ADVANCED NUCLEAR FOR HEAT AND HYDROGEN (AN4H)

Expert insight on how to accelerate the delivery of a demonstrator

NATIONAL NUCLEAR LABORATORY

FOREWORD

The COVID-19 pandemic impacted the UK economy by over 20% in Quarter 2 of 2020 and attention has rightly focused on mechanisms that can enable a sharp V-shaped recovery. Government investment in programmes that create jobs and deliver regional economic impact are likely to be prioritised to combat a recession and long-term unemployment.

However, the challenge to develop an affordable, reliable, and diverse carbon-neutral energy system remains.

Advanced nuclear technologies are a low-carbon heat and power source, including for the generation of hydrogen at scale, which looks to be an increasingly important option. The typical time estimate to demonstrate an advanced nuclear technology is, however, not fast enough in today's post-COVID world and the net zero clock is ticking.

The National Nuclear Laboratory (NNL) exists to support the development of nuclear technologies to benefit society. If acceleration is required, then why not think differently and challenge the assumptions and inherited wisdom that lead to this outcome?

NNL has therefore sought the advice of a diverse group of international experts on how to halve the time needed to demonstrate advanced nuclear technology for heat/hydrogen production.

I was delighted by the positive, enthusiastic and thoughtful approach taken by those we spoke to. The breadth of understanding, depth of insight, and quality of advice have made the production of this report a challenge and a delight. I am also immensely grateful to the team at NNL who undertook the analysis and shaped this report. Thank you to everyone involved.

I hope that this report stimulates decision makers to focus on the few important things that would enable advanced nuclear technologies to grow jobs and economic impact in parts of the country that need them most whilst also helping to create a new and dynamic carbon-neutral future in the UK and around the world.

Professor Andrew H. Sherry FREng

Special Advisor, National Nuclear Laboratory (NNL)

EXECUTIVE SUMMARY

This is not a science project. This is an engineering programme to create jobs and regional economic growth by demonstrating advanced nuclear technology as an accelerator for decarbonisation and the hydrogen economy within a decade.

Conventional wisdom suggests a timescale of ~15-years within the UK's gold-standard nuclear regulatory regime to design, build, and commission an advanced nuclear reactor; this is an unattractive timescale when jobs and economic impact are needed urgently to drive a V-shaped bounce-back from the economic impact of COVID-19.

The benefits of an accelerated Advanced Nuclear for Heat and Hydrogen (AN4H) programme could be considerable: high grade design, manufacturing, and construction jobs, new supply chains for components and systems as well as securing the UK's fuel capability to supply the first-of-a-kind demonstrator and follow-on systems for the domestic and international markets.

To identify the main factors that would accelerate an AN4H programme, the National Nuclear Laboratory (NNL) sought the advice of independent experts around the world. Using the "Seven Questions" technique, views were obtained, reviewed and analysed by NNL. This report summarises the main insights, which can help decision makers focus on the few important things that would accelerate an AN4H programme.

It is not the maturity of the technology that prevents delivery by 2030; technology has already been proven around the world with significant expertise and experience in the UK[1]. Delivery to this timescale requires that government, industry and regulators address three main factors effectively in the short term.

1. Decisive Government Commitment

As is the case internationally, any new nuclear programme requires government to be an active enabler, not a passive observer. Government should articulate clear policy, including on clean energy (power, heat and hydrogen), the role of advanced nuclear technology and therefore of an AN4H demonstrator. Government should provide enabling financing in the demonstration phase, including an appropriate financial model, though a transition to commercial funding models would be expected as the demonstrator programme transitions to a domestic fleet and international exports. Government leadership on international strategy is crucial to secure an international partner to accelerate an AN4H design and in opening future markets for reactors, fuel and hydrogen generation. Finally, government should lead on site identification, enable owner/operator development (see below) and support public engagement.

'It is a matter of fact that in any part of the world a nuclear programme is only successful with strong governmental support'

[1]See examples of international reactor demonstrations in Appendix 1.

2. Single Delivery Team with an Inspirational Leader

An accelerated AN4H programme requires a single owner/operator[2] organisation with inspirational leadership to bring together and align an integrated project team with clarity of purpose to focus on delivery. This "dream team", released from their parent organisations to focus solely on AN4H, requires domestic capability selected on the basis of skill, experience and (importantly) attitude. The organisational culture established should be one of challenge to do things differently to deliver the outcome. To enable this, the regulators should be pushing enabling regulation to the limit, without compromising safety and independence.

Public engagement will be a crucial element of an accelerated AN4H programme, with active engagement focused on understanding the local views and agreeing mechanisms to partner for success.

'One mind, one vision'

'Ultimately the demonstrator underpins the cost estimates for the commercial reactor.'

3. International Partnership to Adopt a Near Complete Design

The owner/operator should, with government support, engage an international partner that has recent design and operational experience of advanced nuclear technology. There must be an agreed strategy to adopt the technology, implemented with a relentless focus on simplicity, and the development of a domestic capability. Any design change decisions should be based on economics, cost of the product or safety. The domestic supply chain should be aligned fully behind large (not piece meal) contracts that are incentivised for delivery as outlined in the Project 13 approach[3].

'Technically, the technology must already be reasonably well known.'

These three main factors, addressed effectively in the short term, provide the basis of a successful accelerated demonstrator programme that would enable a future AN4H fleet and exports with considerable economic and clean energy benefits.

'Getting to a demonstrator is not a research exercise it is a confidence builder.'

Whilst the AN4H is not a research project and this concept has already been proven internationally, there are four technology areas that could impact on its delivery if not given enough focus:

- **Fuel supply and fuel cycle** – need to develop and qualify an indigenous advanced fuel supply; this should be given as much attention as the demonstrator.
- **Component and materials qualification** – access to experimental infrastructure, including high temperature materials testing facilities, is key.
- **Coupling** – heat exchanger technology will need to be proven.
- **Hydrogen production** – although there are proven hydrogen production methods available, thermochemical production is yet to be proven. A programme in parallel should be run to demonstrate and mature the technology while proving the economics.

Supporting infrastructure will accelerate delivery by providing regulatory confidence in a 'safe space' through technology development and demonstration in parallel to the main construction project.

[2]See for example: Initiating Nuclear Power Programmes: Responsibilities and Capabilities of Owners and Operators, IAEA Nuclear Energy Series NG-T-3.1(Rev1) https://www.iaea.org/publications/8212/initiating-nuclear-power-programmes-responsibilities-and-capabilities-of-owners-and-operators

[3]Project 13 is an industry response to infrastructure delivery models led by the Institution of Civil Engineers (ICE): http://www.p13.org.uk/

INTRODUCTION

Overview

This 'Issues Paper' has been produced by the National Nuclear Laboratory (NNL) with the support of a range of international experts to inform decision makers. It is a compilation of the outputs from interviews conducted during July 2020. It is not intended to be a comprehensive review and appraisal, but rather a spotlight on key areas that influence the ability to accelerate an advanced nuclear demonstrator programme. Key insights have been summarised and are presented; the detailed transcripts of the interviews are not included. The insights have been grouped into eleven themes, with three highlighted as crucial focus areas when considering an accelerated programme. Note these areas are broadly relevant to any large infrastructure programme.

This paper is structured as follows:

- Process: An overview of the exam question and the '7 questions' interview process
- Themes and key insights
- The critical path

The need for acceleration

The UK needs all the clean energy tools in its toolbox to achieve the legally binding net zero targets by 2050. Accelerated demonstration programmes can support a bounce-back from the economic impact of COVID-19. To do this, engineering development and performance demonstration are required at pace followed by commercial deployment at scale, Figure 1 (also see Appendix 1 for deployment examples of engineering and performance demonstrators). Advanced high temperature reactor systems are one such technology which have the potential to play a role in the UK's clean energy future.

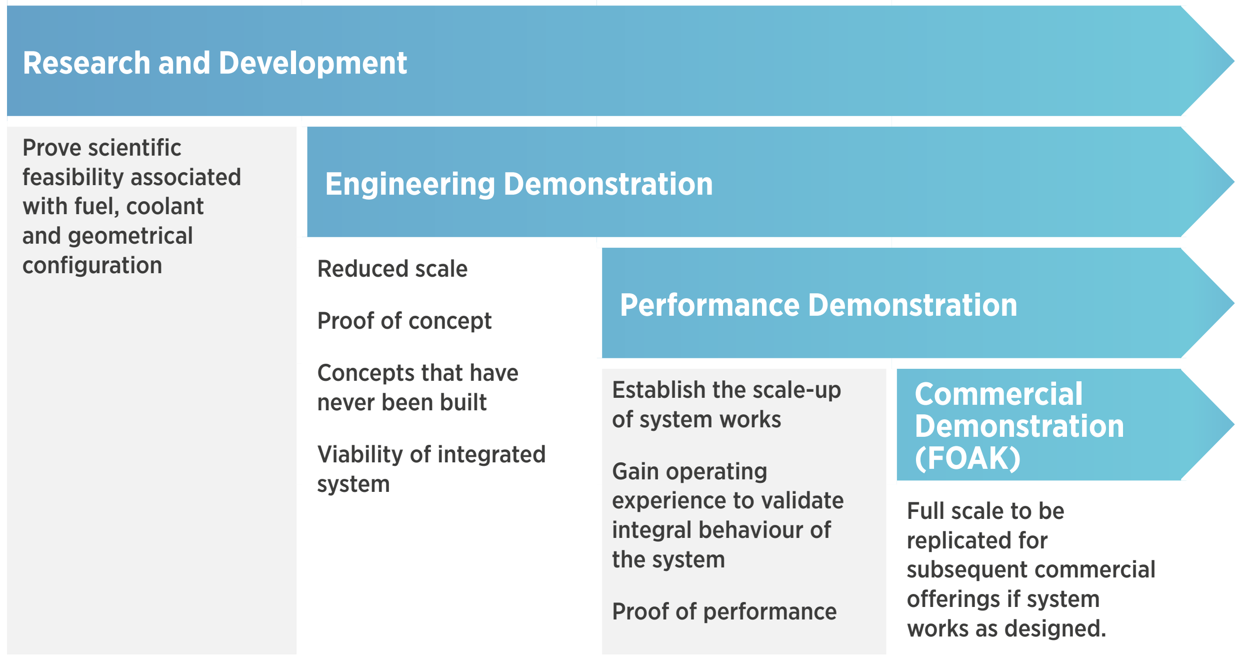


Figure 1 Definition of demonstrators and commercial demonstration (First of a Kind (FOAK))

In 2020, the Nuclear Innovation and Research Advisory Board (NIRAB) provided the following recommendation to the UK Government:

'Government should enable an Advanced Modular Reactor demonstrator in the period 2030 to 2035. An appropriate down selection should be completed as soon as possible, against a baseline of High Temperature Gas Reactors'

A performance demonstrator is widely understood to be possible by 2035; however, in the current post-COVID-19 economic climate and with the aim of net zero by 2050, this timescale is considered unattractive by some.

A different, innovative and robust approach is needed to set out how High Temperature Reactor system deployment could be accelerated and what challenges need to be overcome – a performance demonstrator must be delivered before 2030, which necessitates a step change in the delivery of nuclear projects relative to historical trends.

Through a series of interviews, NNL brought together some of the brightest and creative minds from industry, national laboratories, regulators and academia in the UK and internationally[4] to consider the following question:

How can the UK demonstrate the use of advanced nuclear technology for heat/hydrogen generation by 2030, with a high temperature reactor performance demonstrator commissioned by 2028? (halving the current 15 year (2035) often quoted timeframe)

[4] see Appendix 2 for contributors

PROCESS: AN OVERVIEW OF THE EXAM QUESTION AND THE '7 QUESTIONS' INTERVIEW PROCESS

To gain new insight, NNL used the "7 Questions" approach; an interview technique for gathering strategic insights.

The seven interview questions were as follows

Q1.

If you could speak to someone from the future who could tell you anything about advanced nuclear demonstration and deployment by 2030 what would you like to ask?

Q2.

If things went well, being optimistic but realistic, talk about what you would see as a desirable outcome.

Q3.

What are the dangers of not achieving the vision of delivering a high temperature reactor demonstrator by 2028?

Q4.

What needs to change (systems, relationships, decision making processes, culture for example) if the aim of a high temperature reactor demonstrator by 2028 is to be realised?

Q5.

Looking back, what are the successes we can build on? The failures we can learn from?

Q6.

What needs to be done now (i.e. priority) to ensure the aim of 2028 becomes a reality?

Q7.

If you had absolute authority and could do anything, is there anything else you would do?

Appendix 2 includes details of those individuals that kindly gave their time and insight. Over 500 individual responses (or quotes) from 27 interviews were received and collated. These have been grouped by theme and considered against the level of agreement or disagreement in the responses. The 'database' of responses is not included in this document but can be provided separately. A summary of the key messages and quotes are included in the following sections.

THEMES AND KEY INSIGHTS

Overview

The following sections outline the key themes emerging from the analysis of the interviews; these themes have been grouped into four areas:

Getting Going

Government | Organisation | Finance | Regulation | Focus of demonstrator

Technical Solution

Technology | Fuel and fuel cycle | Hydrogen

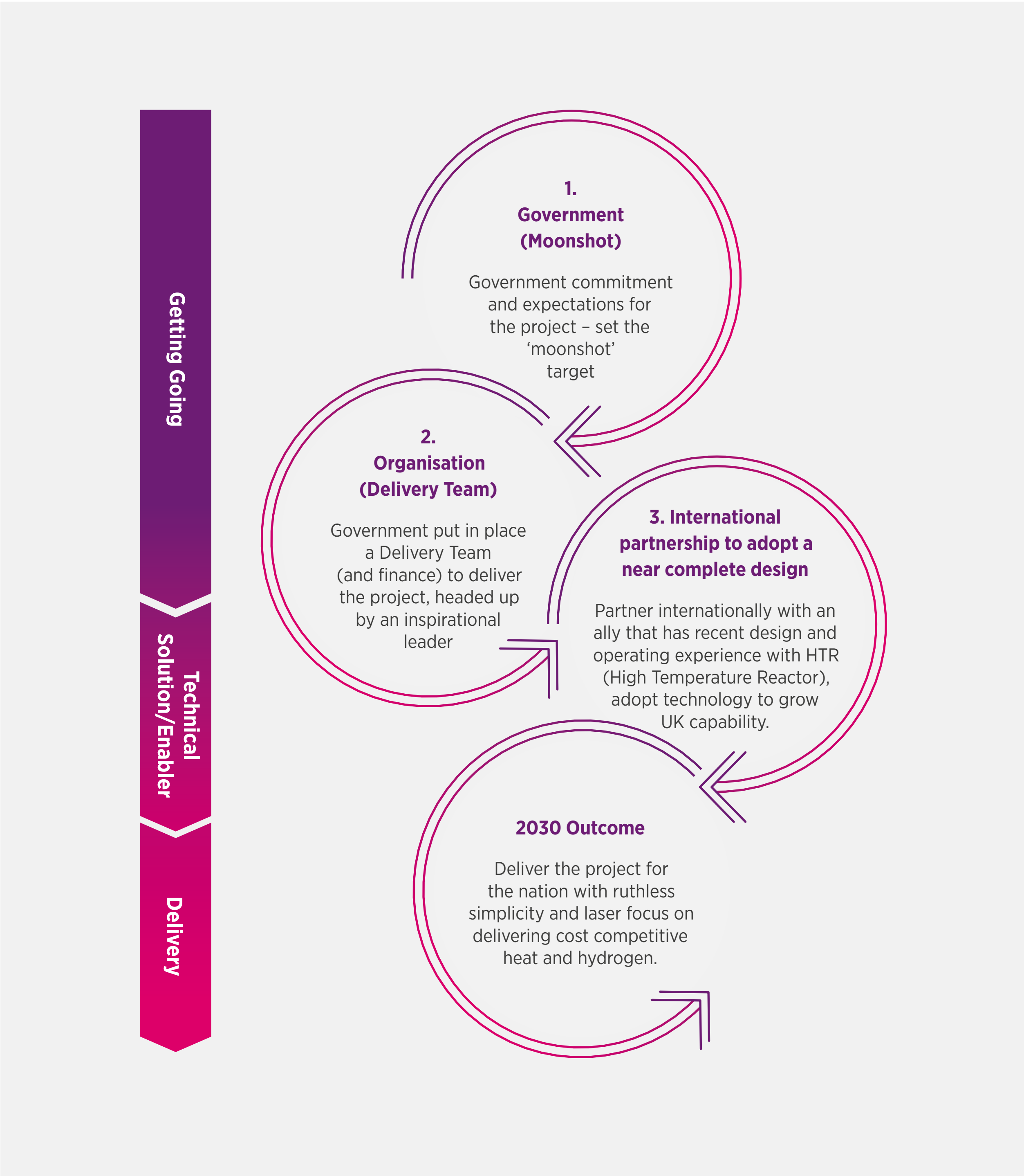
Delivery

Integrated programme | Construction, manufacturing and supply chain

Enablers

International partnering

Each of these four areas will be expanded on in the following sections. But, three themes were consistently recognised as having the biggest impact on acceleration and are outlined on the following page.



The 'critical path' and impact of the themes on a demonstrator delivery roadmap is considered later in the paper. The following sections consider the four areas and respective themes highlighting the key quotes and insights against the themes.

PHASE 1: GETTING GOING

Overview

In a project or programme when considering delivering on accelerated timeframes it is important to start well and 'get going'. The insights and themes in this section are crucial to the start of any demonstrator programme.

Government

1. **Long term active commitment – quick and informed decisions to enable Clean Energy 'Moonshot' by 2030**

- Clear government expectations for any demonstrator are required
- Make a site available for demonstration and plan for sites for Nth of a kind (NOAK)
- Clarity on the policy for hydrogen in the UK and recognition of the role of nuclear
- Coordinated and enabled UK nuclear programme across defence, large, small advanced and fusion, which would together maximise opportunity for UK supply chain and enable common test facilities

2. **Government funding is needed in the demonstration phase**

- Treasury commitment in funding a demonstrator(s) and getting going quickly
- Investment signals a commitment; this is needed to get going and to attract the private sector

3. **A clear strategy on the international stage to enable timely demonstrator delivery partnerships and open export markets**

- Ensure the UK product that will be demonstrated can access international markets, this includes putting in place ability to provide complete packages (finance, technology, fuel, fuel take back).

Direct Quotes:
'It is a matter of fact that in any part of the world nuclear programme is only successful with strong governmental support'
'Government need to be an active enabler rather than a passive observer'
'In the 'spin' for the last decade waiting for decisions.'
'decision making on a faster timeframe'
'...committed to this. Rather than just accepting that this is just another one of many advanced nuclear opportunities, government skin in the game.'
'A project for the first one will need to be funded by government in equity and cash. Then look to attract private.'
'Needs to be run as 'Apollo to the moon'. Government has to say they want it and put money in it.'
'Needs to be some agreement that the UK needs nuclear for heat and hydrogen – don't think this is agreed yet. Need to agree this early'
'Understand expectations – mismatch on expectations can be real issue.'

Organisation

1. **New leadership and 'dream team' with delivery mindset focused on clear outcomes**

- Inspirational leader of integrated project team with system thinking
- International partner with recent design and operational experience
- Down select vendor quickly
- Team goal ahead of individual organisational drivers
- Large contracts with incentives to all pull to same goal

2. **Selected on ability and attitude**

- Culture to challenge and do things differently
- Diverse players: right skills, mutual trust & clarity of purpose

3. **Stakeholder and public engagement are crucial**

- Clean Energy Sector: Create a UK alliance for a common effort to a transition to a clean energy system
- Government and Local Council: consider from their position – job creation, regional benefit, high value manufacturing
- Work with key environmental 'influencers'
- Consider how to break the view that nuclear is complicated, special, slow, expensive
- Share the local benefits clearly and openly with community around site, e.g. low-carbon technology, jobs, supply chain.

Direct Quotes:

'One mind, one vision'

'Select team on mindset as well as technical skills'

'All the key players have commitment and want progress... Need to captivate groups and bring together.'

'Distraction and competing priorities will impact this.'

'Get all the very most senior management of every department together and get them fully aligned, do not want teams to be distracted.'

'Dedicated resource together separated from the business, only allow them in the door if checked their attitude before coming. Anyone who thinks this is delivering in the same way not allowed in. Need the mindset and willingness to challenge. Want a bunch of people that are never satisfied. How can we do better and quicker.'

'Competitive tension at NOAK, not at the demonstrator stage!'

Finance

1. **A clear financing model needs to be established at the outset**

- Encompassing the project term irrespective of parliamentary cycles

2. **Understand the risk profile and plan to mitigate risks early and quickly**

- Initial focus on understanding the project risk profile
- Recognition that there will be 'unknown unknowns', with contingency agreed up front that can be drawn down on quickly

3. **Line of sight all the way through to a commercial product (Nth of a kind (NOAK))**

- Balance of public/private support beyond the demonstrator that encourages investment, including infrastructure and supply chain development
- Export financing options in place

Direct Quotes:

'Only reason private sector does not invest is the uncertainty.'

'UK leads world on creative use of capital'

'The fuel of new nuclear and decarbonisation is capital'

'Ultimately the demonstrator underpins the cost estimates for the commercial reactor.'

'Developers don't like buying out of design. They want something that has been built.'

'Only thing is capex, opex and lifetime of the asset.'

Regulation

1. **Regulators recognise need for accelerated enabling approach whilst maintaining independence**

- Enabling fast track, streamlined licensing and regulatory framework – current Generic Design Assessment (GDA) approach won't deliver on timescales
- Once approval achieved for FOAK regulatory risk is removed for NOAK

2. **Early engagement with regulators is crucial**

- Need regulatory "safe space" to understand/enable innovation that accelerates programme
- Regulators need the right attitude at all levels and the ability to enable innovation to ensure the as low as reasonably practicable (ALARP) principle is applied
- Modelling tools should be used within regulation

3. **Recognise the international dimension to accelerate international export**

- UK regulation gold standard – consider how to interface with international regulatory regimes
- Share learning with international partners; if they are ahead of the UK then use the learning to accelerate UK programme by years

Direct Quotes:

'Need to push enabling regulation further without overstepping the mark'

'Early engagement is a must in that regard. Regulator happy to engage with industry on what would be acceptable'

'Get ONR in the room. Providing it is safe this needs to be licensed. No reason why licensing should be challenging. The technology isn't that novel. A different more agile licensing approach.'

'Regulators being recognised as enabling both domestic and international. Work with fellow regulators to facilitate learning and learn from others.'

'Adapt the regulatory framework for advanced technology.'

'Work with fellow (international) regulators to facilitate learning and learn from others'

Focus of demonstrator

1. **Start with the end in mind - clarity on outcomes**

- Ruthless simplicity aligned to agreed government expectations and outcomes
- Need to demonstrate business viability as well as technology, not R&D

2. **Whole system thinking required – not just the reactor**

- Consider the holistic system and ensure associated development of hydrogen, fuel cycle, supply chain is also accelerated
- Ensure the links with other technologies (e.g. renewables, thermal storage), are considered with a focus on the best way to deliver a product, not just a reactor demonstrator

Direct Quotes:

'The desirable outcome is the outcome in terms of your customer. The benefit they get as a result of you doing this project, which will allow you to accelerate faster.'

'Generate heat hydrogen and electricity, the ability to test these things out.'

'Advantage of high temp over normal reactor is the economics so must prove this.'

'Getting to a demonstrator is not a research exercise it is a confidence builder. If you can't build a reproducible reactor, you shouldn't start.'

'Demonstrator has to also demonstrate business viability of the proposal'

'Leads to commercial plants which is when success starts'

'Every reactor demonstration on the plans has focus on the end use'

Summary: Getting Going

		'Getting going'
Government	1.	Long term active commitment - quick and informed decisions to enable Clean Energy 'Moonshot' by 2030
	2.	Government funding is needed in the demonstration phase
	3.	A clear strategy on the international stage to enable timely demonstrator delivery partnerships and open export markets
Organisation	1.	New leadership and 'dream team' with delivery mindset focused on clear outcomes
	2.	Selected on ability and attitude
	3.	Stakeholder and public engagement are crucial
Finance	1.	A clear financing model needs to be established at the outset
	2.	Understand the risk profile and plan to mitigate risks early and quickly
	3.	Line of sight all the way through to a commercial product (NOAK)
Regulation	1.	Regulators recognise need for accelerated enabling approach whilst maintaining independence
	2.	Early engagement with regulators is crucial
	3.	Recognise the international dimension to accelerate international export
Focus of demonstrator	1.	Start with the end in mind - clarity on outcomes
	2.	Whole system thinking required – not just the reactor

PHASE 2: TECHNICAL SOLUTION

Overview

The technology aspects provide opportunities to make decisions that could accelerate a programme, but it is also crucial to ensure that the technical solution meets the intended outcomes – delivering the wrong thing fast or meeting technical 'speed bumps' must be avoided. The insights and themes in this section consider the more technical aspects. In addition, throughout the interview process specific technical details and challenges were highlighted, these have been summarised and collated in Appendix 3.

Technology

1. **Use technology that needs little or no development (international partnering), select quickly and complete the design 'yesterday'**

- Use a reactor technology assessment process (e.g. IAEA)
- UK adopt a technology from an international partner and plan to develop technology leadership for future export
- Build UK research skills and infrastructure to ensure the capability is available in the UK to rapidly test technology and answer questions that arise and may delay demonstrator delivery

2. **Not just the nuclear technology - what delivers the best product in a future market?**

- Use the Government estate (e.g. Nuclear Decommissioning Authority (NDA), Defence) as a stimulus and first customer for UK technology
- High temperature may not be the most economical or technically best way to produce viable products, especially if trying to achieve 2028

Direct Quotes:
'Technically, the technology must already be reasonably well known.'
'The best technology doesn't exist; it is the best technology for the needs.'
'The bloke from 2035 would say 'if only we had kept it simple'.'
'About the platform. Learn so much from building. Size doesn't matter. Starting small could be the better approach.'
'The economic cost of providing higher temperatures needs to be factored into the overall cost of the system.'
'Love to see neat and tidy nuclear power stations, everyone living a low carbon lifestyle.'
'Test to failure, no-one gets hurt. Safe space for prototypes; you learn from it. Every other industry learns from this. Jet engine, they blow it up. Car they test to failure. Space programme, SpaceX blew up their first three rockets'

Fuel and Fuel Cycle

1. **Invest time and money in the fuel cycle so it does not become a rate determining step**

- Decisions on fuel and fuel cycle required as quickly as the decisions on reactor, a role for Government
- Fuel qualification and supply needs to be considered early; timescales may necessitate using an international product initially while developing UK capability

2. **Develop an independent UK sustainable fuel cycle so decisions are made in the UK**

- Without a UK fuel supply and fuel cycle there will be dependency on an international partner and decisions made outside of the UK
- Accelerate the development of UK capability to deliver a cost competitive fuel for the demonstrator and international market
- Fuel and fuel cycle capability enable attractive propositions to be made in a future export market for fuel and reactor technology
- Sustainability criteria should be considered, driving a positive public profile

Direct Quotes:

‘Not a UK proposition without this, decisions made internationally not in the UK.’

‘Private industry will not bring the fuel cycle’

‘Absolute necessity to have a holistic approach to fuel cycle. Developers have put that on the backburner and that will hurt them.’

Hydrogen

1. **An understanding of nuclear and hydrogen combined economics required**

- Need to understand the hydrogen demand before committing to making hydrogen
- Economic validation of reactor and hydrogen production process is hugely important and should be based on market understanding, e.g. hydrogen is not all the same (purity)

2. **Ensure the viability of co-locating hydrogen and nuclear**

- Need to consider how to co-locate nuclear plant with hydrogen production plant from an ALARP perspective
- Development of adjacent hydrogen technology in parallel

3. **Test one or more hydrogen process at scale in parallel to the demonstrator programme**

- With multiple processes for hydrogen production available, a decision on the process or processes for development anddemonstration should be based on market understanding
- Need to develop nuclear hydrogen skills and supply chain in parallel

Direct Quotes:

‘Demonstrate technical performance at scale and within a regulatory framework that will allow the technology to be cost competitive when fully commercialised.’

‘Should the UK be investing in the adjacent plant technology as well? Either hydrogen or thermal storage needs to consider alongside the demonstrator.’

‘The assumption with HTR is an economic advantage, there is some efficiency gain in the product. Say twice as efficient in producing hydrogen but if the low temp is cheaper at producing hydrogen, go with the low temp version.’

‘Engineering orientated and take into account the TRL.’

‘The vision for success is the HTGR delivering high temperature heat from a nuclear licensed site through a hole in the fence. On the other side of the fence, and off the nuclear licensed site, you have co-located plant for thermal energy storage, electricity generation or hydrogen production, so you decouple the two development programmes, but also shrinks the size of the nuclear licence site.’

‘Electrolysis of hydrogen is likely to find a market (fuel cells), as it is higher purity and can justify producing it at higher cost in the short term. All hydrogen is not the same.’

‘for thermochemical methods like sulphur-iodine, it will require significant investment to complete the technologies and complete the R&D’

Summary: Technical Solution

		‘The technical solution’
Technology	1.	Use technology that needs little or no development (international partnering), select quickly and complete the design ‘yesterday’
	2.	Not just the nuclear technology - what delivers the best product in a future market?
Fuel/Fuel Cycle	1.	Invest time and money in the fuel cycle so it does not become a rate determining step
	2.	Develop an independent UK sustainable fuel cycle so decisions are made in the UK
Hydrogen	1.	An understanding of nuclear and hydrogen combined economics required
	2.	Ensure the viability of co-locating hydrogen and nuclear
	3.	Test one or more hydrogen process at scale in parallel to the demonstrator programme

PHASE 3: DELIVERY

Overview

Acceleration through the execution of a programme or project is considered here in these themes. Further detail on these themes is included in the following sections.

Integrated Programme

1. Integrated programme building on and working with existing UK programmes

- Demonstrator piggy backs off the shoulders of other programmes, common themes across nuclear programmes
- Share learning and technology development infrastructure across UK programmes
- Avoid duplicating effort with the limited UK resource base
- A strategic plan required to ensure skills across all programmes are available at the right time

2. Fast and data-informed decision making

- After understanding the baseline plan, an exercise that goes bottom up to justify an accelerated plan is required. This should leverage existing data to back up and underpin this new plan.
- Avoid decisions that take longer than the actual process due to the evidence required
- Parallel working required to accelerate the programme

3. Contracts and incentives to achieve outcomes

- Avoid getting single line contracts - small packets of funding generate small contracts that aren’t integrated. Need integration up front.
- Procurement is a critical thing and getting it right can accelerate programmes

Direct Quotes:
‘Just a boring project, set a date hit it, set another hit it. Nuclear will become boring. But you want a boring project.’
‘Everyone needs to work on reduction of risk.’
‘Go big enough to get the right people interested, they need skin in the game. If you spend most of your time integrating afterwards it will kill the programme.’
‘Decide we are going to do it, then just do it.’

Construction, Manufacturing and Supply Chain

1. **Engage early on to ensure opportunities for construction/manufacturing improvements are included in the design**

- Need for a collaborative development process - not just smart folks developing the design but also the people that will manufacture and construct in the room from the start
- Use standardisation and off-the-shelf products where possible
- Explore the opportunity to regulate at the point of manufacture

2. **Build on the experience and learning gained from existing projects and transfer as much as possible**

- Utilise organisations and supply chain engaged in HPC and UKSMR where appropriate
- Keep as much of the 'power station' the same across projects and only change the reactor
- Build supply chains in parts of the country that need an economic boost

3. **Leverage the wider government strategy around construction**

- Considering modular, off-site and procurement mechanisms beyond nuclear should also benefit nuclear
- Pipeline and visibility of the pipeline is important to drive procurement and deliver
- Avoid the decision and planning process being the rate determining step

Direct Quotes:

'If you do one-off projects, you get one-off results. Long term relationships allow organisations to invest.'

'We are seeing synergy across the whole infrastructure and construction space. Trying to leverage the examples through.'

'Don't trickle into it, supply chain won't know what to do.'

'If we have the know-how and capacity in the design teams and the supply chain working in this area, if you must tweak the design for heat/hydrogen that can be done. The rest of the delivery mechanism is consistent. The logistics, the joining for seismic performance, manufacturing that underpins, on-site assembly as factory process – all this can be reproduced and should be reproduced. Re-use what you can.'

'Relationship between government and manufacturing industry has been passive, they need to be proactive.'

Summary: Delivery

		'Delivery'
Integrated Programme	1.	Integrated programme building on and working with existing UK programmes
	2.	Fast and data-informed decision making
	3.	Contracts and incentives to achieve outcomes
Construction, Manufacturing and Supply Chain	1.	Engage early on to ensure opportunities for construction/manufacturing improvements are included in the design
	2.	Build on the experience and learning gained from existing projects and transfer as much as possible
	3.	Leverage the wider government strategy around construction

ENABLERS

How do you enable acceleration of programme delivery? International was the key theme here and the key insights are outlined.

International Partnering

1. **Maximising international collaboration can accelerate the process by building on experience from existing programmes**

- Building on and learning from existing programmes
- Government role in facilitating collaborations and providing commitment
- Coordinating effort to avoid duplication
- But in any collaboration the UK needs to take a lead (e.g. fuel cycle) to avoid being left behind

2. **Regulation across borders is vital for global deployment**

- Timescales can be accelerated by taking on board existing licensing

3. **Establish a route for technology transfer into international markets through collaborative agreements**

- Export financing options are crucial to enable UK export opportunities

Direct Quotes:

'Maximising the international collaboration available now'

'building from nothing in the UK - from nothing without input is brave'

'We can come together as multiple countries demonstrating multiple technologies, with multiple use cases and figure out the pros and cons of all.'

'Started to engage on collaboration between US, UK and Canada on convergence of standards so you have standardisation of designs. Had to take a step back now. US and Canada signed cooperation, UK couldn't as wasn't committed.'

'Russia and China making attractive and comprehensive offers to new entrants – time window'

'UK being left behind, US and Canada forge ahead and dominate world markets'

As an example, recent international experience through the Japanese Atomic Energy Authority (JAEA) High Temperature Test Reactor (HTTR) was frequently discussed throughout the interviews, some key learning points from the JAEA HTTR programme are therefore summarised in Appendix 3.

THE CRITICAL PATH

Accelerating the deployment roadmap

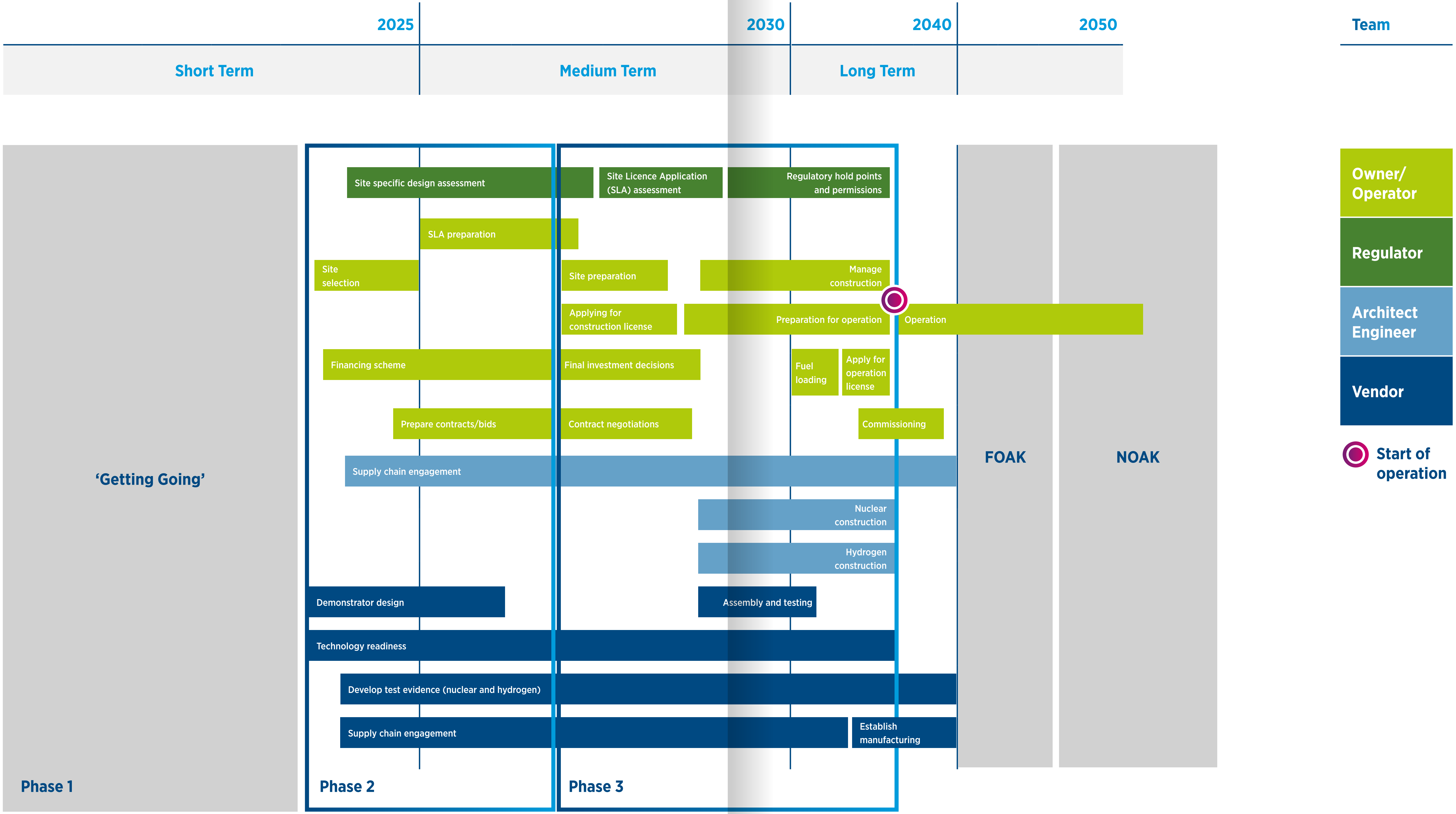
The previous section highlighted the key themes that bring together the insights in relation to accelerating the delivery of an advanced reactor demonstrator. This section considers the elements of a deployment pathway that need to be considered and how they might impact the delivery timeframe.

The diagram on the following pages provides a high-level indicative 'roadmap' for 2035 and 2028 pathways; the roadmaps include many of the elements that make up the critical path for delivery of an advanced reactor demonstrator (they are not intended to be a comprehensive and underpinned project plan but are used for illustrative purposes). The table illustrates the potential impact on acceleration of each of the themes outlined in the previous section.

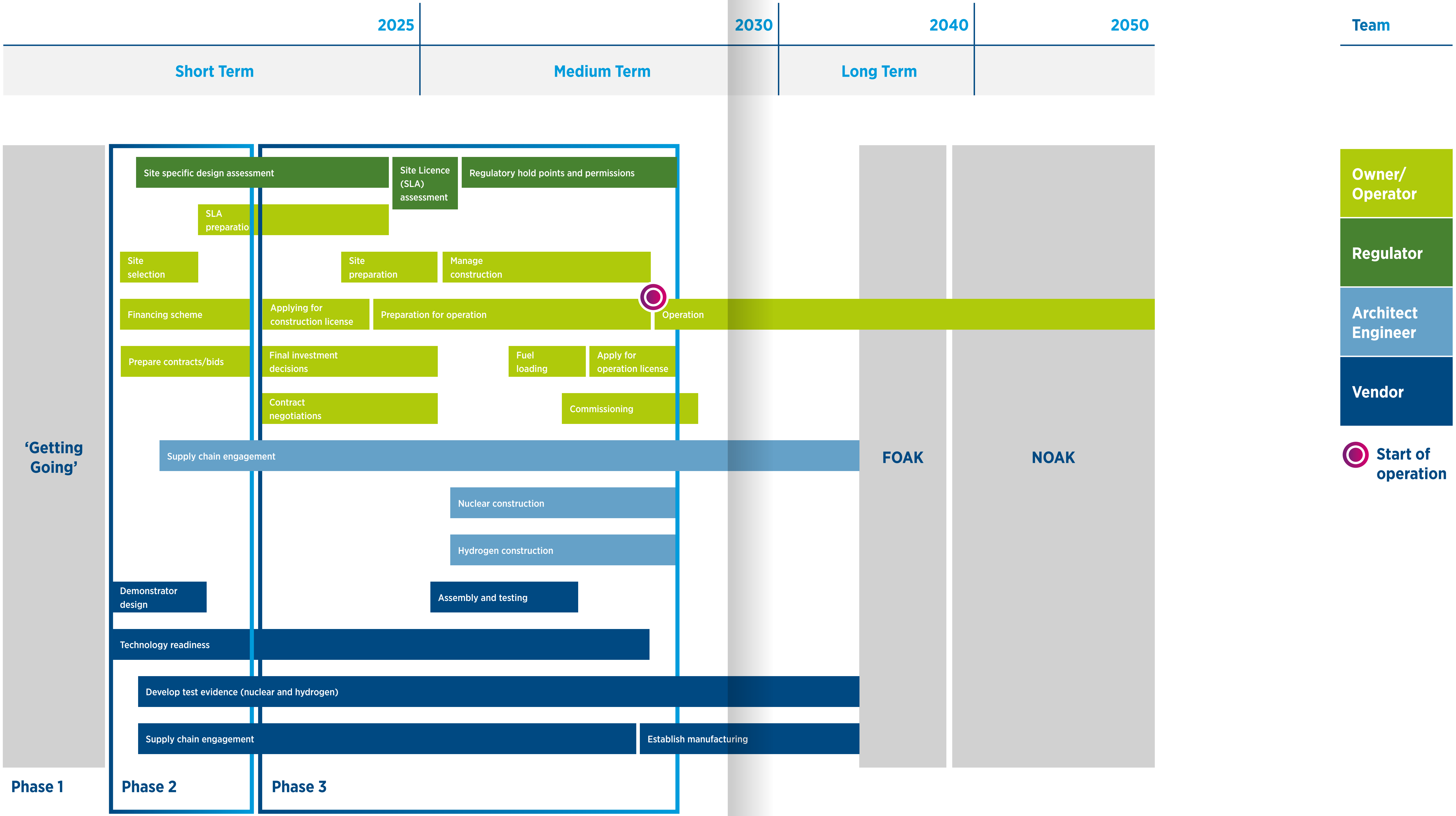
Insight from the expert interview process has highlighted the real opportunity and scope to accelerate Phase 1 or 'Getting Going', the potential impact of this is highlighted in the 'roadmap' diagrams on the following pages.

		Demonstrator deployment phase		
		Phase 1	Phase 2	Phase 3
Getting Going	Government	Large	Moderate	Moderate
	Organisation	Large	Large	Large
	Finance	Large	Moderate	Limited
	Regulation	Large	Large	Large
	Focus of demonstrator	Large	Limited	Limited
Technical Solution	Technology	Moderate	Large	Large
	Fuel/Fuel Cycle	Moderate	Large	Large
	Hydrogen	Moderate	Large	Large
Delivery	Integrated Programme	Moderate	Large	Large
	Construction, Manufacturing and Supply Chain	Limited	Moderate	Large
Enabler	International	Limited	Large	Moderate
Key (relative potential impact of theme on acceleration in Phase)		Large	Moderate	Limited

EXAMPLE 2035 PATHWAY



EXAMPLE ACCELERATED 2028 PATHWAY



SUMMARY

This expert elicitation exercise has indicated three main factors that would accelerate an Advanced Nuclear for Heat and Hydrogen programme. These are:

- Decisive government commitment,
- Creation of a single owner/operator with inspirational leadership, and
- Partnership with an international organisation with design and operational experience.

This is not a research project, but there are four technical areas that require clear focus: fuel supply and fuel cycle, component and material qualification, proving heat exchanger technology and hydrogen production.

APPENDIX 1. DEMONSTRATOR DEPLOYMENT EXAMPLES

The following table provides examples of demonstrator reactors to illustrate the demonstrator definitions, it is not intended to be a comprehensive catalogue of international reactor technology development and deployment:

	Sodium Fast Reactor (SFR)	High Temperature Gas Reactor (HTGR)
R&D for scientific feasibility	SEFOR – (20 MWth), TREAT CABRI	
Engineering Demonstration	EBR-1 – (1.4 MWth) EBR-11 – (20 MWe) Dounreay – (14 MWe), Rhapsodie – (40 MWth)	Peach Bottom (40 MWe) DRAGON (20 MWth) HTR-10 (10 MWth) HTTR (30 MWth) AVR (15 MWe)
Performance Demonstration	Fermi-1 – (69 MWe) FFTF – (400MWth) Phenix (233 MWe) Monju (300 MWe) BN-300 & -600 (300 & 600MWe) PFR (250 MWe)	
Commercial Demonstration	Superphenix – (3000 MWth) BN-800 (800 MWe)	HTR-PM (200 MWe)

APPENDIX 2. CONTRIBUTORS

Thanks are gratefully acknowledged to all those who kindly gave their time and expert insight to enable this paper to be produced. Contributors included:

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APPENDIX 3. EXAMPLE TECHNICAL CHALLENGES AND LEARNING

Area	Gaps for demonstrator
Computer codes	Validation of codes in support of licensing Modelling of source-term (dust formation and transport)
Components	Component qualification in large scale facilities Development and qualification of IHX
Fuel	Fuel testing and qualification HA-LEU supply
Materials	Graphite qualification (including oxidation under accident conditions)
Safety analysis and demonstration	Large scale loop for component testing Compliance of plant design with safety regulation
Multi-purpose plant	Demonstration and licensing Demonstration of coupling with energy commercial products, e.g. hydrogen production Licensing strategy for a coupled nuclear reactor site
Design and system integration	Demonstrator design and test programme
Development of licensing framework	Assess existing licensing framework for suitability to license HTR demonstrator for cogeneration
Fuel/graphite waste minimisation and recycling	Qualify decontamination and recycling of irradiated graphite Evaluate direct disposal vs reprocessing for fuel cycles

The following table summarises some key points in relation to the learning from the JAEA HTTR project provided during these interviews:

Area	Detail
Government involvement	• Without government involvement, it would have been difficult to develop the HTTR in Japan. Must have government involved.
Design	• The HTTR was designed 30 years ago. Design and manufacture based on the technology of that period; advanced manufacturing technologies not used. • HTTR operates at 950°C, if wish to increase the outlet temperature to 1100°C new materials will be required. Qualifying new materials will take a lot of time. JAEA consider that 950°C is enough for hydrogen production.
Fuel	• Within 10 years, it would be possible to develop a UK fuel supply if it is based on technology and experience from Japan, then subsequently develop the fuel technology in the UK. • Before the HTTR, JAEA irradiated fuel in a materials test reactor. After this the irradiated fuel was heated to 2000°C to check fission product release. This data was shown to the regulator. Regulator confirmed the integrity at 1600°C, then failure starts at greater than 2000°C. The temperature of the HTTR fuel remains below 1495°C during normal operations and below 1600°C in accidents including pressurized accidents. The integrity of the fuel is therefore assured. The regulator also inspected the fuel manufacturing process. • Enrichment of the HTTR fuel, is average 6% and the highest is 9.9%. In any future reactor based on the HTTR, around 15% is considered optimum, i.e. the need for HA-LEU should be studied as part of any UK programme.
Core design	• When the HTTR was designed, it was designed conservatively. The core design has lots of redundancy. The number of control rods is much more than the necessary number. It is now possible to optimise the core design. Also, the regulator had only regulated LWR technology which needs containment vessels. The designers knew at the time that the HTTR did not need containment vessels but they could not convince the regulators to understand the HTTR technology in the early days. HTTR has containment vessels; if demonstrated now in the UK it should not need containment vessels and it would be possible to optimise the core design. It would also be possible to reduce costs by using the Japanese design and accessing the knowledge/test database.

Area	Detail
Design and fabrication	• In Japan, Mitsubishi/Toshiba/Hitachi can design and fabricate (except fuel and graphite). One of the big nuclear makers has the responsibility to deliver the reactor systems. Hence,one engineering company plays an integrator role, bringing together the required capabilities need for delivery.
Hydrogen	• Regarding hydrogen, it would be possible to demonstrate steam reforming in 10 years. But for thermochemical methods like sulphur-iodine, it will require significant investment to complete the technologies and complete the R&D. • To accelerate, work that connects the hydrogen production system could be run in parallel to the reactor build. This would involve not only design and commissioning of the reactor, but work on the hydrogen supply at the same time. This means initially not using the reactor heat and then connecting later.
Research infrastructure	• Research infrastructure is required to support construction. To support delivery of the HTTR a high temperature helium test loop was built to test the performance of components. In addition, criticality facilities (VHTR-C) were built prior to the HTTR to understand core performance.

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