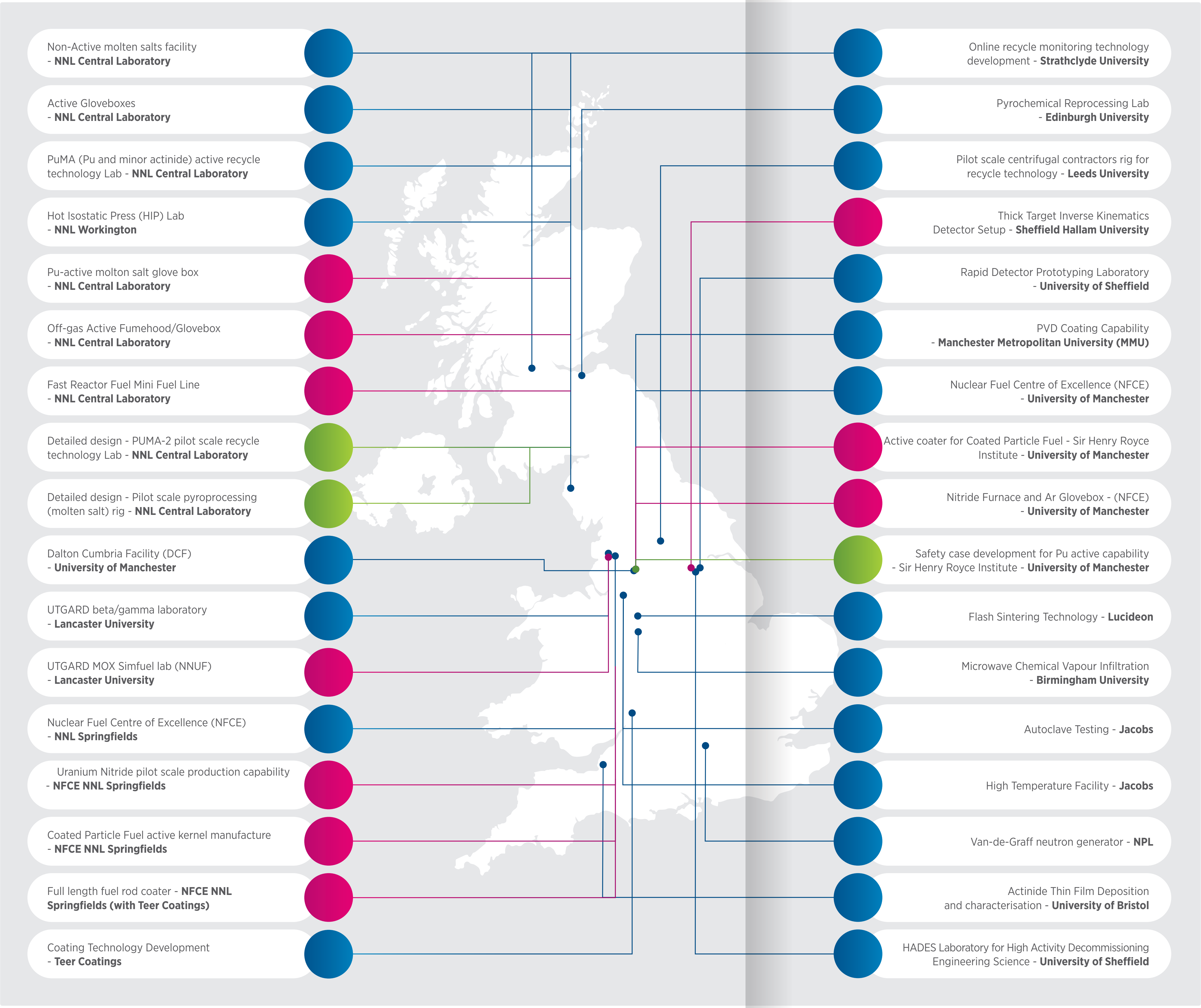
[19] NIRAB, The UK Civil Nuclear R&D Landscape Survey, March 2020 (https://www.nirab.org.uk/download_file/131/0)



- 🔵 Non-Active molten salts facility - **NNL Central Laboratory**
- 🔵 Active Gloveboxes - **NNL Central Laboratory**
- 🔵 PuMA (Pu and minor actinide) active recycle technology Lab - **NNL Central Laboratory**
- 🔵 Hot Isostatic Press (HIP) Lab - **NNL Workington**
- 🟣 Pu-active molton salt glove box - **NNL Central Laboratory**
- 🟣 Off-gas Active Fumehood/Glovebox - **NNL Central Laboratory**
- 🟣 Fast Reactor Fuel Mini Fuel Line - **NNL Central Laboratory**
- 🟢 Detailed design - PUMA-2 pilot scale recycle technology Lab - **NNL Central Laboratory**
- 🟢 Detailed design - Pilot scale pyroprocessing (molten salt) rig - **NNL Central Laboratory**
- 🔵 Dalton Cumbria Facility (DCF) - **University of Manchester**
- 🔵 UTGARD beta/gamma laboratory - **Lancaster University**
- 🟣 UTGARD MOX Simfuel lab (NNUF) - **Lancaster University**
- 🔵 Nuclear Fuel Centre of Excellence (NFCE) - **NNL Springfields**
- 🟣 Uranium Nitride pilot scale production capability - **NFCE NNL Springfields**
- 🟣 Coated Particle Fuel active kernel manufacture - **NFCE NNL Springfields**
- 🟣 Full length fuel rod coater - **NFCE NNL Springfields (with Teer Coatings)**
- 🔵 Coating Technology Development - **Teer Coatings**

- 🔵 Online recycle monitoring technology development - **Strathclyde University**
- 🔵 Pyrochemical Reprocessing Lab - **Edinburgh University**
- 🔵 Pilot scale centrifugal contractors rig for recycle technology - **Leeds University**
- 🟣 Thick Target Inverse Kinematics Detector Setup - **Sheffield Hallam University**
- 🔵 Rapid Detector Prototyping Laboratory - **University of Sheffield**
- 🔵 PVD Coating Capability - **Manchester Metropolitan University (MMU)**
- 🔵 Nuclear Fuel Centre of Excellence (NFCE) - **University of Manchester**
- 🟣 Active coater for Coated Particle Fuel - Sir Henry Royce Institute - **University of Manchester**
- 🟣 Nitride Furnace and Ar Glovebox - (NFCE) - **University of Manchester**
- 🟢 Safety case development for Pu active capability - Sir Henry Royce Institute - **University of Manchester**
- 🔵 Flash Sintering Technology - **Lucideon**
- 🔵 Microwave Chemical Vapour Infiltration - **Birmingham University**
- 🔵 Autoclave Testing - **Jacobs**
- 🔵 High Temperature Facility - **Jacobs**
- 🔵 Van-de-Graff neutron generator - **NPL**
- 🔵 Actinide Thin Film Deposition and characterisation - **University of Bristol**
- 🔵 HADES Laboratory for High Activity Decommissioning Engineering Science - **University of Sheffield**

🔵 In operation and used in current AFCP

🟣 New capability ready by 2021

🟢 Design/safety case ready by 2021

Figure 5 Advanced fuel cycle infrastructure in the UK used as part of AFCP and additional infrastructure added through AFCP investment

Technology readiness levels (TRLs)

From a technology development perspective, investment in AFCP has raised the technology maturity of several areas related to advanced fuels and fuel cycles. Table 1 provides an overall high-level indication of the developments as part of AFCP. Where the TRL[20] has not increased, this is largely in areas where capacity and capability have nevertheless increased within the current TRL category in preparation for maturing technology in the future, depending on future investment and focus. This assessment of readiness from AFCP demonstrates that public investment can not only build capability and capacity but also has a significant impact on maturing technology towards a level such that it can be industrialised and commercialised (ie TRL 7 upwards (Appendix 1)).

The UK Advanced Fuel Cycle Programme (AFCP) (2016 – 2021)		TRL at start of AFCP	TRL at 2021
Accident tolerant fuels (ATF) or advanced technology fuels for light water reactors (LWRs)	High density fuels	1	3
	Coated cladding	2	6
	SiC cladding	2	3
Coated particle fuels (CPF) for high temperature reactors (HTRs)	Kernels	3	4
	Coating	3	3
Fast reactor fuels		3	3
Advanced aqueous fuel recycle technology		2	4
Pyro-processing fuel recycle technology		2	2

Table 1 Judgement on technology readiness level of advanced fuel and fuel cycle areas developed as part of AFCP in the UK (based on expert opinion from within AFCP)

Identifying opportunities

Opportunities bridge present capability with future potential. The identification of opportunity areas involves developing a detailed understanding of current capability, then matching that against the established vision and the challenges faced to achieve that vision.

AFCP's opportunity areas span advanced fuels and sustainable advanced fuel cycles. Each of these opportunities are presented below as roadmaps. Within each roadmap, applications indicate where technology or capability could be put into 'operation' to fulfil a market need or demand.

Developing technology roadmaps

The pathway described in this section establishes technology roadmaps, which chart potential routes to realise opportunities and achieve a vision. The following section sets out advanced fuel cycle roadmaps based on this approach.

At the highest level, roadmaps are broken into four themes, each building upon the last:

Trends and Drivers: These define the context within which opportunities will be realised. This theme encompasses the established vision, drivers of change and understanding of future energy system markets.

Opportunity Areas: These arise from linking current capabilities with future needs. Each roadmap presents a unique advanced fuel cycle opportunity area, with specific applications within the area identified throughout.

Technologies and Capabilities: Realising the applications within each opportunity area will require certain technologies and capabilities to be developed. This theme includes both the existing and future concepts needed to achieve relevant applications.

Enablers: Key actions – which include strategic planning, industry collaboration and Government support – will enable the development of new and enhanced technologies and capabilities.

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[20] Technology Readiness Level (TRL) is based upon: US Department of Energy, "Technology Readiness Assessment Guide," US Department of Energy, Washington, D.C., US, 2009. See Appendix 1. This is an approximation based on expert opinion from within AFCP.

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ADVANCED FUEL CYCLE RD&D ROADMAPS

Overview

As detailed the AFCP roadmaps are each structured around four themes: trends and drivers, opportunity/application areas, technologies and capabilities, and enablers. A high-level overview of these themes within UK advanced fuel and fuel cycle is shown in Figure 6. In addition, Table 2 sets out key opportunity areas for the UK. These opportunity areas form the basis of the technology roadmaps, which are included in the following sections:

- Advanced fuels roadmaps
    - Advanced technology fuels (ATF)
    - Coated particle fuels (CPF)
    - Fast reactor fuels and fuel cycle
- Sustainable advanced fuel cycle roadmaps
    - Advanced recycle of LWR fuel to produce future fuels
    - Advanced recycle technology of ATF to produce future fuels
    - Pyrochemical (molten salt) recycle technology to produce future fuels

These roadmaps represent a view of how a programme or programmes could evolve to meet the UK's clean energy ambitions; they are not intended to be detailed project plans. Key technology areas are highlighted with associated enablers. These roadmaps should be considered live documents which evolve as trends and drivers evolve over time.

The roadmaps demonstrate a pathway to realising UK economic opportunities, which are potentially significant, maintaining UK indigenous capabilities and securing a path towards a sustainable fuel cycle future for the nuclear sector and nation.

NOTE: While the opportunity for molten salt reactors is recognised, a roadmap has not been included here for molten salt fuel or fuel cycle as it is not part of the current AFCP scope. Future programmes will need to consider this and develop roadmaps as appropriate.

Trends and Drivers

Short Term

2021 - 2025

Net zero legislation drives thinking about new nuclear. Sector deal outlines need to support domestic fuel capability.

Phase out of advanced gas reactors (AGRs) requires focus on new fuel products and markets. Plans for LWR GW build, light water SMR programme and AMR technology develops. Industrial-scale reprocessing ends. UK re-engages with Gen IV forum.

Medium Term

2025 - 2035

Closure of remaining AGRs and associated fuel market. Expansion of new build programme in the UK. Light water SMR programme expects to deliver first of a kind (FOAK) by ~2030 with subsequent commercial deployment. Net zero drives demand for low-carbon heat, hydrogen and synthetic fuels. Demonstration of advanced technology in the UK and internationally, with subsequent FOAKs built. A drive for a sustainable fuel cycle.

Long Term

2035 - 2050

Expansion of new build market for LWR fuels (GW and SMR). Rollout of nth of a kind (NOAK) AMRs in support of net zero, plus demonstration of further AMR technology. Expansion of domestic deployment requires consideration about the fuel cycle.

Sustainability of the fuel cycle becomes more important. UK begins to export nuclear technology with fuel cycle solutions.

Vision

2050+

UK supplies the fuel cycle needs of Gen III(+) and advanced nuclear technologies (ANTs), enabling a significant nuclear contribution to achieving net zero in the UK and a sustainable future.

UK industry has a strong domestic capability from fuel enrichment and manufacture to fuel recycling and waste minimisation, storage and disposal.

Opportunity Areas

Advanced Fuels

Advanced fuels development focuses on making fuels for current and future reactors, which is crucial if the UK is to retain an indigenous fuel manufacture capability.

Fuel development is a significant undertaking in terms of time and cost; the route to market is over 10 years in duration for new fuels and costs £10s millions.

Maintaining and developing an indigenous fuel manufacturing capability — a strategic capability — will require an understanding of both the UK and international nuclear deployment plans and subsequent fuel markets.

The UK is well placed to build on its substantial heritage and capability in the near term with ATF for the LWR market and also the developing markets for advanced fuels for SMR and AMRs (in particular CPF for HTRs is an immature market with significant opportunities).

The UK needs to ensure the fuels of the future are available to underpin UK nuclear ambitions; it is also recognised that international collaboration is essential to support and enable fuel development and manufacture in the UK.

Advanced Fuel Cycle Technologies

Advanced fuel cycles offer the opportunity to make future fuels by recycling used fuel. This both increases sustainability and minimises the requirements on the geological repository from the management of spent nuclear fuel (SNF). Factors that may be critical in enabling the expanded use of nuclear energy.

In the field of SNF, fuel recycling technologies to produce future fuels provide substantial opportunities to reduce fuel cycle costs, wastes and environmental impacts as well as enhancing safety, security and proliferation resistance compared to current reprocessing technology.

Advanced technologies that are flexible and possibly modular or scalable, that can be adapted to various future scenarios, could be developed.

The strategic development of fuel cycle capabilities provides an opportunity to enable UK ambitions in a sustainable way with opportunities for UK industry, while also maintaining the UK reputation on the international stage. Staying at the cutting edge of fuel cycle technology is crucial for the UK as a nuclear nation.

Technologies and Capabilities

Industrialisation

In the short term, only capability currently existing in the sector can be used to realise the opportunities that have been identified. This reflects the lead times to production associated with developing or adapting technology for manufacture and deployment.

At the right level of maturity, TRL 6+, there is a transition to focus on commercialisation opportunities. These are known and existing technologies and the focus is on securing UK market share.

In the short term, industrialisation activities will focus on supporting Nuclear Sector Deal ambitions and largely based on current LWR market – post AGR market.

It is important to develop capacity in the supply chain in parallel to maturing technologies to ensure that commercial opportunities can be realised.

Research, Development and Demonstration

There are many examples where future needs can be identified but underlying technology has not reached the level needed to realise the opportunity.

A focus is required on moving through the TRLs and taking concepts to TRL 6 by working across academia, national laboratories and industry.

Developing technologies will require suitable infrastructure to scale up to meet market opportunities.

Early engagement in technology development supports the development of capacity in the supply chain.

By identifying the gaps now, development programmes can realise commercial capabilities in the long-term.

Strategic Capabilities

The future is uncertain and difficult to predict. Therefore maintaining strategically important skills and capabilities is crucial for the UK.

Strong investment in strategic and fundamental research will give the UK the knowledge and capability to address a range of future needs that may not yet be fully understood.

Enablers

Strategic Planning

An immediate need is the strategic planning and a phased approach to decision making around the fuel cycle. There are a number of potential future pathways in the UK depending on Energy and Industrial Strategy.

A stage-gated strategic approach should be developed to decision making, underpinned by detailed analysis.

Industry Collaboration

Building on the success of the Advanced Fuel Cycle Programme (AFCP), a coordinated approach from all stakeholders is required.

A collaborative approach and alignment to objectives are important, this also maximises the opportunity for UK industry and leverages UK institutions and national laboratories.

Education and Training

A skills pipeline is required to ensure the UK has the required capabilities to support future ambitions. Recent investments have started to re-build UK capability, however there needs to be a real focus on this to ensure the skills are there when required and in the areas needed.

Government Support

Government support across three broad areas is required: policy, infrastructure and international. Elements of the fuel cycle are national strategic capabilities and require Government support to maintain; in addition, industry investment is unlikely in some areas due to long lead times and policy uncertainty. National infrastructure is required in some areas to aid development and maintain capability. Government support to international partnering and access to capabilities is critical (eg irradiation facilities).

Figure 6 High level overview of trends and drivers, opportunity areas, technology and capabilities, and enablers for an advanced fuel and fuel cycle RD&D roadmap

Opportunity Areas

Short Term	**2020 - 2025**	**Coated cladding advanced technology fuel (ATF)** supplied to the domestic and international LWR markets	**Apply fuel cycle separations chemistry to recovery of commercially valuable isotopes** from reprocessed products: (eg for medical applications)		
Medium Term	**2025 - 2035**	**Revolutionary advanced technology fuel (ATF) concepts** supplied to the domestic and international LWR/ AMR markets	**UK developed coated particle fuel (CPF) product supplied to high temperature reactor (HTR)** demonstrator(s) (UK and international) CPF product supplied to emerging domestic and international commercial HTR markets with used fuel management options	**Advanced recycle technology to produce future fuels** credible and competitive technical options for advanced reprocessing of LWR (and MOX) used fuels	**Americium-241 supply** production of Am-241 for space power and other applications
Long Term	**2035 - 2050**	**Fast reactor fuel cycle** fuel fabrication and supply to a reactor demonstrator and technology demonstration for recycle of used fuels	**Advanced recycle of ATF to produce future fuels** credible and competitive technical options for reprocessing of used ATF	**Supply of molten salt fuels to reactor demonstrator** and technology demonstration for used fuel management	
Vision	**2050+**	**UK supplying the fuel cycle needs of Gen III(+) and advanced nuclear technologies (ANTs), enabling a significant nuclear contribution to achieving net zero in the UK and a sustainable future**	**UK industry has a strong domestic capability from fuel enrichment and manufacture to recycling and waste minimisation, storage and disposal**		

Table 2 Advanced fuel and fuel cycle opportunity areas

Advanced fuels roadmaps

Advanced technology fuels (ATF)

The fuels which power the current LWR fleets are a focus for innovation for both performance and economic reasons. This has driven the development of ATFs, coined from their initial acronym — accident tolerant fuels — for their characteristically robust properties. These fuels are currently undergoing rapid innovation. To meet energy demand — especially as ATF deployment continues to rise — future fuels must deliver improved performance and economics.

AFCP's ATF work has been aligned with the Westinghouse EnCore™ ATF products through its subsidiary Springfields Fuels Limited, as they are the only fuel vendor with an operational fuel manufacturing site in the UK. Westinghouse and its network of partners have developed EnCore™ fuel with support from the US Department of Energy's (DOE) accident tolerant fuel programme. Through Government investment in AFCP, the UK was able to align with the Westinghouse programme.

The ATF technology roadmap (Figure 7) represents an independent UK view and is not intended to be fuel vendor specific. It focuses on three technology areas building on the work undertaken in AFCP:

Near term:

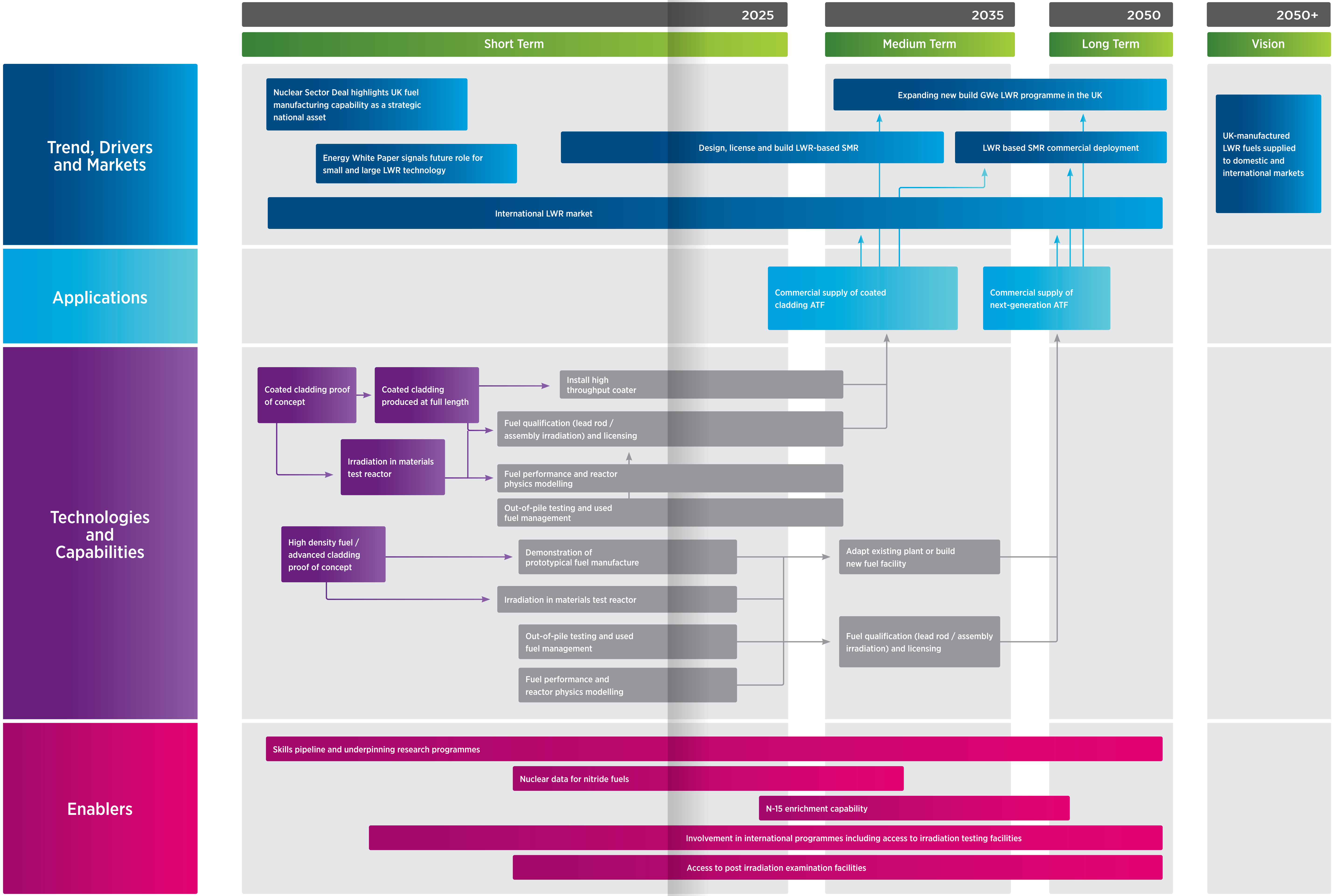
- Coated Zr alloy cladding

Longer term 'revolutionary' options:

- High density fuels (eg uranium nitride)
- Advanced cladding (eg silicon carbide (SiC) composites)

Roadmap summary:

- There is opportunity for commercial coated cladding and next-generation ATF to potentially be manufactured in the UK in the next 10 to 15 years, supplying a possibly growing UK and international LWR market.
- Fuel qualification including irradiation testing, out-of-pile testing and used fuel management assessments will be an important focus over the next three to five years.
- Delivery of these ATF products via the pathway identified by the roadmap would help to secure indigenous fuel manufacturing capability in the UK while opening a potentially significant UK revenue.
- Enablers have been identified within the roadmap, including international partnering, access to irradiation and post-irradiation examination (PIE) facilities, and nuclear data requirements for new fuel qualification.



2025 Short Term

2035 Medium Term

2050 Long Term

2050+ Vision

Trend, Drivers and Markets

- Nuclear Sector Deal highlights UK fuel manufacturing capability as a strategic national asset
- Energy White Paper signals future role for small and large LWR technology
- International LWR market
- Design, license and build LWR-based SMR
- LWR based SMR commercial deployment
- Expanding new build GWe LWR programme in the UK
- UK-manufactured LWR fuels supplied to domestic and international markets

Applications

- Commercial supply of coated cladding ATF
- Commercial supply of next-generation ATF

Technologies and Capabilities

- Coated cladding proof of concept
- Coated cladding produced at full length
- Irradiation in materials test reactor
- Install high throughput coater
- Fuel qualification (lead rod / assembly irradiation) and licensing
- Fuel performance and reactor physics modelling
- Out-of-pile testing and used fuel management
- High density fuel / advanced cladding proof of concept
- Demonstration of prototypical fuel manufacture
- Irradiation in materials test reactor
- Out-of-pile testing and used fuel management
- Fuel performance and reactor physics modelling
- Adapt existing plant or build new fuel facility
- Fuel qualification (lead rod / assembly irradiation) and licensing

Enablers

- Skills pipeline and underpinning research programmes
- Nuclear data for nitride fuels
- N-15 enrichment capability
- Involvement in international programmes including access to irradiation testing facilities
- Access to post irradiation examination facilities

Figure 7 Advanced technology fuels roadmap

▨ Indicates where work is currently ongoing

▨ Indicates gaps / need

Coated particle fuels (CPF)

CPF, commonly known as TRISO (tristructural-isotropic) fuels, consist of a core or 'kernel' of fissile material, typically uranium dioxide, coated with the following layers:

- A buffer of porous carbon to accommodate fuel swelling and the accumulation of gaseous fission products
- Two dense protective layers of isotropic pyrolytic carbon
- A dense silicon carbide (SiC) layer to provide structural integrity and a barrier to fission products

There is significant and growing interest in CPF technology related to the development and deployment of high temperature reactors (HTRs), which have the potential to flexibly deliver electricity, heat and hydrogen. CPF technology is also being considered for LWR applications, and for applications involving novel micro-reactor and space reactor systems. For this technology and these applications to be successful, a secure fuel supply is required. Through AFCP, the UK is re-establishing capabilities to manufacture CPF:

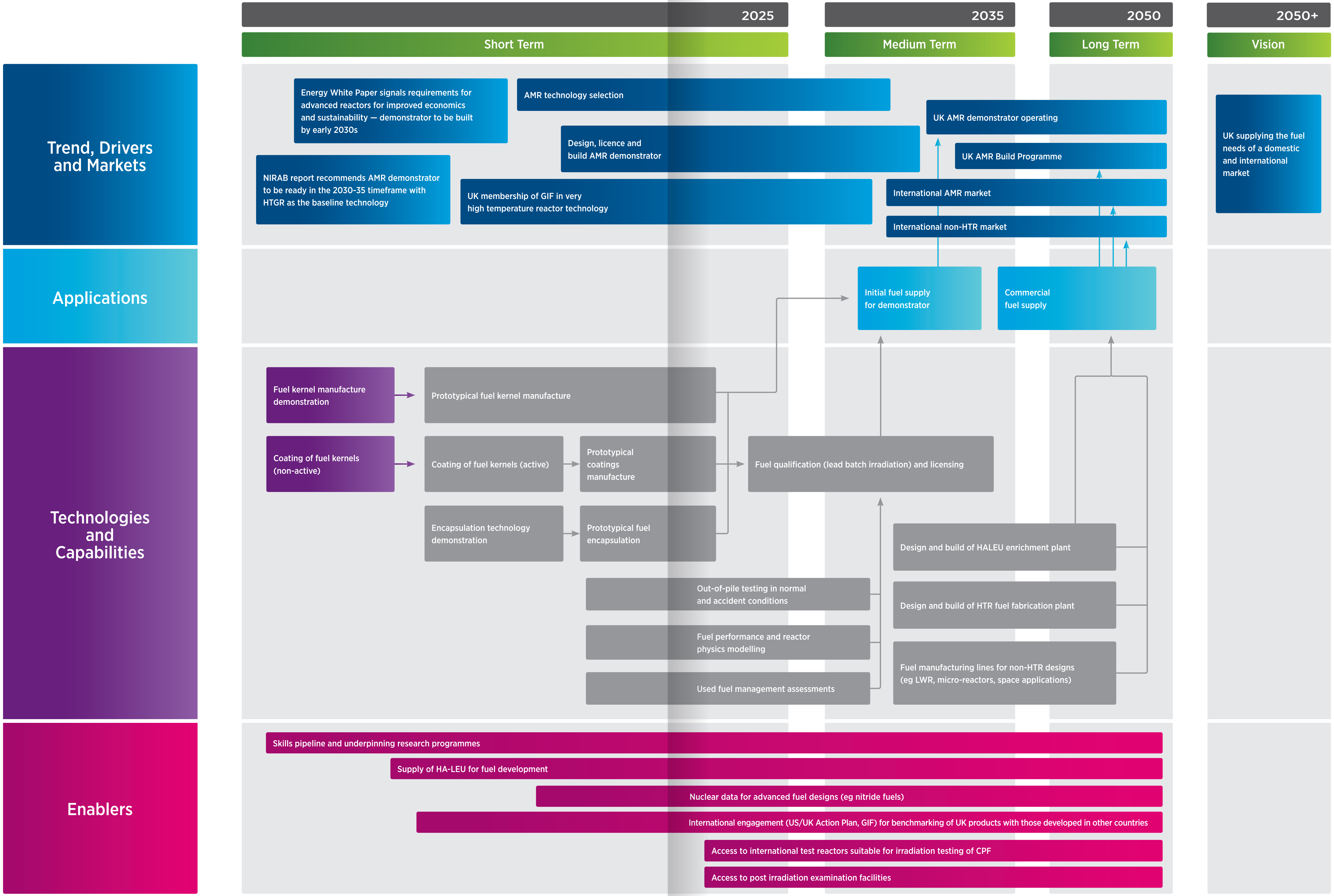
- Kernel fabrication: under the framework of the UK Nuclear Fuel Centre of Excellence (NFCE), the installation and active commissioning of kernel production equipment will be complete in 2021 at NNL Preston Laboratory on the Springfields site.
- Kernel coatings: under the framework of the Sir Henry Royce Institute, the installation and commissioning of a new fluidised bed chemical vapour deposition coater is ongoing at the University of Manchester.

The CPF technology RD&D roadmap (Figure 8) focuses on developing kernel and coating technology, as well as encapsulation technology (ie forming into pebbles or compacts).

Roadmap summary:

- Opportunities focus on near-term supply of fuel for a demonstrator by the early 2030s and then commercial-scale fuel manufacture and supply on a longer timeframe.
- These scenarios are aimed at the stated ambition within the Energy White Paper[3] for an AMR demonstrator in the UK by the early 2030s, and the anticipated growth in both the UK and international HTR markets.
- Prototypical fuel, coating and encapsulation development towards fuel qualification and licensing for a demonstrator is a near-term focus.
- This includes fuel performance and reactor physics modelling, irradiation testing, out-of-pile testing in normal and accident conditions as well as used fuel management assessments.
- Enablers have been identified within the roadmap, including securing a supply of high-assay low-enriched uranium[21] (HA-LEU), international partnering, access to irradiation and post-irradiation examination (PIE) facilities, and nuclear data requirements for new fuel qualification.

[21] HA-LEU contains 5-20% of fissile uranium-235. HTRs under development require fuel with enrichment above 5% which is the current limit for most LWR fuels.



2025 | 2035 | 2050 | 2050+

Short Term | Medium Term | Long Term | Vision

Trend, Drivers and Markets

- Energy White Paper signals requirements for advanced reactors for improved economics and sustainability — demonstrator to be built by early 2030s
- AMR technology selection
- UK AMR demonstrator operating
- Design, licence and build AMR demonstrator
- UK AMR Build Programme
- NIRAB report recommends AMR demonstrator to be ready in the 2030-35 timeframe with HTGR as the baseline technology
- UK membership of GIF in very high temperature reactor technology
- International AMR market
- International non-HTR market
- UK supplying the fuel needs of a domestic and international market

Applications

- Initial fuel supply for demonstrator
- Commercial fuel supply

Technologies and Capabilities

- Fuel kernel manufacture demonstration
- Prototypical fuel kernel manufacture
- Coating of fuel kernels (non-active)
- Coating of fuel kernels (active)
- Prototypical coatings manufacture
- Fuel qualification (lead batch irradiation) and licensing
- Encapsulation technology demonstration
- Prototypical fuel encapsulation
- Design and build of HALEU enrichment plant
- Out-of-pile testing in normal and accident conditions
- Design and build of HTR fuel fabrication plant
- Fuel performance and reactor physics modelling
- Fuel manufacturing lines for non-HTR designs (eg LWR, micro-reactors, space applications)
- Used fuel management assessments

Enablers

- Skills pipeline and underpinning research programmes
- Supply of HA-LEU for fuel development
- Nuclear data for advanced fuel designs (eg nitride fuels)
- International engagement (US/UK Action Plan, GIF) for benchmarking of UK products with those developed in other countries
- Access to international test reactors suitable for irradiation testing of CPF
- Access to post irradiation examination facilities

Figure 8 Coated particle fuels roadmap

🟪 Indicates where work is currently ongoing ⬜ Indicates gaps / need

Fast reactor fuels and fuel cycle

Fast reactor technology is a valuable tool in developing sustainable fuel cycles, with a range of fuel options available depending on the application. There is a need to maintain and develop capability to support options which could underpin UK policy. The UK has a distinguished history in the development and operation of fast reactor technology and the supporting fuel and fuel cycle; until the mid-1990s, the UK operated and fuelled the sodium-cooled Prototype Fast Reactor in Dounreay, Scotland. The UK is revitalising its expertise in this area through AFCP in order to address the needs of the continued interest in fast reactor systems, such as the BEIS AMR programme.

AFCP focuses on installing UK capability to research and optimise the manufacture of fast reactor fuel pellets within the NNL Central Laboratory at Sellafield in Cumbria. The aim will be to manufacture UK fast reactor specification MOX fuel for the first time in over 20 years using a new, state-of-the-art flexible fuel line. AFCP is also developing broader capabilities that will contribute to the UK input to the GIF on development of sodium fast reactor technology.

In addition, fast reactor fuel recycle technology is being explored as part of AFCP, building on collaborative European R&D programmes, such as the GENIORS project[22]. While the aqueous-based technologies used for recycling LWR fuel can be used for the recycling of fast reactor fuels, there are some specific challenges that need to be addressed: notably the high plutonium contents, high radiation levels and significant heat generation. A recycle process based on the Group Actinide Extraction (GANEX) process is being developed as part of AFCP to recycle uranium, plutonium and minor actinides for use in fast reactors.

The fast reactor fuel and fuel cycle RD&D roadmap (Figure 9) covers both uranium-based fuels with steel cladding (a near-term option being explored for AMR fast reactor technology, exemplified by the Westinghouse Lead Fast Reactor concept and based on a once-through fuel cycle), and plutonium and minor actinide (MA) based fuels and cladding with the enabling recycle technology.

Roadmap summary:

- Advanced uranium-based fuels with next-generation steel cladding are aimed at the stated ambition within the Energy White Paper[3] for an AMR demonstrator in the UK by the early 2030s. While HTR is the current assumed baseline technology (as outlined by NIRAB[23]) it does not preclude a potential decision to focus on fast reactor technology with economic benefits and a potential pathway to advanced fuel cycles.
- Wider work on fast reactor plutonium and MA fuels focuses on an anticipated growth in UK and international markets for fast reactor fuel over a longer timeframe.
- Prototypical fuel development towards fuel qualification and licensing for a demonstrator is a near-term focus. This includes fuel performance and reactor physics modelling, irradiation testing and out-of-pile testing as well as used fuel management assessments.
- Development of plutonium and MA fuel manufacture requires development of infrastructure and fuel recycle technology.
- Enablers have been identified within the roadmap, including access to high active (HA) cells for used fuel management testing, international partnering, access to irradiation and post-irradiation examination (PIE) facilities, and working closely with the NDA (on the plutonium disposition programme) to develop common R&D infrastructure.

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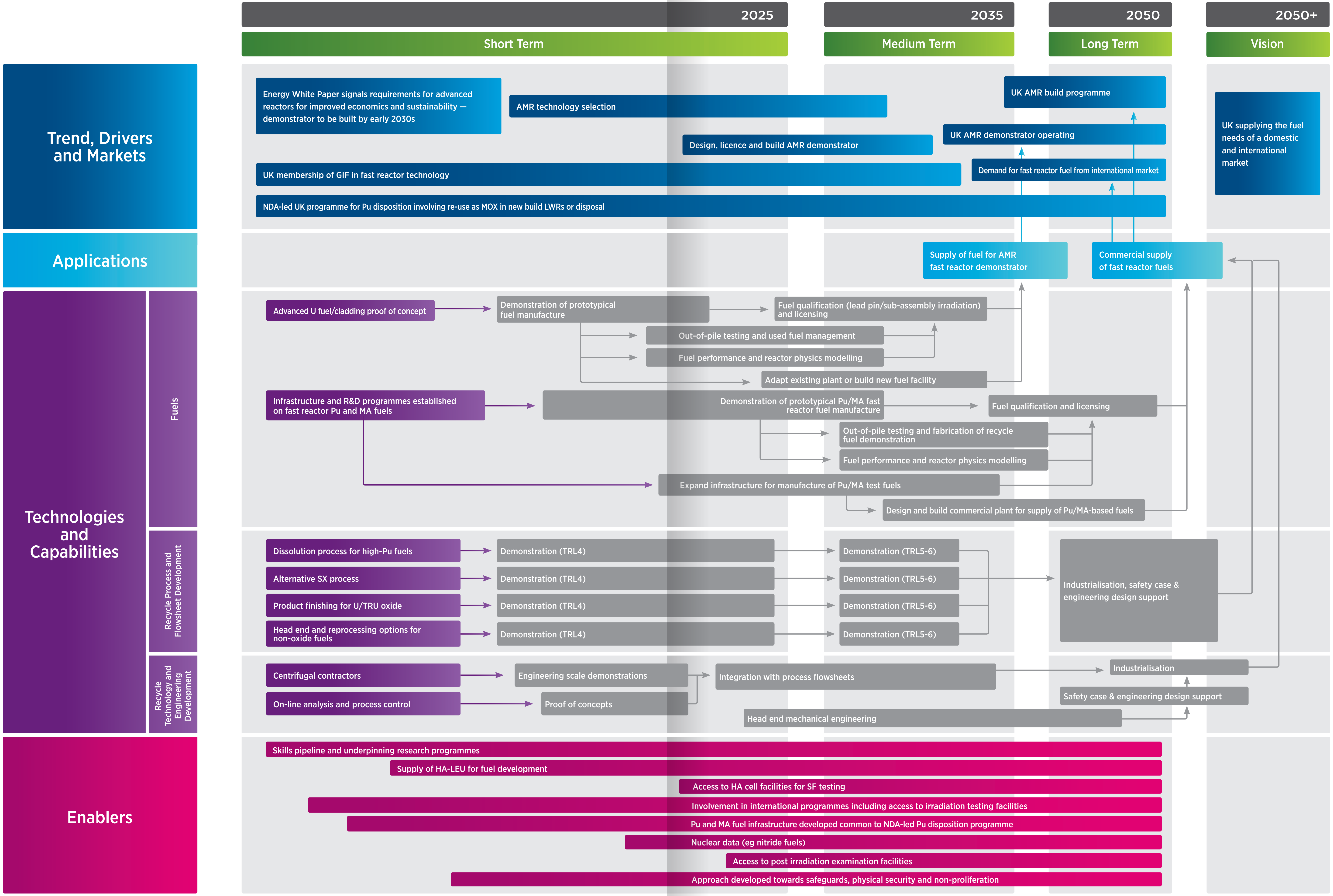
[22] GENIORS – GENeration IV Integrated Oxide fuel Recycling Strategies project funded by the European Union's Horizon 2020 programme (Stéphane Bourg, Andreas Geist, Jean-Marc Adnet, Chris Rhodes, Bruce C. Hanson, Partitioning and transmutation strategy R&D for nuclear spent fuel: the SACSESS and GENIORS projects, EPJ Nuclear Sci. Technol. 6 35, 2020)

[23] NIRAB Annual Report 2020 - Achieving Net Zero: The role of Nuclear Energy in Decarbonisation (https://www.nirab.org.uk/download_file/138/0)



2025 | 2035 | 2050 | 2050+

Short Term | Medium Term | Long Term | Vision

Trend, Drivers and Markets

- Energy White Paper signals requirements for advanced reactors for improved economics and sustainability — demonstrator to be built by early 2030s
- AMR technology selection
- Design, licence and build AMR demonstrator
- UK AMR demonstrator operating
- UK AMR build programme
- Demand for fast reactor fuel from international market
- UK membership of GIF in fast reactor technology
- NDA-led UK programme for Pu disposition involving re-use as MOX in new build LWRs or disposal
- UK supplying the fuel needs of a domestic and international market

Applications

- Supply of fuel for AMR fast reactor demonstrator
- Commercial supply of fast reactor fuels

Technologies and Capabilities

Fuels

- Advanced U fuel/cladding proof of concept
- Demonstration of prototypical fuel manufacture
- Fuel qualification (lead pin/sub-assembly irradiation) and licensing
- Out-of-pile testing and used fuel management
- Fuel performance and reactor physics modelling
- Adapt existing plant or build new fuel facility
- Infrastructure and R&D programmes established on fast reactor Pu and MA fuels
- Demonstration of prototypical Pu/MA fast reactor fuel manufacture
- Fuel qualification and licensing
- Out-of-pile testing and fabrication of recycle fuel demonstration
- Fuel performance and reactor physics modelling
- Expand infrastructure for manufacture of Pu/MA test fuels
- Design and build commercial plant for supply of Pu/MA-based fuels

Recycle Process and Flowsheet Development

- Dissolution process for high-Pu fuels
- Demonstration (TRL4)
- Demonstration (TRL5-6)
- Alternative SX process
- Demonstration (TRL4)
- Demonstration (TRL5-6)
- Product finishing for U/TRU oxide
- Demonstration (TRL4)
- Demonstration (TRL5-6)
- Head end and reprocessing options for non-oxide fuels
- Demonstration (TRL4)
- Demonstration (TRL5-6)
- Industrialisation, safety case & engineering design support

Recycle Technology and Engineering Development

- Centrifugal contractors
- Engineering scale demonstrations
- Integration with process flowsheets
- Industrialisation
- On-line analysis and process control
- Proof of concepts
- Safety case & engineering design support
- Head end mechanical engineering

Enablers

- Skills pipeline and underpinning research programmes
- Supply of HA-LEU for fuel development
- Access to HA cell facilities for SF testing
- Involvement in international programmes including access to irradiation testing facilities
- Pu and MA fuel infrastructure developed common to NDA-led Pu disposition programme
- Nuclear data (eg nitride fuels)
- Access to post irradiation examination facilities
- Approach developed towards safeguards, physical security and non-proliferation

Figure 9 Fast reactor fuels and fuel cycle roadmap

🟪 Indicates where work is currently ongoing

▨ Indicates gaps / need

Sustainable advanced fuel cycle roadmaps

Advanced recycle of LWR fuel to produce future fuels

In the field of fuel recycling, AFCP is exploring novel technologies that provide substantial opportunities to reduce fuel cycle costs and environmental impacts, as well as enhance safety, security and proliferation resistance compared to current recycle technology; this is enabling a pathway to realise the benefits of recycling strategies compared to the once-through (or open) fuel cycle strategy where used fuel is disposed. Reimagining the approach to and perception of fuel recycling and sustainability must complement the deployment of future fuels in order to deliver a modernised fuel cycle. The technologies developed through these roadmaps provide an alternative to the once-through fuel cycle which is the currently assumed UK baseline approach to used fuel management. Developing these recycle options in parallel will reduce risks to the large-scale deployment of new nuclear and meeting net zero carbon emissions for the long term beyond 2050.

An advanced PUREX (plutonium uranium refining by extraction) process is being developed within AFCP which aims to shrink the current PUREX approach — such as that used in the UK, France, Russia and elsewhere at industrial scale.

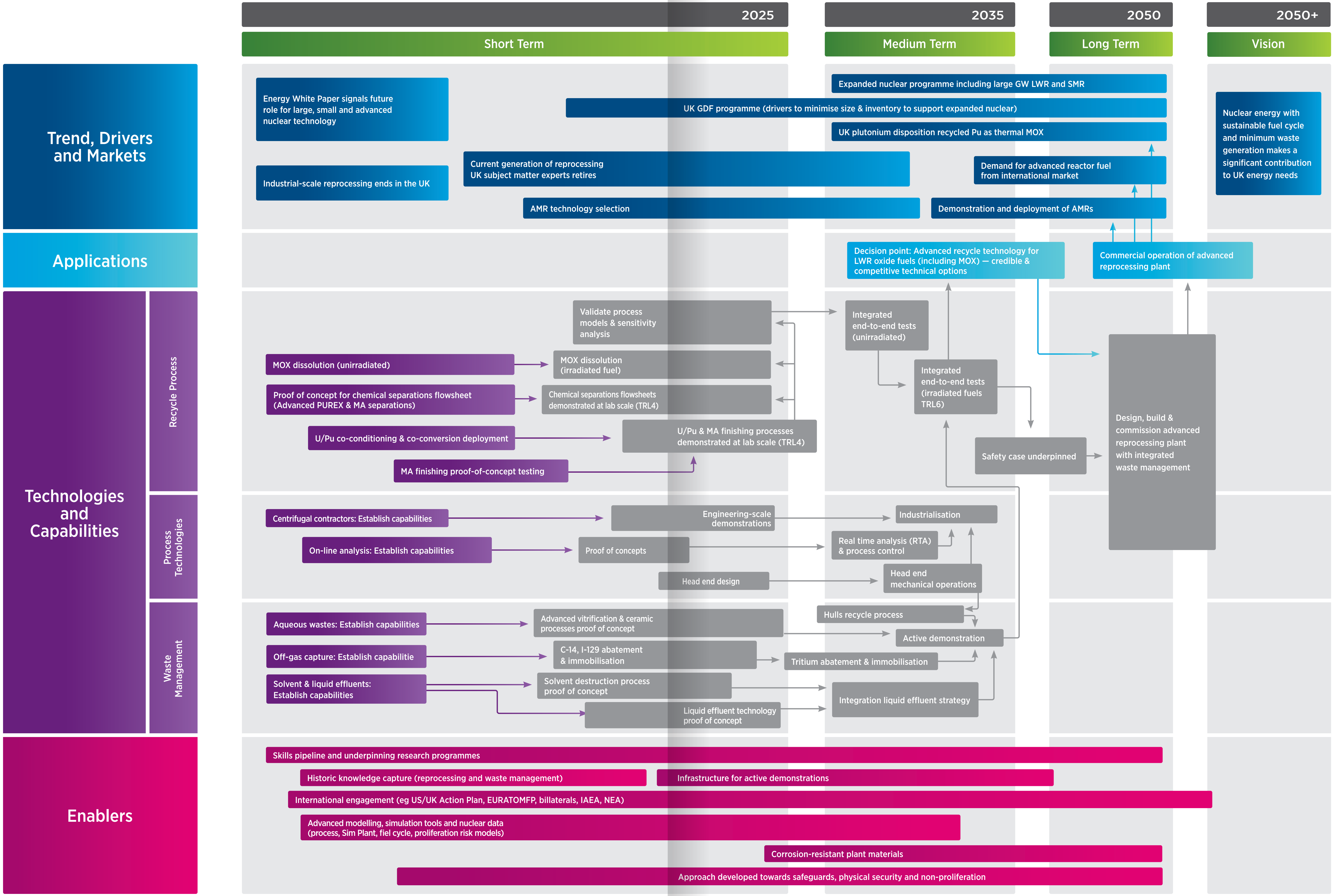
An advanced PUREX process will use a much smaller single cycle process as well as more innovative concepts that simplify operations, add proliferation barriers and increase flexibility. The secondary wastes generated will be minimised at source. The option for separating the minor actinides to reduce the burden on the high-level waste treatment and disposal will also be developed as an ‘add-on’ to the process. As well as the core separations processes, AFCP includes the development of innovative technologies to manage both high- and intermediate-level liquid by-products and capture off-gases, including new materials for long-term storage. This clear focus, complementing the innovation around core separation processes, ensures the wastes are minimised at source and final treatments are optimised as part of the overall fuel recycle strategy, thereby reducing environmental impact and minimising overall fuel cycle costs.

The advanced recycle technology RD&D roadmap (Figure 10) focuses on the core recycle process, process technologies and key waste management technologies. The key technology development needs are:

- Head end operations, including shearing, fuel dissolution and conditioning of uranium oxide (UOX) and MOX fuels
- Intensified processes for the separation of uranium and plutonium (and potentially neptunium) from fission products, avoiding a pure plutonium stream at any point in the process
- Simple processes for recovery of the minor actinides from high level liquid wastes
- Co-conversion of mixed products to fuel precursors with acceptable properties for fuel fabrication
- Integrated and optimised secondary waste management strategy based on advanced abatement and immobilisation technologies
- Applications of innovative online analysis tools for process monitoring, control and safeguards

Roadmap summary:

- A potentially expanded UK nuclear programme including large, small and advanced systems are trends driving the requirement to have credible technical options for fuel recycle within the next 10 to 15 years.
- In addition, work on plutonium disposition and re-use as MOX together with a potential drive to minimise the size and inventory of a geological disposal facility (GDF) provide drivers for capability development. A possible future market for advanced reactor fuel is also outlined as a driver.
- Technology development focuses on maturing towards TRL 6 on the near to medium term to underpin decisions around credible options; this will require, for example, dissolution studies on irradiated fuel and integrated end-to-end process tests.
- Enablers have been identified within the roadmap, including infrastructure for active demonstrations, international partnering and advanced modelling and simulation tools.
- Finally, in the fuel cycle arena the UK has extensive, globally unique experience from several decades of reprocessing and waste management from pilot to commercial scales; the roadmap identifies that near-term efforts are needed to capture this experience before it is lost with the completion of industrial reprocessing at Sellafield.



2025 | 2035 | 2050 | 2050+

Short Term | Medium Term | Long Term | Vision

Trend, Drivers and Markets

Energy White Paper signals future role for large, small and advanced nuclear technology

Industrial-scale reprocessing ends in the UK

Current generation of reprocessing UK subject matter experts retires

AMR technology selection

Expanded nuclear programme including large GW LWR and SMR

UK GDF programme (drivers to minimise size & inventory to support expanded nuclear)

UK plutonium disposition recycled Pu as thermal MOX

Demand for advanced reactor fuel from international market

Demonstration and deployment of AMRs

Nuclear energy with sustainable fuel cycle and minimum waste generation makes a significant contribution to UK energy needs

Applications

Decision point: Advanced recycle technology for LWR oxide fuels (including MOX) — credible & competitive technical options

Commercial operation of advanced reprocessing plant

Technologies and Capabilities

Recycle Process

MOX dissolution (unirradiated)

Proof of concept for chemical separations flowsheet (Advanced PUREX & MA separations)

U/Pu co-conditioning & co-conversion deployment

MA finishing proof-of-concept testing

Validate process models & sensitivity analysis

MOX dissolution (irradiated fuel)

Chemical separations flowsheets demonstrated at lab scale (TRL4)

U/Pu & MA finishing processes demonstrated at lab scale (TRL4)

Integrated end-to-end tests (unirradiated)

Integrated end-to-end tests (irradiated fuels TRL6)

Safety case underpinned

Design, build & commission advanced reprocessing plant with integrated waste management

Process Technologies

Centrifugal contractors: Establish capabilities

On-line analysis: Establish capabilities

Engineering-scale demonstrations

Proof of concepts

Head end design

Industrialisation

Real time analysis (RTA) & process control

Head end mechanical operations

Waste Management

Aqueous wastes: Establish capabilities

Off-gas capture: Establish capabilitie

Solvent & liquid effluents: Establish capabilities

Advanced vitrification & ceramic processes proof of concept

C-14, I-129 abatement & immobilisation

Solvent destruction process proof of concept

Liquid effluent technology proof of concept

Hulls recycle process

Active demonstration

Tritium abatement & immobilisation

Integration liquid effluent strategy

Enablers

Skills pipeline and underpinning research programmes

Historic knowledge capture (reprocessing and waste management)

Infrastructure for active demonstrations

International engagement (eg US/UK Action Plan, EURATOMFP, bilaterals, IAEA, NEA)

Advanced modelling, simulation tools and nuclear data (process, Sim Plant, fiel cycle, proliferation risk models)

Corrosion-resistant plant materials

Approach developed towards safeguards, physical security and non-proliferation

Figure 10 Advanced recycle of LWR fuel to produce future fuels roadmap

▆ Indicates where work is currently ongoing ▆ Indicates gaps / need

Advanced recycle of ATF to produce future fuels

The advanced recycle RD&D roadmap for a revolutionary concept ATF (Figure 11) will very much depend on the fuel concept taken forward but will have strong overlaps with the roadmap for advanced recycle of LWR fuel to produce future fuels (Figure 10). The advanced recycle technology for ATF RD&D roadmap focuses on the key steps at a high level and outlines a simplified approach. This roadmap focuses on the additional R&D needed to address revolutionary concept ATF recycle which is expected to mainly impact the head end fuel preparation steps.

Roadmap summary:

- Drivers include the development and qualification of an ATF product, a potentially expanded nuclear programme in the UK and the possible deployment of AMRs using advanced fuels.
- The application opportunity focuses on having credible technical options for fuel recycle within the next 10 to 15 years, supporting and enabling a decision on the requirement for future reprocessing and recycle of fuel in the UK.
- It is assumed as part of this roadmap that the development listed in the LWR oxide fuel recycle roadmap is in-progress and, therefore, feeds much of the general recycle technology needs to this roadmap. Additional development would focus on, for example, nitrogen-15 recovery should a uranium nitride ATF concept be taken forward.
- Enablers include the ability to make simulant fuels, international engagement and access to infrastructure for active demonstrations.

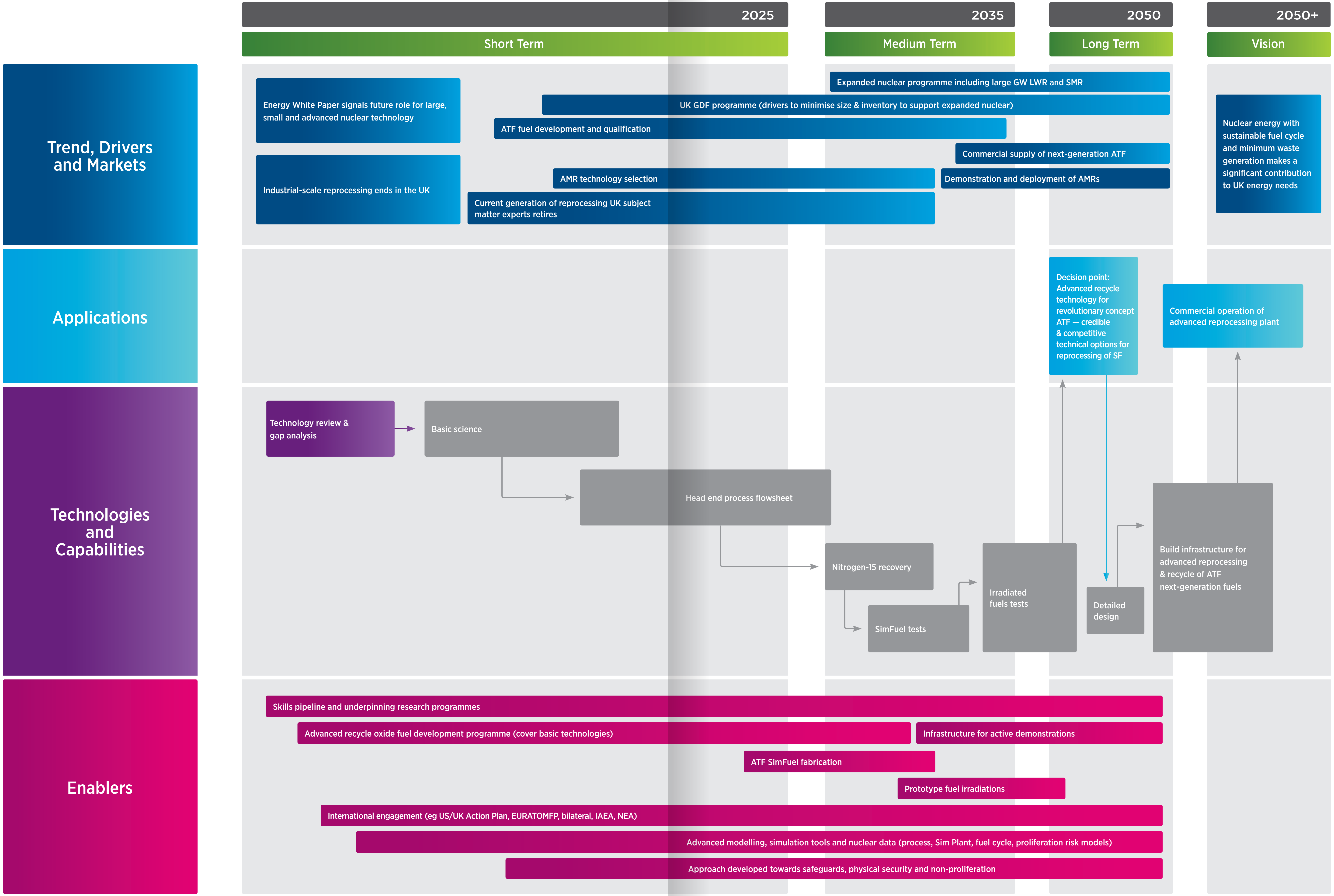


Figure 11 Advanced recycle of ATF to produce future fuels roadmap

▨ Indicates where work is currently ongoing ▨ Indicates gaps / need

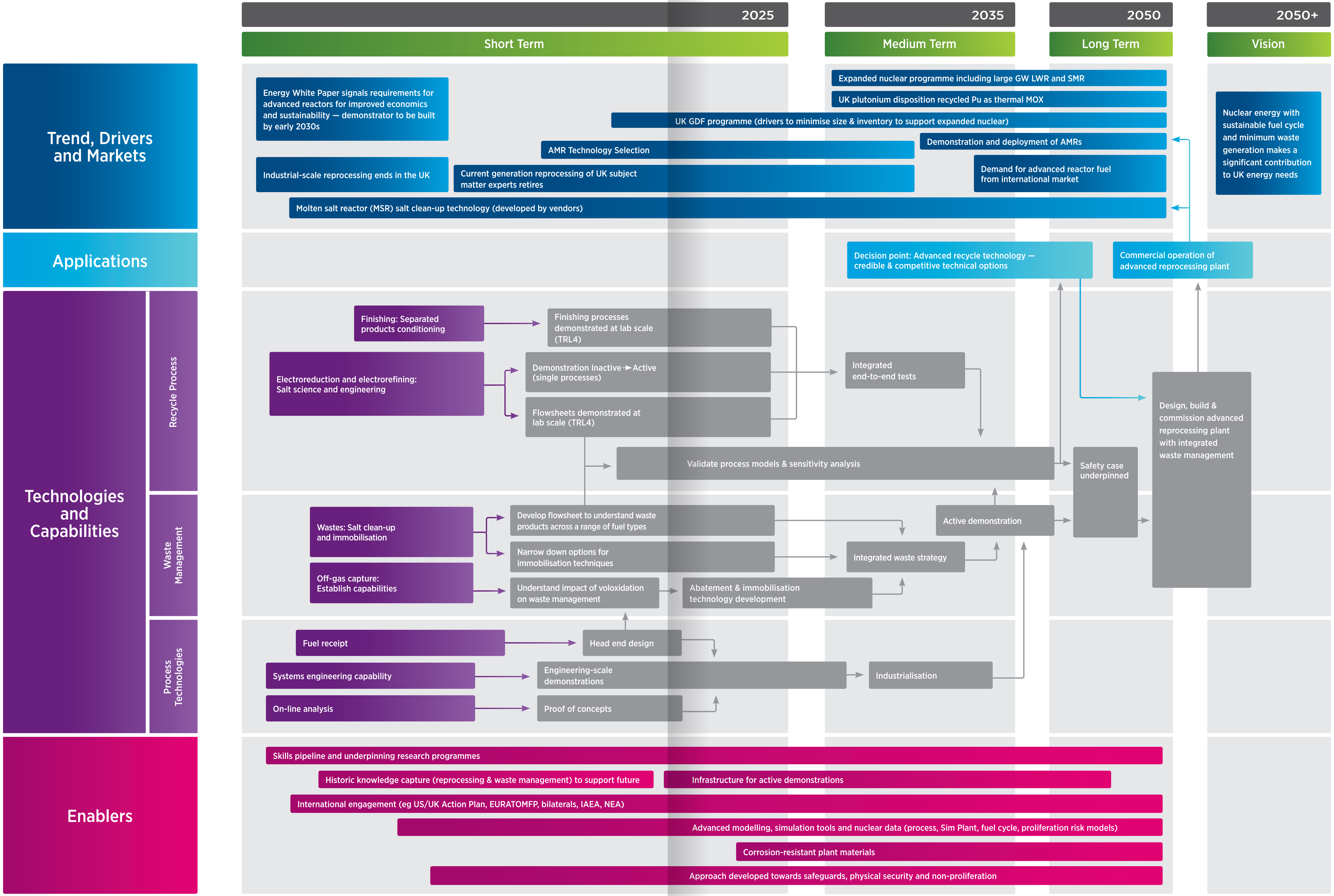
Pyrochemical (molten salt) recycle technology to produce future fuels

This complementary approach to aqueous recycling is based primarily on the electrorefining of fuels. AFCP is placing a strong focus on salt chemistry and engineering to re-build UK expertise in this field and better understand its science and engineering challenges. As well as the core metal electrorefining processes, the programme is looking at the extensions of pyro-processing to oxide fuels, via electroreduction, and some of the cross-cutting challenges with molten salt advanced reactor (MSR) technologies. Finally, off-gas capture and salt treatment and immobilisation are key strands.

Pyrochemical processing RD&D builds capability that supports not only fuel processing but also reactor or other molten salt applications, such as tritium production or energy storage. This roadmap (Figure 12), however, focuses on the development of an advanced recycle process for high burn-up fuel — the skills developed here will support wider UK ambitions.

Roadmap summary:

- A potentially expanded UK nuclear programme including large, small and advanced systems raises trends which drive the requirement to have credible technical options for fuel recycle within the next 10 to 15 years.
- In the technology area, electroreduction and electrorefining will focus on maturing through the TRLs. Electroreduction features in the head end preparation for the conditioning of fuel into a suitable format for electrorefining. Electrorefining selectively separates the recyclable elements of used fuel from the remaining waste. The ability to separate minor actinides along with uranium and plutonium produces a waste that will reduce the burden on high-level waste treatment.
- Waste management development includes technology for clean-up of the salt from the recycle process (note this will also be a requirement of MSRs) and treatment of any resulting waste products to produce a suitable waste form.
- These three core areas are inextricably linked with the chemistry and electrochemistry of each, impacting the processes before and after.
- Key enablers identified in the roadmap include building a skills pipeline (national laboratory, industry and academic capability), knowledge capture, international engagement and developing the supporting infrastructure for active demonstrations.



2025 | 2035 | 2050 | 2050+

Short Term | Medium Term | Long Term | Vision

Trend, Drivers and Markets

Energy White Paper signals requirements for advanced reactors for improved economics and sustainability — demonstrator to be built by early 2030s

Industrial-scale reprocessing ends in the UK

Current generation reprocessing of UK subject matter experts retires

AMR Technology Selection

UK GDF programme (drivers to minimise size & inventory to support expanded nuclear)

Expanded nuclear programme including large GW LWR and SMR

UK plutonium disposition recycled Pu as thermal MOX

Demonstration and deployment of AMRs

Demand for advanced reactor fuel from international market

Molten salt reactor (MSR) salt clean-up technology (developed by vendors)

Nuclear energy with sustainable fuel cycle and minimum waste generation makes a significant contribution to UK energy needs

Applications

Decision point: Advanced recycle technology — credible & competitive technical options

Commercial operation of advanced reprocessing plant

Technologies and Capabilities

Recycle Process

Finishing: Separated products conditioning

Finishing processes demonstrated at lab scale (TRL4)

Electroreduction and electrorefining: Salt science and engineering

Demonstration Inactive → Active (single processes)

Flowsheets demonstrated at lab scale (TRL4)

Integrated end-to-end tests

Validate process models & sensitivity analysis

Safety case underpinned

Design, build & commission advanced reprocessing plant with integrated waste management

Waste Management

Wastes: Salt clean-up and immobilisation

Develop flowsheet to understand waste products across a range of fuel types

Narrow down options for immobilisation techniques

Off-gas capture: Establish capabilities

Understand impact of voloxidation on waste management

Abatement & immobilisation technology development

Integrated waste strategy

Active demonstration

Process Technologies

Fuel receipt

Head end design

Systems engineering capability

Engineering-scale demonstrations

Industrialisation

On-line analysis

Proof of concepts

Enablers

Skills pipeline and underpinning research programmes

Historic knowledge capture (reprocessing & waste management) to support future

Infrastructure for active demonstrations

International engagement (eg US/UK Action Plan, EURATOMFP, bilaterals, IAEA, NEA)

Advanced modelling, simulation tools and nuclear data (process, Sim Plant, fuel cycle, proliferation risk models)

Corrosion-resistant plant materials

Approach developed towards safeguards, physical security and non-proliferation

Figure 12 Pyrochemical (molten salt) recycle technology to produce future fuels roadmap

🟪 Indicates where work is currently ongoing

⬜ Indicates gaps / need

5

SUMMARY

As part of AFCP, this paper has outlined advanced fuel and fuel cycle roadmaps for key technology areas of interest for the UK. These do not cover the entire possible future UK fuel cycle but represent significant opportunities that could support the UK in developing future fuel cycles.

There is an opportunity to build on the foundations of the BEIS investment in AFCP and continue to develop world-leading fuel cycle capability in the UK. Key enablers that would support this — strategic planning, industry collaboration and Government support — are set out in this document. Government support is important across three broad areas: policy, infrastructure and international. Elements of the fuel cycle could be considered national strategic capabilities (from a security and non-proliferation perspective) and would require Government support to maintain UK capability; in addition, due to long lead times and policy uncertainty industry investment is unlikely in some areas. Government support to international partnering and access to capabilities is also beneficial.

A strategic approach to the UK fuel cycle will ensure that the nation can achieve its nuclear ambitions set out in the Ten Point Plan, the Energy White Paper and beyond. The roadmaps presented here can support the continued development of such a plan and the pathways outlined could set the UK out as a leader on the international stage through world class science and technology.

Appendix 1. Technology readiness level (TRL) criteria

Technology readiness assessment and approximation is based upon the following[18]:

Definition	Description
TRL 9: Actual system operated over the full range of expected conditions	The technology is in its final form and operated under the full range of operating conditions. Examples include using the actual system with the full range of wastes in hot operations.
TRL 8: Actual system completed and qualified through test and demonstration	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental testing and evaluation of the system with actual waste in hot commissioning. Supporting information includes operational procedures that are virtually complete. An Operational Readiness Review (ORR) has been successfully completed prior to the start of hot testing.
TRL 7: Full-scale, similar (prototypical) system demonstrated in relevant environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Examples include testing full-scale prototype in the field with a range of simulants in cold commissioning. Supporting information includes results from the full-scale testing and analysis of the differences between the test environment, and analysis of what the experimental results mean for the eventual operating system/environment. Final design is virtually complete.
TRL 6: Engineering/ pilot-scale, similar (prototypical) system validation in relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step up in a technology's demonstrated readiness. Examples include testing an engineering-scale prototypical system with a range of simulants. Supporting information includes results from the engineering-scale testing and analysis of the differences between the engineering scale, prototypical system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. TRL 6 begins true engineering development of the technology as an operational system. The major difference between TRL 5 and 6 is the step up from laboratory-scale to engineering-scale and the determination of scaling factors that will enable design of the operating system. The prototype should be capable of performing all the functions that will be required of the operational system. The operating environment for the testing should closely represent the actual operating environment.
TRL 5: Laboratory-scale, similar system validation in relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Examples include testing a high-fidelity, laboratory-scale system in a simulated environment with a range of simulants and actual waste. Supporting information includes results from the laboratory-scale testing, analysis of the differences between the laboratory and eventual operating system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. The major difference between TRL 4 and 5 is the increase in the fidelity of the system and environment to the actual application. The system tested is almost prototypical.
TRL 4: Component and/ or system validation in laboratory environment	The basic technological components are integrated to establish that the pieces will work together. This is relatively 'low fidelity' compared with the eventual system. Examples include integration of ad hoc hardware in a laboratory and testing with a range of simulants and small-scale tests on actual waste. Supporting information includes the results of the integrated experiments and estimates of how the experimental components and experimental test results differ from the expected system performance goals. TRL 4-6 represent the bridge from scientific research to engineering. TRL 4 is the first step in determining whether the individual components will work together as a system. The laboratory system will probably be a mix of on-hand equipment and a few special purpose components that may require special handling, calibration, or alignment to get them to function.
TRL 3: Analytical and experimental critical function and/or characteristic proof of concept	Active research and development (R&D) is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative tested with simulants. Supporting information includes results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. At TRL 3 the work has moved beyond the paper phase to experimental work that verifies that the concept works as expected on simulants. Components of the technology are validated, but there is no attempt to integrate the components into a complete system. Modelling and simulation may be used to complement physical experiments.
TRL 2: Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies. Supporting information includes publications or other references that outline the application being considered and that provide analysis to support the concept. The step up from TRL 1 to TRL 2 moves the ideas from pure to applied research. Most of the work is analytical or paper studies with the emphasis on understanding the science better. Experimental work is designed to corroborate the basic scientific observations made during TRL 1 work.
TRL 1: Basic principles observed and reported	This is the lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples might include paper studies of a technology's basic properties or experimental work that consists mainly of observations of the physical world. Supporting Information includes published research or other references that identify the principles that underlie the technology.

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