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Identification of potential opportunities for development of UK R&D capability and strategic UK supply chain to the deployment of Advanced Modular Reactors - Key Points

The Committee on Climate Change (CCC) has recommended that significant decarbonisation of the energy sector is required to meet the UK Governments' ambitious and legally binding net zero emissions by 2050. The Department of Business, Energy and Industrial Strategy (BEIS) expects new nuclear power to play a role in supporting this deep decarbonisation and in maintaining energy supply and security.

Small Modular Reactors (SMRs) and Advanced Modular Reactors (AMRs) are technologies that are designed to be manufactured and assembled in purpose built, off-site facilities before being transported to the site. These Advanced Nuclear Technologies (ANTs) could have a potential role to play in the UK's future energy mix, providing low carbon energy that is easier to finance and quicker to deploy than conventional large nuclear technology. In addition to electricity generation, AMRs use cooling systems or fuels that can offer additional benefits, including high temperature heat for hydrogen production, industrial process heat, desalination and the re-use of spent fuel to minimise waste. These applications could play an important role in decarbonising industry, heat and transport.

This report was commissioned to understand the current capability of the UK's nuclear R&D sector and domestic supply chain to support future AMR deployment, and understand how this can be developed[1]. An overarching finding showed that the UK R&D sector and the supply chain have a number of development needs which must be met before the UK is able to deploy AMRs. It is also interesting to highlight that the current development needs which exist in the R&D and supply chain are not always technology specific but are applicable across multiple AMRs and in some instances SMRs. For example, for all modular reactors, modelling and simulation studies are required and fuel cycle and waste management research. Prior to AMR deployment, licensing gaps including a lack of nuclear codes and design standards will need to be overcome for all Generation IV AMRs.

This report found that the R&D development needs for more developed AMRs (TRL = 7) include modelling and simulation, fuel and spent fuel management, and reactor equipment - particularly instrumentation and control (I&C). More conceptual designs (TRL = <5) have additional R&D needs which include fundamental materials R&D and reactor equipment development (heat exchangers and pumps). Roadmaps produced for each AMR system show that the majority have similar R&D needs, and this is a key observation that could enable the development of several technologies through cross-cutting, targeted R&D programmes. This

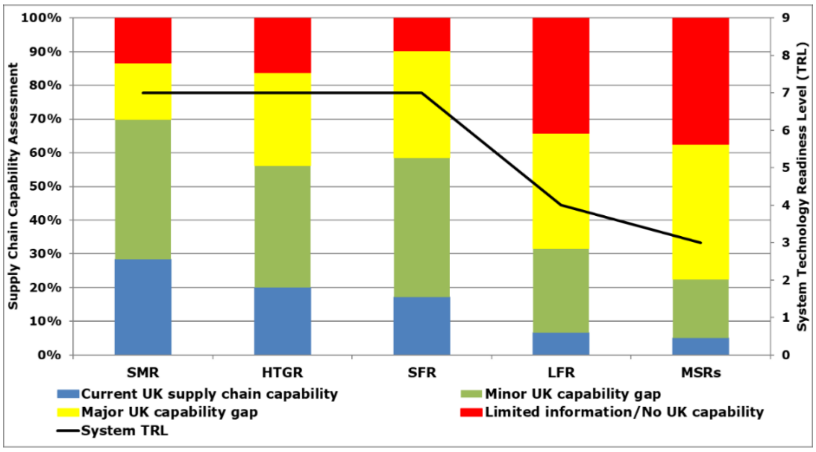
[1] National Nuclear Laboratory, Identification of potential opportunities for development of UK R&D capability and strategic UK supply chain to the development of Advanced Modular Reactors, NNL 14790

would also align with government's current position which is to understand the feasibility of AMR technologies.

Current UK capability to support the R&D needs of AMRs is highly variable. Key barriers to the UK R&D realising domestic and international opportunities include a lack of verification and validation facilities (e.g. environmental test loops, zero-power research or materials test reactors), as well as a lack of suitably qualified and experience personal (SQEP). It is important to note that this work found global infrastructure gaps, that if overcome could support AMR development. This includes: active molten salts facilities, zero-power reactors and demonstration reactors. Waste management, modelling, fuels and materials development could, given suitable R&D programmes and priority, be carried out by UK academia, national research centres or the supply chain.

On the supply chain aspect of this report, it was found that key UK manufacturing needs exist across all AMRs. This is driven by a need for domestic facilities able to produce reactor vessels, equipment and high temperature valves from advanced materials, control rods and fuels. Once the facilities are in place this can support and develop the domestic supply chain.

The UK supply chain capability to support the manufacturing needs of AMRs is low - a maximum of 20% of the components assessed in this study can currently be manufactured. This report found that the capability of the UK supply chain is greater for AMR systems that the UK has historic experience in due to supply chain familiarity. For example, capability gaps were identified for 10% of the SFR components assessed in this study, this could be due to UK experience from the UK Fast Reactor Programme.



Currently, the UK supply chain is focused on waste management which offers less opportunity for innovation, compared to new build. There is a barrier for innovative small and medium-sized enterprises (SMEs) to get involved with the early manufacturing of AMR components as orders are *potentially* many years away.

The potential for technology transfer from outside of the nuclear sector (for example aerospace, rail and oil and gas) are domestic strengths and these existing skills could support an AMR supply chain in the UK. This report found that key opportunity areas for the supply chain include: advanced (digital) instrumentation and control (I&C) systems, fuels, and the application of advanced manufacturing and materials to reactor components.

Importantly, a modular assembly facility is a significant global gap that could benefit all modular reactors. Establishing this domestically could position the UK supply chain in a world leading position, especially if regulatory engagement is included in the remit.

To support AMR technology development and deployment, HMG could carry out several potential actions, including:

- Continue with an enabling domestic policy environment for AMRs to support UK's net-zero legislation;
- Identify international programmes or facilities with likeminded nations to pool resources and collaboratively overcome cross-cutting R&D, regulatory and manufacturing needs;
- Steer R&D and innovation funding towards a UK AMR hub which could include coolant test loops for materials and equipment, a modular assembly and testing facility or a demonstration reactor;
- Continue fission R&D programmes, such as the Nuclear Innovation Programme, as a means to develop fundamental UK skills and infrastructure;
- Support the UK supply chain to demonstrate new ways of making key, high-value nuclear components and design systems through implementation of cutting-edge technology and processes and technology transfer from other sectors;
- Promote the engagement of Small and Medium-sized Enterprises (SMEs) with technology vendors and Tier-1 suppliers to facilitate innovation.

High Temperature Gas-cooled Reactor (HTGR)

Helium-cooled, thermal spectrum (graphite core) reactors that operate at circa 750°C with electrical outputs from 5 MWe to 200 MWe. Prismatic core designs can be refuelled or have a single core for the reactor life, while Pebble Bed cores are continuously fed with fuel spheres. Coated particle (TRISO) fuel is a key feature of HTGRs and is intended for direct disposal (open fuel cycle).

- HTGRs have been assessed as TRL 7. The R&D needs include: **modelling and simulation**, particularly for pebble bed reactors; **instrumentation and control**; and **fuel cycle** and **waste management**, due to the use of TRISO fuel.
- UK capability to address these R&D needs is variable. Academia and the supply chain can support **modelling and simulation** (using AGR and international data). Initial **instrumentation and control** development can be carried out. Uranium **fuel** R&D and PIE on irradiated materials can be carried out in the UK, however both are limited to single UK facilities. On **waste management** R&D, the UK has the experience to manage wastes arising from HTGRs; however, there is no experience with the spent fuel form.
- A lack of UK testing and qualification facilities exist to advance HTGRs above the assigned TRL. These facilities exist internationally, including in Japan, China and US.
- Existing codes and standards are expected to be suitable for HTGR materials. There are gaps in regulation for fuel manufacture, fuel transportation, spent fuel disposal, co-generation and modular/advanced manufacturing.
- A key barrier to the UK supply chain is the lack of domestic facilities to manufacture graphite, HTGR fuel, large pressure vessels and the offsite modular assembly of

HTGR-AMRs. There is also a lack of awareness of HTGR needs – due to the time since the construction of an HTGR in the UK.

Very High Temperature gas-cooled Reactor (VHTR)

Helium-cooled, thermal spectrum (graphite core) reactors with outputs between 5 MWe and 200 MWe. Electricity generation requires a Brayton Cycle and the VHTR outlet temperature of circa. 950°C offers the potential to decarbonise industrial processes or for hydrogen production. Prismatic and Pebble Bed core designs exist, and VHTRs are expected to be refuelled. Various coated particle (TRISO) fuel concepts exist for VHTRs with direct disposal of spent fuel (open fuel cycle).

- VHTRs have been assessed as TRL 5. The R&D needs include: **modelling and simulation**, especially for pebble bed reactors; **materials development**; **reactor equipment** and **instrumentation and control** demonstration; research into **Brayton Cycles** for power generation; and **fuel cycle** and **waste management**, due to the uniqueness of the fuel form.
- UK capability to address these R&D needs is variable. Academia and the supply chain can support **modelling and simulation** (using some AGR and international data); low TRL **materials development** (via the High Temperature Facility), however only initial: **reactor equipment** and **instrumentation and control** development can be carried out in the UK. A lack of UK facilities exist to develop **Brayton Cycles**. Uranium **fuel** R&D and PIE on irradiated materials can be carried out in the UK, however both are limited to single UK facilities. On **waste management** R&D, the UK has experience of managing wastes arising from HTGRs; however, there is no experience with VHTRs or the spent fuel form.
- A lack of UK testing and qualification facilities exist to advance VHTRs above the assigned TRL. Some of these facilities exist internationally, including in Japan.
- VHTRs are not covered by existing codes and standards. There are gaps in regulation for fuel manufacture, fuel transportation, disposal of spent fuel, electricity generating equipment, co-generation and the use of advanced manufacturing processes.
- A key barrier to the UK supply chain is the lack of domestic facilities to manufacture graphite, VHTR fuel, large pressure vessels from advanced materials and the offsite modular assembly of VHTR-AMRs. There is also a lack of awareness of opportunities – due to limited experience with VHTRs exists.

Sodium-cooled Fast Reactor (SFR)

Liquid sodium-cooled reactors operate at ~550°C and are not pressurised reactors. Fast neutron reactors require fuels with high fissile material contents and spent fuel reprocessing (closed fuel cycle) is an important feature. Secondary sodium loops are often included between the reactor and steam cycle, with SFR electrical outputs of 100 to 300 MWe typical. SFRs have gathered over 400 reactor operating years of experiences; including 40 in the UK.

- SFRs have been assessed as TRL 7. The R&D needs include: **modelling and simulation**; **reactor equipment** (heat exchangers and pumps); **instrumentation and control**; **fuel cycle** and **waste management**.

- UK capability to address these R&D needs is variable. Academia and the supply chain can support **modelling and simulation** (using historic UK and international data). A sodium test loop is required for demonstration of **reactor equipment** and **instrumentation and control** systems - this does not exist in the UK. **Fuel cycle** research can be carried out in the UK, at a single plutonium active or separate uranium active facility. On **waste management** R&D, the UK has the experience to manage wastes arising from the operation and decommissioning of SFRs.
- Existing codes and standards are not suitable for SFRs. There are gaps in regulation for fuel manufacture, fuel transport, spent fuel reprocessing and modular/advanced manufacturing.
- A key barrier to the UK supply chain is a lack of facilities to manufacture SFR fuel and to carry out the offsite modular assembly of SFR-AMRs. There is a lack of awareness of SFR needs – due to the time since the construction of an SFR in the UK.

Lead-cooled Fast Reactor (SFR)

Liquid lead-cooled reactors are limited to circa 500°C and are not pressurised reactors. Fast neutron systems require fuels with high fissile material contents and are expected to employ spent fuel reprocessing (closed fuel cycle). Core refuelling or single fuel loads have been proposed. Pool- or loop-type designs exist with electrical outputs of 50 to 200 MWe via a steam cycle.

- LFRs have been assessed as TRL 4. The R&D needs include: **modelling and simulation**; **instrumentation and control**; **reactor equipment** (fuel assemblies, pumps and heat exchangers); **materials development**; **fuel cycle** and **waste management.**
- UK capability to address many of these needs is limited, due to a lack of liquid lead facilities and suitably qualified experienced personal (SQEP) to work on them. A lead test loop does not exist in the UK. This is required for **materials development**; experimental validation of **modelling and simulation** needs; demonstration of **instrumentation and control** and **reactor equipment**. **Fuel cycle** research can be carried out in the UK, at a single plutonium active or separate uranium active facility. On **waste management** R&D, the UK has no experience or facilities for coolant or operational waste.
- A lack of UK facilities exist to advance LFRs above the assigned TRL. Internationally test loops exist in Belgium, Russia and China, however a significant global gap is the operation of a demonstration reactor.
- Existing codes and standards are not suitable for LFRs. There are gaps in regulation for fuel manufacture, fuel transport, spent fuel reprocessing and advanced manufacturing.
- Key barriers to the UK supply chain include supply chain facilities gaps and a lack of awareness of opportunities – due to limited experience with the technology. This includes limited facilities able to manufacture reactor components from advanced materials; no LFR fuel manufacturing facilities and an absence of facilities to assemble LFR-AMRs.

Molten Salt-fuelled Reactors (MSRs)

Molten salt-fuelled Reactors are not pressurised and operate at 700°C. Fast neutron or thermal (moderated) core designs exist. Fissile material is typically dissolved in the salt and circulates throughout the reactor, requiring online reprocessing and multiple coolant salt loops. Electricity generation (<300 MWe) uses technology already demonstrated in the solar sector.

- MSRs have been assessed as TRL 4 (thermal) and TRL 3 (fast). The R&D needs include: **modelling and simulation**; **materials development**; **instrumentation and control**; **reactor equipment** (pumps and heat exchangers); **fuel cycle** and **waste management**.
- UK capability to address these needs is limited, due to a lack of molten salt facilities and suitably qualified experienced personal (SQEP) to work on them. **Modelling and simulation** requires experimental validation data that may not exist internationally. A molten salt test loop is required for **materials development**, **instrumentation and control** and **reactor equipment** demonstration – this does not currently exist in the UK. **Fuel cycle** and **waste management** research could be carried out on the laboratory scale in academia and national labs.
- A lack of UK facilities exist to advance MSRs above the assigned TRL. Internationally test loops exist in the US and Czech Republic, however there is a significant global gap for active fuel cycle development; zero-power and demonstration reactors.
- Current codes and standards are not suitable for MSRs. There are gaps in regulation for liquid fuels, fuel reprocessing, fuel transport, advanced manufacturing processes.
- Key barriers to the UK supply chain include a lack of awareness of opportunities – due to limited experience with the technology; and supply chain facilities/ infrastructure gaps. This includes limited facilities able to manufacture reactor components from advanced materials; a lack of fuel manufacturing facilities; and an absence of facilities to assemble MSR-AMRs.

AMR Technology Readiness Level (TRL) Assessment

Key Component	Subsystem (Additional System Components)	HTGR (750 °C)	VHTR (950 °C)	SFR	LFR	MSThR	MSFR	SMR
22. Reactor Equipment	**Reactor Equipment**	7	6	6	3	3	2	7
	Reactor vessel	7	6	6	3	3	2	7
	Reactor Internals		5			3	2	
	Reactivity Control	7	6		3	3	2	
	Materials/ Coolant Chemistry	8	7	8	3	4	3	8
	Main Heat Transport System	7	5	7	3	3	3	7
	Core Cooling Mechanism	7	5	7	3	3	3	7
	Piping, Valves & Pumps		6	6	3	3	3	
	Safety Systems	7	5	6	4	3	3	6
	Passive	7	5	6	4	3		6
	Active			7	4	3		
	Emergency Shut down			7	3	3		
	Radioactive Waste Processing	5	4	7	3	2	2	6
	Management of Waste arising from Decommissioning	5	4	7	3	2	2	6
	Other Reactor Plant Equipment	7	4	7	3	4	3	8
	Supplementary Circulation Systems	7	7	7	N/A	5	5	N/A
	Coolant Purification System	7	6	7	3	3	2	8
	Reactor Instrumentation and Control (I&C)	7	5	6	4	4	2	8
	Instrumentation & Control Systems	7	5	6	4	4	2	8
	Inspection & Maintenance							
23. Turbine/ Generator Equipment	**Turbine Generator(s)**	8	3	7	3	5	5	8
	Rankine Cycle (Steam)	8	N/A	7	3	5		8
	Brayton Cycle (He, N_2, S-CO2)	3	3	3	2	2		N/A
	H_2 Production facility	3	4	2	2	2		N/A
84. Nuclear Fuel	**Nuclear Fuel**	7	5	7	5	3	2	9
	Initial Fuel	7	6	MOX: 7	MOX: 5	U: 4	U/Pu - 2	UO_2: 9
	Initial Fuel Cladding		4	7	3	3	2	9
	Initial Fuel	N/A	N/A	Metal: 6	Nitride: 4	Th: 2	Th 2	N/A
	Initial Fuel Cladding			7	2-3	2	2	N/A
	Advanced Fuel	5	3	Nitride: 4 MA: 4	MA: 2	MA: 1	MA: 1	N/A
	Advanced Cladding	4	3	3	2	N/A	N/A	4
	Reactor Core	7	5	7	4	3	2	8
86. Fuel Reprocessing	**Fuel Reprocessing**	N/A	N/A	6	4	3	2	8
	Conventional Aqueous Reprocessing (PUREX)	N/A	N/A	6	4	N/A	N/A	9
	Advanced Aqueous Reprocessing	N/A	N/A	2	2	N/A	N/A	3
	Advanced Pyro-metallic Reprocessing	N/A	N/A	1	1	1	1	N/A
Experience	**International Experience**	7	6	8	4	3	2	8
	UK Experience	6	3	6	3	2	1	7
Licensing	**International Regulator acceptance**	6	4	6	3	2	1	7
	UK Regulator acceptance	5	4	5	2	1	1	5
Overall International TRL		7	5	7	5	4	2	7

Supply Chain Capability Assessment

		HTGR (<750°C)	MSR	LFR	SFR	SMR
Reactor Vessel	Reactor Vessel	Red / Amber	Red / Amber	Red / Amber	Amber / Green	Amber / Green
	Reactor Safety/ Containment Vessel	Amber	Red / Amber	Red / Amber	Amber	Amber
	Shielding	Amber / Green	Amber	Amber / Green	Green	Amber / Green
	Coolant Inlet Manifold	Amber / Green	Red	Red	Amber / Green	Amber / Green
	Reactor Vessel Materials	Amber / Green	Red	Red	Blue	Green / Blue
Reactor Internals	Reactor Core (structure)	Amber	Red	Red / Amber	Amber / Green	Amber / Green
	Reflectors	Red	Red / Amber	Red / Amber	Amber	Amber / Green
	Fuel Handling Manipulators	Green	N/A	Amber	Green	Green
Reactivity Control	Control Rod	No Information available - International Supply Chain				
	Control Rod Drive Mechanism	No Information available - International Supply Chain				
Core Cooling Mechanism	Heating & Ventilation (incl. Ductwork Systems)	Green	Amber	Amber	Green	Green
	Cooling System (Condensers & Towers)	Amber	Red	Red / Amber	Amber	Amber / Green
Piping, Pumps & Valves	General Valves	Green	Green	Green	Green	Blue
	General Pumps	Blue	Green	Green	Green	Green / Blue
	High Integrity Pumps/Blowers	Blue	Red	Red	Amber	Green / Blue
	High Integrity Valves	Amber	Red	Red / Amber	Amber	Green / Blue
	Insulation	Green / Blue	Amber	Green / Blue	Green / Blue	Green / Blue
	Pipework & Spools Larger Bore	Blue	Red / Amber	Red / Amber	Blue	Green
Active Safety	Drain/dump Tanks	N/A	Red / Amber	Red / Amber	Amber	Green / Blue
	Emergency Controls (SCRAM system)	No information of suppliers in UK nuclear sector				
Emergency Shutdown	Shutdown Assembly	No information of suppliers in UK nuclear sector				
	Emergency Diesel Generators	Blue	Blue	Blue	Blue	Blue
Waste Management	Waste Container - Flasks & Casks	Green / Blue	Red	Red / Amber	Green / Blue	Green / Blue
	Spent Fuel Transportation	Blue	Red	Green	Blue	Blue
Secondary Circulation System/Loop	Intermediate Heat Exchanger	Blue	Red / Amber	N/A	Amber / Green	N/A
	Pipework	Blue	Amber	N/A	Blue	N/A
	Valves	Green	Amber	N/A	Green	N/A
Instrumentation & Control Systems	Instrumentation Control - Reactor Control	Green	Red	Amber	Amber / Green	Green
	Electrical Panels, Switchgear & Cabling	Blue	Blue	Blue	Blue	Blue
Inspection & Maintenance	Visual	Amber	Amber	Red	Amber	Amber
	Electronic Sensors	Amber	Amber	Red / Amber	Amber / Green	Green / Blue
Steam (Rankine) Cycle	Main Steam Generator System[1] (Rankine Cycle)	Green	Amber	Red / Amber	Green	Green / Blue
	Steam Turbine - Main System	Green	Green	Green	Green	Green
Brayton Cycle (N_2, s-CO_2)	Turbine system: N_2	Amber / Green	Amber / Green	Amber / Green	Amber / Green	N/A
	Turbine system: s-CO_2	Amber	Amber	Amber	Amber	N/A
	Heat Exchanger	Green	Red	Red / Amber	Green	N/A
	Compressors	Amber / Green	Amber / Green	Amber / Green	Amber / Green	N/A
H_2 Production Facility	High Temperature Isolation Valves	Amber	Amber	Amber	Amber	N/A
	Thermal Insulation	Green	Green	Green	Green	N/A
	Distillation Column	Green	Green	Green	Green	N/A
	Gas Separators	Green	Green	Green	Green	N/A

[1] Assumes a shell and tube heat exchanger (helical designs are a lower SCRL)

Red	i) Public domain information not sufficient to assess capability; or ii) sufficient information available and the UK supply chain doesn't currently have the capability to produce the required components
Amber	The supply chain has the potential to be able to produce the required component but some major capability & capacity gaps exist
Green	The supply chain is expected to be able to produce the required component in the near future, but a small number of minor capability & capacity gaps currently exist
Blue	The supply chain has the capability and capacity to produce the component now; subject to the provision of detailed component information