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

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Executive Summary

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 aimed 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. 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.

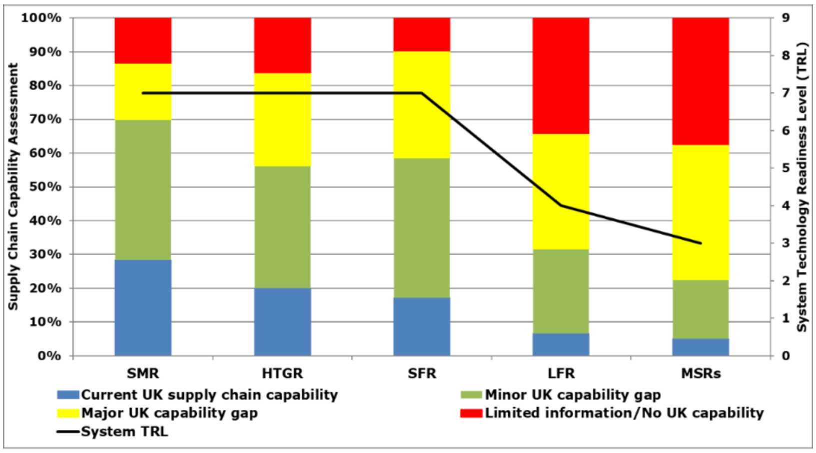
This report found that the R&D development needs for more developed AMRs (TRL = 7) include modelling and simulation, fuel and spent fuel management, and reactor equipment - particularly instrumentation and control (I&C). More conceptual designs (TRL = <5) have additional R&D needs which include fundamental 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 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.

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

- 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.

Verification Statement

This document has been verified and approved in accordance with NNL's procedures for the reporting of work.

History Sheet

Issue Number	Date	Comments
Draft 1	January 2019	First draft provided to BEIS for comment
Draft 2	July 2019	Addition of AMR Summaries to report and Draft provided to BEIS for comment
Draft 3	November 2019	Inclusion of Reactor Key Points
Issue 1	February 2020	Issued report

Identification of Information

The Technology Readiness Level (TRL) assessment was produced using public domain information identified between June 2018 to November 2018. The Technology Road Maps are based on the outputs of a workshop involving Suitably Qualified and Experienced Persons held in July 2018. The Supply Chain assessment was carried out by the Nuclear Advanced Manufacturing Research Centre (N-AMRC) based upon public domain information identified during July 2018 to November 2018. The Supply Chain development needs were identified during a N-AMRC led workshop involving representatives from the UK Nuclear industry in August 2018.

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1. Background and Process Overview

1.1. Brief History of Nuclear

Since the advent of the nuclear age and operation of the first civil nuclear power station at Calder Hall in 1956, nuclear reactor technology has been evolving. Each generation of reactor is considered to be a significant technological advancement (in terms of performance, safety or cost) compared to the previous generation and can be aligned into four groups, these are:

- Generation I (1950-1965): early prototypes of several designs
- Generation II (1965-2010): commercial power plants
- Generation III (1995-2010): modern reactor design
- Generation III+ (2010+): improved modern designs (evolutionary improvements)
- Generation IV (2025+): revolutionary designs (compared to Gen. III)

1.2. Modular Reactors

Multiple Modular Reactor concepts have been identified (Table 1), the majority of those are based upon Generation IV designs. The exceptions to this are SMRs, which in the UK are limited to water-cooled thermal systems that are smaller-scale versions of Generation III/III+ designs; and HTGRs which are envisaged as a "stepping stone" towards VHTRs.

Table 1: Typical Modular Reactor properties

Reactor System	Neutron Spectrum	Coolant	Fuel Cycle	Outlet Temperature	Pressure
High Temperature Gas-cooled Reactor **HTGR**	Thermal	Helium	Open	<800°C	7 MPa
Very High Temperature gas-cooled Reactor **VHTR**	Thermal	Helium	Open	>800°C (circa 950°C)	7 MPa
Molten Salt-fuelled Thermal Reactor **MSThR**	Thermal	Halide Salts	Closed	700°C	0.1 MPa
Molten Salt-fuelled Fast Reactors **MSFR**	Fast	Halide Salts	Closed	700°C	0.1 MPa
Lead-cooled Fast Reactor **LFR**	Fast	Lead	Closed	500°C	0.1 MPa
Sodium-cooled Fast Reactor **SFR**	Fast	Sodium	Closed	550°C	0.1 MPa
Small Modular water-cooled Reactor **SMR**	Thermal	Light Water	Open	300-350°C	8-16 MPa

To avoid the duplication of research and accelerate deployment of Generation. IV reactors, an international collaboration was set up; the Generation IV International Forum (GIF) [1].

1.3. Scope of Work

The purpose of this study is to outline the existing international R&D status and UK capability to enable AMR deployment; assess the current state of the UK Supply Chain and identify domestic manufacture gaps. A wide range of conceptual designs are available for most Generation IV technologies and to avoid assessing a specific vendor concept, a generic reactor concept was assessed.

1.4. Methodology Summary

The methodology used to assess the current R&D state of AMRs and ability of the UK supply chain to manufacture identified AMRs components is based on the following processes:

i. Define the advanced reactor concepts to be evaluated;

The assessment of hypothetical reactors was based on previously developed descriptions used as part for the Techno-Economic Assessment (TEA) series of reports [2] and the generic designs of the Generation IV International Forum (GIF) [1]. For the purposes of this study, AMRs are defined as Generation IV reactor technologies that operate at or below 300 MWe and are designed to be factory fabricated and the modular components assembled onsite and are limited to those listed in Table 1.

ii. Determine the reactor components to be assessed;

A top down process was used to determine the reactor components to be assessed. This was based on the internationally accepted, GIF G4-ECONS system breakdown, which provided the list of "key components" (Reactor Equipment, Generator Equipment, Nuclear Fuel and Fuel Reprocessing) and "subsystems" (Reactor Equipment, Main Heat Transport System, Safety Systems, Radioactive Waste Processing, Other Reactor Plant Equipment, Instrumentation and Control, Power Generation, Nuclear Fuel and Fuel Reprocessing) [3], [4]. An additional layer of detail was included for the TRL assessment; resulting in the assessment of 27 "Additional System Components" across the nuclear island, non-nuclear island and fuel cycle for each AMR. While for the SCRL assessment, two additional layers of detail were included identifying 41 "Reactor Components" for assessment (Figure 1).

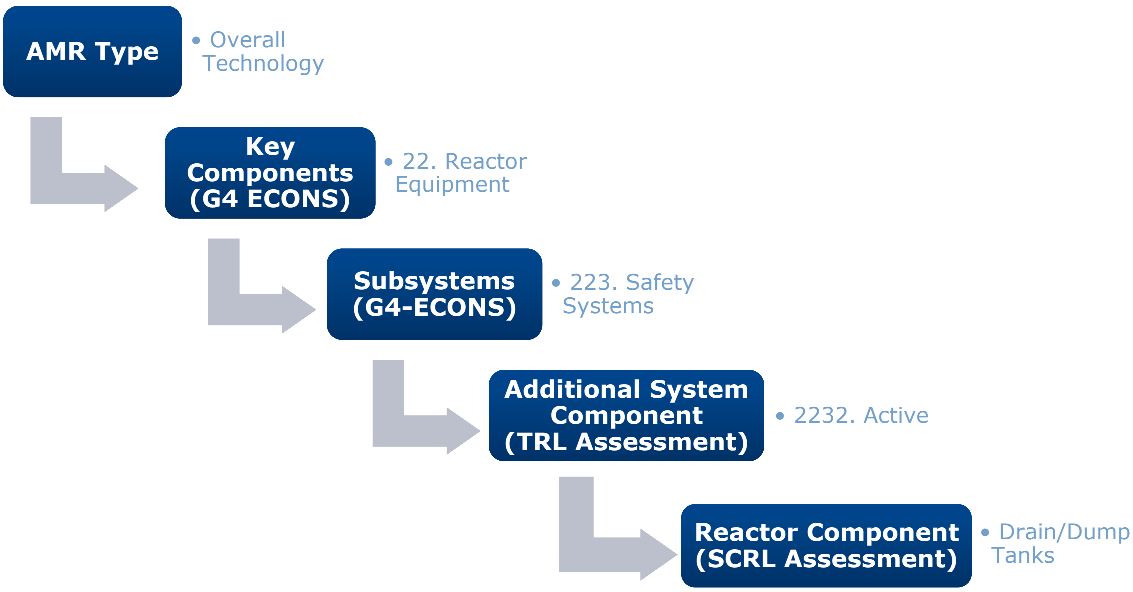

Figure 1: Work breakdown structure used to determine reactor components

iii. Utilise a robust and standard assessment methodology to assess the AMRs from a technical and supply chain perspective;

The TRL assessment criteria used was based on the established US Department of Energy (DoE) methodology [5]. The DoE methodology is a version of the National Aeronautics and Space Administration (NASA) and US Department of Defense (DoD) technology assessment model that was pioneered in the 1980s and runs from TRL 1 (lowest) to 9 (highest). Nuclear-Advanced Manufacturing Research Centre (N-AMRC) undertook the Supply Chain Readiness Level Assessment and ranked capability using a Blue (current capability), Green (requires minor development), Amber (requires significant development) and Red (capability gap). Fuel and fuel cladding manufacture were excluded from the supply chain assessment. For the steam (Rankine) power generation cycle, only features unique to the reactors were assessed. As it was viewed that existing ancillary systems (e.g. pipework, turbines, condenser, pumps) for the steam cycle could be used from the wider energy sector

iv. Review the publicly available technical information for each reactor design and assign the readiness levels for each AMR;

Each additional system component was assessed individually based upon public domain literature [6] to assign a value and provide a referenceable justification for the apportioned TRL. The readiness of the supply chain to manufacture the identified reactor components was assessed using public domain information and assigned a colour (RAGB) relating to its status, by N-AMRC [7], [8]. This "bottom-up" approach assessed the system components on their own merits, and they were not made to fit to an overall TRL for the entire system.

v. Identification of R&D to advance reactor systems and UK capability

A workshop involving an independent group of academics and technology experts was convened to identify the R&D needs of each reactor technology. Encompassing academics and industry experts from the Universities of Liverpool and Manchester, Wood Group and Integrated Decision Management (IDM).

vi. Identification of supply chain needs to manufacture AMR components

A workshop involving companies from across the supply chain was convened to discuss the manufacturability of a prepared list of reactor components (reactor vessel; pumps [blowers for HGTR]; valves and pipework; steam generators; intermediate heat exchangers; control systems; waste containers and flasks; and drain/dump tanks) using existing techniques [9]. In addition, the use of advanced manufacturing, joining and assembly techniques was also discussed for AMRs, including the development needs required to use these.

1.5. Summarising the assessed TRLs

The 27 individual TRL assessments undertaken on the "Additional System Components" for each AMR were used to calculate the TRLs of the 9 Subsystems (Reactor Equipment, Main Heat Transport System, Safety Systems, Radioactive Waste Processing, Other Reactor Plant Equipment, Instrumentation and Control, Power Generation, Nuclear Fuel and Spent Fuel Reprocessing). A similar process was undertaken to determine the overall system TRL of the AMR, based upon the values of the 27 "Additional System Component" TRLs.

2. Gas-cooled Thermal Reactors (GCR): summary of current state and development needs

2.1. High Temperature Gas-cooled Reactor (HTGR) Key Points

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.

2.2. Very High Temperature gas-cooled Reactor (VHTR) Key Points

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 facilities exists 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.

2.3. Overview of Gas-Cooled Reactors

In the context of this study, Gas-Cooled Reactors (GCRs) use helium as the coolant, have graphite (moderator) cores and operate in the thermal neutron spectrum (Figure 2) [1]. HTGRs and VHTRs typically operate with helium pressures of 7 MPa. The single-phase helium is chemically inert, as well as optically and electromagnetically transparent. Fissile material fuel kernels of uranium oxide or uranium oxycarbide (UO_2 or UCO) are encased in multiple layers to give Coated Particle Fuels (CPFs). Typically, this involves three layers of pyrolytic-carbon (PyC) and silicon carbide (SiC) as a coating that has led to the fuel being known as Tristructural-Isotropic (TRISO) fuel. The multiple layers are a key feature of the fuel as they retain fission products that form in the fuel during reactor operations. To distinguish between the challenges and R&D needs that are present with operating at high and very high temperatures, GCRs are split into two different classes:

i) High Temperature Gas-cooled Reactors (HTGRs), have maximum coolant outlet temperatures below 800°C and typically are typically 750°C. Reactor pressure vessels (RPVs) have previously been produced from low alloy or carbon steels (e.g. SA508 or SA508/333) and are covered by existing codes and standards. Power generation has been demonstrated via a Rankine (steam) cycle. HTGRs could use a Brayton power conversion cycle to improve thermal efficiency or the outlet temperatures could decarbonise industrial processes or potentially be used for hydrogen production.

ii) Very High Temperature gas-cooled Reactors (VHTRs) are evolutionary designs of HTGRs and intend to operate with coolant outlet temperatures above those of HTGRs (i.e. >800°C) and typically of 950°C. VHTR RPVs require the use of advanced alloys (e.g. nickel-based alloys such as Inconels or oxide dispersion-strengthened alloys), due to the elevated thermal conditions (compared to HTGRS and PWRs). Higher coolant outlet temperatures offer the potential for more efficient power generation, requiring a Brayton power cycle, and addition process heat applications. VHTRs could use TRISO or QUADRISO (four layers of either zirconium or silicon carbide) fuel.

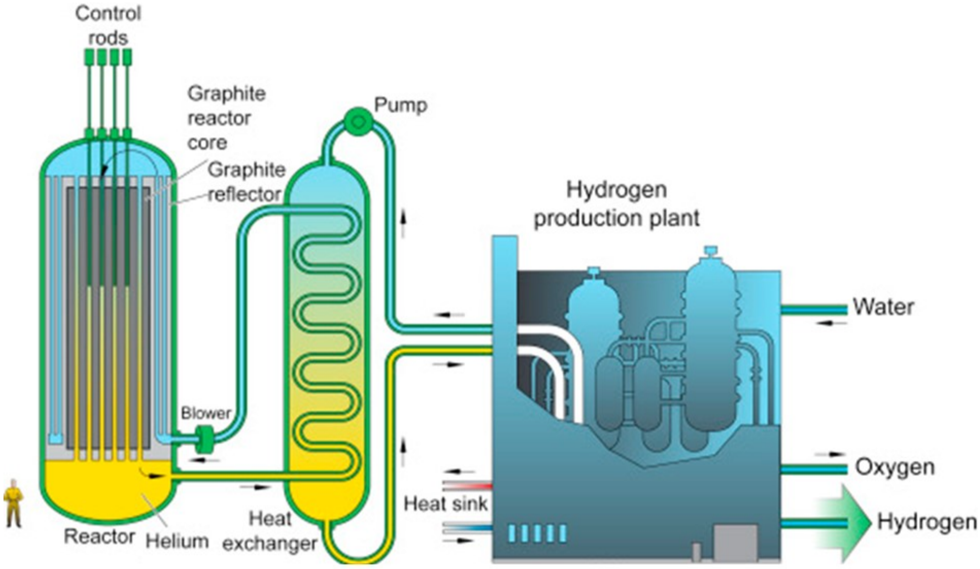

Figure 2: Generic Gas-cooled Reactor (Prismatic Core) with coupled H_2 production facility

An open fuel cycle is proposed for both HTGRs and VHTRs, requiring encapsulation and disposal of spent fuel in suitable facilities. Fuel kernels have a much higher surface area-to-volume ratio than pellet fuels, coupled with less efficient moderation and higher burn-up results in the need for higher enrichment than for other thermal spectrum reactors. This is typically between 8% and 19.75% and significantly greater than PWRs which operate with fuel enrichments of between 3% and 5%.

The individual coated fuel particles are less than 1 mm in diameter and are embedded in an inert matrix (typically graphite) then formed into either prismatic graphite blocks (Prismatic Core) or graphite pebbles (Pebble Bed Core) depending on the reactor. Prismatic core refuelling involves shutting down and depressurising the reactor prior to removing a portion of the fuel and loading new material, as takes place in a PWR. This requires an excess of fissile material to be introduced during loading with neutron poisons, which are gradually burned during operation to ensure an economical time between refuelling outages (i.e. a high capacity factor). A Pebble Bed reactor in comparison has the TRISO fuel incorporated into spheres or "pebbles". This enables online refuelling with pebbles continuously fed in and removed from the reactor during operation. Thus, it is possible to precisely control the fissile material in the reactor without the need for neutron poisons.

The high thermal output of HTGRs and VHTRs (assumed to be 750°C and 950°C in this study) offer the potential for "green" hydrogen (H_2) production, where water is consumed (split) in an otherwise clean cycle. Arguably, the most researched H_2 production process is the sulphur-iodine thermochemical cycle. This requires temperatures above 850°C and will be discussed later in more detail. Alternative, lower temperature processes, including the copper-chloride process that requires temperatures of circa 550°C may be applicable to

GCRs. The high outlet temperature of GCRs also offer the potential to provide process heat for a broad range of industrial applications or co-generation, of both heat and electricity.

The first HTGR to operate was the Dragon reactor in the UK in 1964. Since then, HTGRs have operated in Germany and the US. More recently, China has operated a test HTGR (HTR-10) and is constructing a prototype demonstration HTGR (HTR-PM). Two VHTRs have operated: the first in Germany (AVR) and the HTTR in Japan.

2.4. HTGR Nuclear Island Discussion

Reactor Equipment, Main Heat Transport System and Safety

Nuclear qualified materials exist for HTGRs reactor pressure vessels (RPVs), primary (and secondary if applicable) circuit and reactor core and would not require an irradiation programme in a materials test reactor (MTR). Previously reactor pressure vessels and the primary cooling circuits of helium- or CO_2-cooled reactors have been made from low alloy or carbon steels (e.g. SA508 or SA508/333) and stainless steels, respectively. To utilise these materials in HTGRs the materials must be kept significantly below the maximum coolant outlet temperature, due to the loss of strength at elevated temperatures. The use of such materials has been demonstrated by designing HTGRs with "cold vessels". Where "cooled" coolant at 250°C is directed over the internal skin of the reactor pressure vessel (RPV) prior to passing through the reactor core; thus, maintaining the RPV temperature below the maximum temperatures allowed by the existing nuclear codes and standards. This engineering solution is also applicable to the steam generator/intermediate heat exchanger, which can utilise existing nuclear qualified materials. A similar process is possible for the heat transfer system, enabling the use of stainless steels. However, should innovative materials such as composites, ceramics or advanced alloys be proposed for use in HTGRs, these would require a nuclear qualification programme involving irradiations in a materials test reactor (MTR). Such materials, are not necessary to enable HTGR deployment, given the availability of previously nuclear qualified materials. A discussion of the needs for the use of advanced (and thus not nuclear qualified) materials is contained in the VHTR Nuclear Island discussion.

The key operational and safety processes have been demonstrated on prototype HTGRs, this includes: the interaction of coolant with reactor materials during operation, the movement of coolant (using blowers), coolant purification (predominantly for prismatic cores), power generate using a steam generator (Rankine cycle), and the passive safety of HTGRs. The R&D needs are focused upon efficiency or safety improvements. As such, only two areas for focused studies have been identified and are the coolant purification system for pebble bed systems and the development of models to support the passive safety of HTGRs:

i) Coolant purification system needs are well understood for prismatic cores. However, pebble bed cores have an increased rate of dust/particle generation through the movement of the pebbles through the reactor during operation. A domestic need exists to understand the dust generation mechanism(s) from the AVR and HTR-10 reactors. Building on this information, could inform the design, testing and qualification of suitable processes. This could be in the form of filters, for which early engagement between AMR vendors and the nuclear supply chain to identify requirements would be beneficial.

ii) Detailed modelling of specific vendor designs will be necessary to support the licensing process. This includes studies to validate vendor claims that HTGRs are "walk away safe" and that site Emergency Planning Zones (EPZs) can be reduced. Models will need to be developed and validated using data from operational reactors (information from the recent international HTGRs, potentially supplemented by data from the UK's GCR fleets and Dragon test reactor), if suitable data does not exist, an experimental programme in a thermal hydraulic facility or reactor will be required.

Until the dimensions of HTGRs pressure vessels (RPVs) are clarified, it is not clear if existing UK infrastructure could produce the necessary components, or the support required to enable this. For example, the HTR-PM in China, a 250 MWth HTGR, has an RPV of carbon steel with a length of 25.4 m, diameter of 6.7 m and a wall thickness between 146 mm and 250 mm. The Japanese HTTR, a 30 MWth VHTR, has an RPV length of approx. 13.2 m, a diameter of 5.5 m and is constructed from 2¼Cr-1Mo steel. In comparison, the RPV of the ~3000 MWth AP1000 (PWR) is approx. 12.5 m in length and 4.5 m in diameter.

It is important to note that nuclear qualified seals able to operate at the temperatures required in HTGRs or VHTRs are not available from the UK supply chain and are a gap.

While not a pre-requisite for HTGR deployment, the development of advanced joining, manufacturing and inspection techniques could provide domestic manufacturing with an opportunity to compete internationally for the supply of HTGR components. Advanced techniques including: electron beam or arc welding; hot isostatic pressing (HIP); and advanced material inspection capability are under development as part of existing domestic research facilities (e.g. academia and at National Research Centres).

Nuclear Graphite

Several nuclear graphite grades (e.g. PGA – Pile Grade A, IM1-24, GCMB and IG-110) have been used to produce the core moderator and in-reactor reflectors of gas-cooled reactors. Historically, domestic companies such as Anglo Great Lakes Corporation Ltd. and Union Carbide (and precursors) produced nuclear graphite for gas-cooled reactors (PGA, IM1-24 and GCMB). However, this study has identified only a single grade of nuclear graphite that is currently commercially available, IG110 is available from a Japanese manufacturer with no domestic supply route. Such a capability gap also exists for reflectors, which for HTGRs are constructed from nuclear graphite. To avoid a lengthy materials qualification programme; it would be beneficial to facilitate discussions between the UK supply chain and technology vendors regarding the suitability of historic graphite grades. Should the UK supply chain have capability to produce new material grades, an irradiation programme in a materials test reactor (MTR) followed by Post Irradiation Examination (PIE) would be required. The UK has suitable PIE facilities and expertise, built up through the support of the graphite moderated GCR fleets; however, a UK materials test reactor doesn't exist. Irradiation studies could instead be undertaken at international MTRs, such as those in Petten (the Netherlands), BR1 or 2 (Belgium), the future Jules Horowitz Reactor (France), or test facilities at US National Labs. A qualification programme is a multi-year endeavour to reach representative irradiation exposure.

HTGR-AMRs could lead to an increase in the UK's already significant volume of graphite waste, from the MAGNOX and AGR reactor fleets. The majority of which is categorised as Intermediated Level Waste (ILW) due to the presence of carbon-14, a beta (β) source with a long half-life. The global volume of irradiated graphite has led to multiple international R&D programmes, such as those run by the IAEA and EU. Follow-on projects could identify procedures to reduce the volume of existing waste, as well as minimise waste arising for future HTGRs. The development and implementation of a process to produce nuclear graphite free from chlorine and nitrogen-14 (responsible for production of carbon-14 in nuclear graphite) could minimise the volume of ILW that a HTGR-AMR generates. However, a novel grade or process would require nuclear qualification, involving irradiations in a materials test reactor (MTR). Such a process requires a multi-year commitment and is necessary to demonstrate the materials are compatible with operational conditions in a HTGR.

Instrumentation & Control

Reactor Instrumentation & Control have been demonstrated across both Pebble Bed and Prismatic Core HTGRs. However, in-reactor monitoring beyond start-up has proved challenging due to the thermal conditions which cause the destruction of in-reactor sensors. R&D would be expected to focus upon defining the monitoring needs of a HTGR-AMR. Incorporating learnings from sacrificial components in operational reactors, as well as technology transfer opportunities from analogous (high temperature) sectors, such as aerospace. This could include online monitoring or digital technologies; previously HTGRs have operated with analogue control systems. A capability gap, in terms of the civil nuclear supply chain has been identified for the manufacture of control rods, shut down assemblies and their respective drive mechanisms. These are expected to be required across all reactors, irrespective of coolant. Control rods typically have a 6-year operating life; as such HTGR designs with single core designs, as well as those intending to refuel will require regular replacement or the development and licensing of control rods with suitable lifetimes.

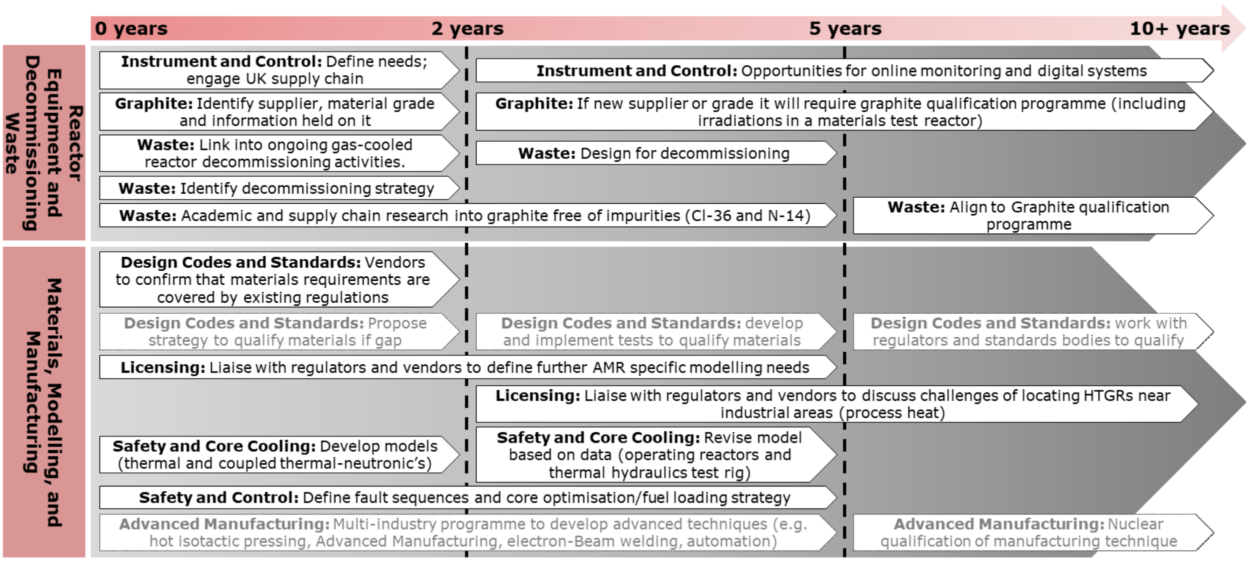

Figure 3: Roadmap of HTGR Nuclear Island needs

2.5. HTGR Power Generation Discussion

Rankine Cycle

Only the steam generators of a Rankine power generating cycle were assessed as part of this study. Ancillary systems (e.g. pipework, turbines, condenser, pumps) were assumed to be standard across the wider energy sector. For HTGRs, no R&D needs were identified for the steam generators (shell and tube) or "traditional" heat transfer system, given international experience with HTGRs and slightly lower temperature CO_2-cooled reactors (e.g. MAGNOX and AGR). The UK supply chain is expected to be able to produce HTGR steam generators, once they have clarity as to HTGR steam generator designs and dimensions.

Brayton Cycle

It is theoretically possible for a Brayton cycle to be included in the primary circuit of a HTGR, with the turbine driven by reactor coolant. Two-loop designs employing nitrogen (N_2) or supercritical carbon dioxide (s-CO_2) Brayton cycles also exist and avoid some of the challenges of a helium cycle, as well as offering the potential for enhanced efficiencies. Significant R&D challenges, including potential technology showstoppers exist for Brayton cycles. These are associated with system (i.e. heat exchanger and turbine) design; materials development due to the environment; containment of the gas/supercritical fluid; modelling; construction; and qualification. Nations such as France and Japan are actively researching Brayton cycles for SFRs and VHTRs respectively, while Germany has previously coupled a gas-power conversion to a fossil-fuelled power station; demonstrating the widespread applicability of the technology. The UK High Temperature Facility (HTF), Catapults or Advanced Manufacturing Research Centres (AMRC) could support low TRL development.

The domestic supply chain is viewed as being well placed to compete internationally for many of the components required for a He or N_2 Brayton Cycle, even considering the uncertainties of Brayton Cycle designs. This is due to the presence of a domestic aerospace sector adept at producing components and turbines for use in high temperature environments out of advanced alloys (e.g. Ni-based alloys rich in Cr) as well as the domestic manufacture of heat exchangers for multiple industries. The manufacture of components for a s-CO_2 Brayton cycle is lower, given the reduced overlap with aerospace sector. The advancement of domestic capability could be carried out by the AMRCs and Manufacturing Technology Centre.

H_2 Production/ Process Heat

The most researched "green" H_2 production process (where only water is consumed), is the Iodine-Sulphur (IS) process. This requires outlet temperatures above those possible with HTGRs (~950°C versus 750°C). As such, a significant R&D programme would be required to evaluate alternative and lower temperature "green" processes. An alternative lower temperature process is the copper chloride process, which requires temperatures of ~550°C and could be compatible with HTGRs. Partnering with a nation actively researching "green" H_2 production, such as Canada (copper chloride) or Japan (IS) could accelerate technology deployment; supporting UK development. It is important to note, that the UK would be expected to actively contribute to enable the sharing of research – currently the UK does not have an active, large scale programme investigating "green" H_2 production using heat from nuclear reactors. Should the UK not wish to partner, it would be reliant on information published in academic journals. This would first have to be captured, prior to process down selection and detailed flowsheet development. Initial R&D and knowledge capture could be undertaken at universities or research centres. Following this, large scale trials would require the construction of suitable facilities to investigate the robustness and scalability of the process. In addition to the technological challenge, there are licensing and safety challenges to be overcome with locating a H_2 production and storage facility so close to a reactor.

For process heat, the technology challenge of transferring steam to an industrial facility is viewed as minimal. The transfer of heat via a secondary gas (e.g. N_2) aligns with the R&D needs of a **Brayton Cycle**, (e.g. IHX). R&D to overcome potential "nitriding" (i.e. the thermochemical hardening of materials) may also be required; potentially having undesirable consequences in an industrial facility. There are also licensing and safety requirements that must be overcome. These include the potential effects of an incident at the HTGR on the wider industrial environment and equally important, mitigating the potential effects on the HTGR due to an incident at the industrial facility (Figure 4).

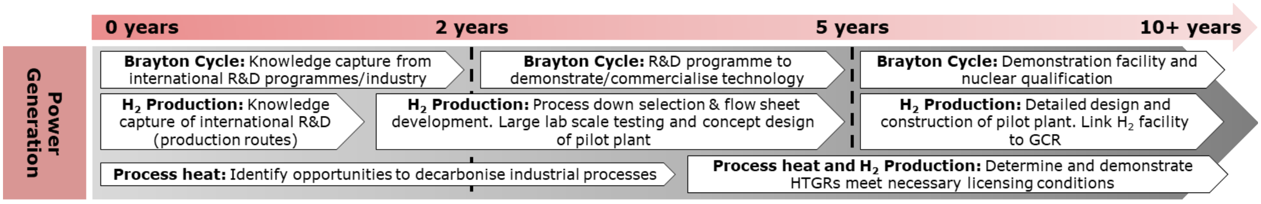

Figure 4: Roadmap of HTGR Power Generation needs

2.6. HTGR Fuel Cycle Discussion

Nuclear Fuel

HTGRs rely on coated particle (TRISO) fuel as the primary barrier to contain fission products. The assumption for HTGRs is that UO_2 or UCO fuel kernels will be encased within successive layers of porous carbon, pyrolytic carbon (PyC), silicon carbide (SiC) and a final outer layer of dense pyrolytic carbon (PyC). Coated particle fuel (diameter <1 mm) is then dispersed through a graphite or ceramic fuel element. HTGRs could operate on a thorium-uranium fuel cycle and have been proposed as plutonium burners; yet require further work to confirm this. The technology to manufacture the coated particle fuel is relatively well understood. At the time of this report, the UK is developing facilities to support coated particle fuel research. This is through the Nuclear Innovation Programme (NIP) with the National Nuclear Labs (NNLs) Preston facility developing lab-scale facilities to produce fuel kernels and the University of Manchester (UoM) hosting non-active coating capability. There is an opportunity to implement learnings from legacy programmes (e.g. Knowledge Capture from Dragon and the Fast Reactor Programme) as a means to rapidly and effectively upskill the UK R&D base. To qualify a domestically developed fuel would require access to a materials test reactor (MTR), a UK facilities gap. Test irradiations could be carried out at internationally hosted facilities, such as those in the Netherlands (Petten), France (the future Jules Horowitz), Belgium (BR1/2) or in the US (National Labs). No domestic supply route for coated particle fuel exists in the UK, with UK fuel manufacturing infrastructure currently limited to AGR and oxide fuel for the UK's current nuclear fleet. Commercially, nuclear qualified coated particle fuel with U-235 enrichments of 8.8% is only available from China, China also has the encase these to form fuel pebbles (pebble bed) and can manufacture ~100,000 pebbles pa.

High Assay Low Enriched Uranium (HA-LEU), with a fissile content of between 8% and 19.9% is required for HTGRs. From a technical perspective, enrichment above 5% (as used in PWRs) is readily achievable using existing technology but not facilities. Existing designs and licences for uranium enrichment and fuel fabrication do not extend to these levels of enrichment due to criticality issues. Transportation packages for fissile material are licensed to PWR fuel i.e. below 5% enrichment. In the UK, uranium enrichment is undertaken at URENCOs Capenhurst facility with fuel manufacture on Westinghouse's Springfields site, near Preston.

Reprocessing and Spent Fuel Disposal

HTGRs intend to utilise an open fuel cycle, with long-term storage of spent fuel prior to packing and disposal in a suitable (geological) facility; as such development of a reprocessing strategy is not intended prior to HTGR deployment. Direct disposal of spent fuel has yet to be demonstrated in part due to the limited operation of test HTGRs; and the lack of spent fuel disposal facilities internationally which has historically been part of the driving force for a closed fuel cycle (i.e. recycle strategy). Leach tests on coated particle fuel has indicated that fission products (e.g. Cs, Sr, I and noble gases) generated during reactor operations will be retained. These tests are for short time periods, relative to the intended disposal timescales and further investigation as to the suitability of the waste form over long time periods (>10 years) would be beneficial. This would provide greater confidence in the modelling and disposal assumptions; supporting HTGR and disposal facility licensing. Such studies could be undertaken at the existing MIDAS (Materials for Innovative Disposition from Advanced Separations) facility, at the University of Sheffield, utilising non-active coated particle fuel produced at the University of Manchester. Testing prior to reactor deployment would be optimal; but further tests could run-in parallel with initial reactor deployment.

Reprocessing of spent coated particle fuels is viewed as a theoretical possibility. To achieve this, significant R&D is required to develop a process of access the fuel kernel, first from the inert matrix and secondly to remove the pyrolytic carbon and silicon carbide coating. The key challenge will be minimising the volume of waste and capture the off-gas during isolation of the fuel kernel. A suitable reprocessing flowsheet will also need to be developed and validated based on reactor physics, fuel form and burn-up. However, all these activities should be preceded by a technical and economic analysis on the potential benefits of operating a closed fuel cycle for HTGRs.

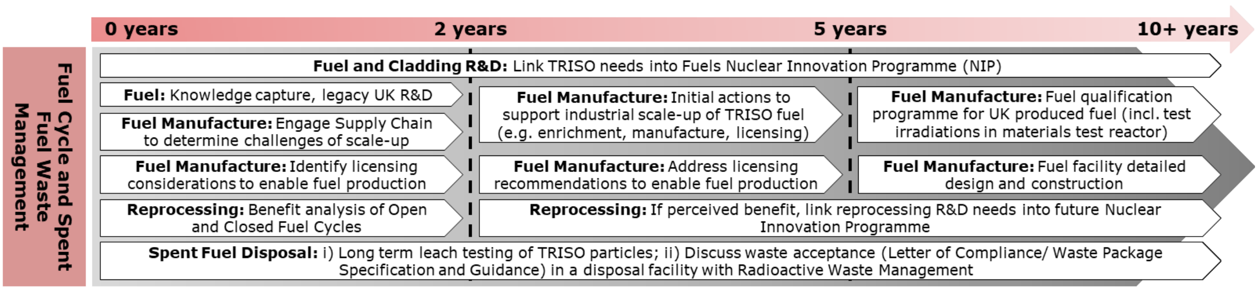

Figure 5: Roadmap of HTGR Fuel Cycle and Spent Fuel Waste Management needs

2.7. VHTR Nuclear Island Discussion

Reactor Equipment, Main Heat Transport System and Safety

Advanced materials are expected to be required for VHTRs as no nuclear qualified materials are compatible with the thermal environments that VHTRs will operate in (i.e. coolant inlet of 550°C and outlet of 950°C). Existing design codes and standards (e.g. American Society of Mechanical Engineers, Boiler and Pressure Vessels) limit the maximum temperature of commercial RPVs to 538°C (<1000°F). While, the reactor core, main heat transfer system and heat exchangers (if 2-loop Brayton Cycle) or turbines (1-loop Brayton) could experience temperatures in excess of 950°C. It has been proposed to fabricate reactor core components from advanced alloys, composites or ceramics to enable the continuous and long-term operation of VHTRs. This could include nickel-based alloys rich in chromium, which have found widespread use in the aerospace sector; these are not covered by existing nuclear codes and standards. To develop and qualify materials would require environmental (thermal) testing and an irradiation programme in a materials test reactor (MTR). The UK has facilities for materials development, at the BEIS funded High Temperature Facility - that can test materials at temperatures at temperatures of 1000°C; or the Henry Royce Institute (a partnership between the Universities of Cambridge, Imperial College London, Liverpool, Leeds, Manchester, Oxford, Sheffield as well as NNL and UKAEA) that will focus upon materials research. As previously discussed, a UK facilities gap exists for a domestic materials test reactor (MTR) to undertake materials qualification.

It is important to note, that the Japanese HTTR is designed to operate with a coolant inlet temperature of 395°C and outlet temperature of 850°C, and only achieve 950°C during the testing of the coupled H_2 production process. Coolant inlet temperatures below 400°C allow the use of materials covered by existing nuclear codes and standards; enabling the use of 2¼Cr-1Mo steel to construct the 13.2 m long and 5.5 m diameter Reactor Pressure Vessel.

The development of nuclear design codes and standards for advanced reactors, is included in the Nuclear Innovation Programme (NIP). There is a gap in the current codes and standards for VHTR materials, as the maximum allowed material temperatures are below those necessary for VHTR operation. The inclusion of new (to nuclear) materials and a significant uplift in the maximum temperature that the materials can operate at is required. An update of nuclear design codes and standards will be an international endeavour, requiring the UK to partner with other likeminded nations to achieve.

The UK nuclear supply chain has limited experience of producing components from advanced alloys necessary for VHTR components; in comparison, the non-nuclear supply chain is more experienced. However, a lack of design clarity, including dimensions and bill of materials means it is difficult to assess the need for and level of support to advance UK capability.

Nuclear Graphite

The HTTR in Japan led to the development of the IG110 grade of nuclear graphite, which is also used in the HTR-10 (HTGR in China). Historically, the UK produced nuclear graphite (e.g. Pile Grade A, IM1-24 and GCMB); this is no-longer the case and a UK capability gap exists. Use of a novel grade of nuclear graphite would require thermal testing due to the temperatures in VHTRs; the domestic High Temperature Facility (HFT) may host the necessary infrastructure to investigate non-irradiated samples. In addition, an irradiation programme in a materials test reactor (MTR) would be required to support material qualification and would take several years to generate the necessary data.

The graphite waste challenges associated with VHTRs are comparable to those of HTGRs and as such, the discussion will not be repeated here (see page 17).

Instrumentation & Control

Instrument and Control (I&C) R&D needs for VHTRs and HTGRs are analogous, given the similar needs and are further discussed on page 18. Additional material selection challenges will exist for VHTR I&C, given the enhanced operating temperatures. Outstanding R&D needs include: definition of the monitoring needs, identifying opportunities for innovation and the incorporation of learnings from sacrificial components in international systems. A UK nuclear supply chain gap has been identified for the manufacture of control rods, shut down assemblies and their respective drive mechanisms for all AMRs.

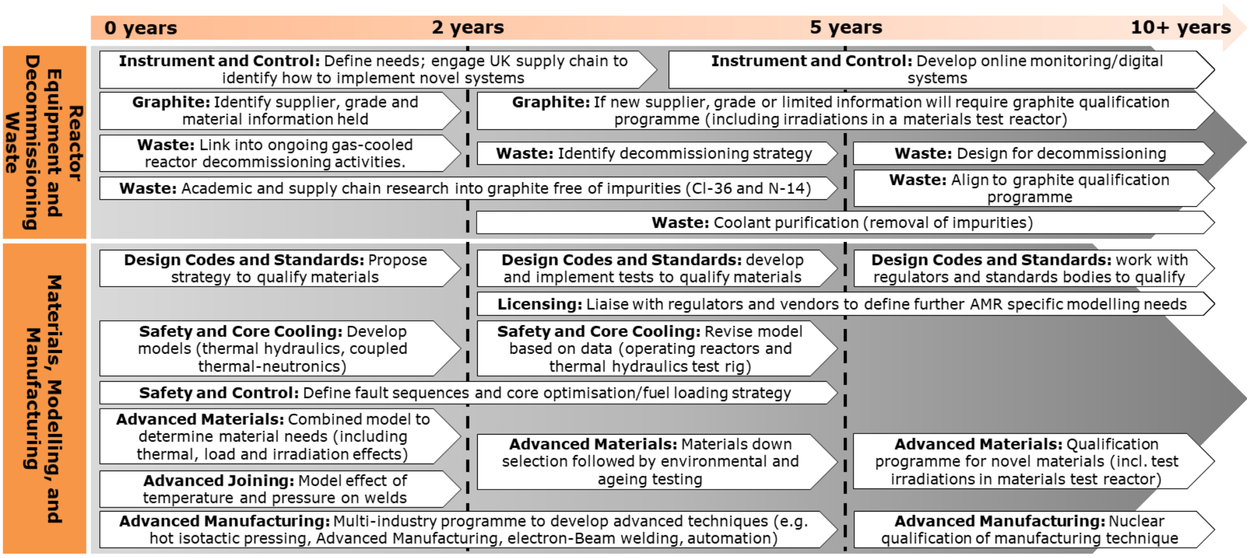

Figure 6: Roadmap of VHTR Nuclear Island needs

2.8. VHTR Power Generation

Brayton Cycle

Brayton power cycles are required for VHTRs to reach the high thermal efficiencies promised. Single loop, where the turbine is incorporated into the primary circuit and driven by helium have the same challenges as for HTGRs (i.e. helium containment, system pressures and the effect on turbine bearings), but are further complicated by the material selection challenges caused by the increased thermal conditions. Two loop systems; using either nitrogen (N_2) or supercritical carbon dioxide (s-CO_2) avoid some of the challenges of a helium cycle (i.e. helium containment) but have their own R&D needs. Cross-cutting R&D needs for all coolants (He, N_2 and s-CO_2) include system (i.e. heat exchanger and turbine) design; containment of the gas/supercritical fluid; materials development due to the environment; modelling; construction; and qualification.

Domestic research facilities (e.g. AMRCs and Catapults) have some of the facilities necessary to support Brayton cycles development that could be used on all AMRs and is necessary for VHTR deployment – this is due to the multi-industry expertise they encompass. The UK supply chain is well placed to compete for the manufacture of Brayton Cycles components, when the design challenges are overcome, this is discussed for HTGRs on page 19.

H_2 Production/ Process Heat

The Iodine-Sulphur (IS) process is arguably the most researched "Green" H_2 production process (where only water is consumed) and requires process heat temperatures of ~950°C. Significant research into the IS process is ongoing internationally; Japan intends to deploy a first of a kind VHTR and H_2 production plant in the 2030s. In addition to the technological challenges associated with developing water splitting reactions (including demonstrating the robustness of and scalability of the process as well as gas containment); there are licensing and safety considerations to be overcome. Especially those associated with locating a H_2 production and storage facility so close to a nuclear reactor. The domestic facility needs are the same as discussed for HTGR (page 19) and will not be repeated here.

For process heat applications, the technology challenge of transferring steam to industrial facilities is viewed as minimal. The movement of a high temperature secondary gas (e.g. N_2) are expected to be similar to the R&D challenges of a Brayton cycle (e.g. IHX and gas containment). Additional research may be required, to understand the potential for and effect of "nitriding" (a metal hardening process) on the heat transfer pipes and on an industrial facility. Licensing and safety requirements will also need to be overcome. This includes investigating the potential effects of an incident at an industrial facility and minimising its effects on the VHTR.

The required developments necessary to enable the supply of process heat (using the thermal output from a VHTR) to industrial facilities or for H_2 production is likely to be a long-term benefit that VHTRs could provide. This is due to the remaining technical challenges (Brayton Cycle and high temperature materials) and licensing considerations that need to be overcome. Quicker VHTR deployment could be enabled, should electricity production (LCOE) from VHTRs become cost competitive (i.e. demonstrating that the high thermal efficiencies offered by Brayton cycles can be commercially achieved). However, this would require a significant research effort to develop and demonstrate a highly efficient Brayton Cycle.

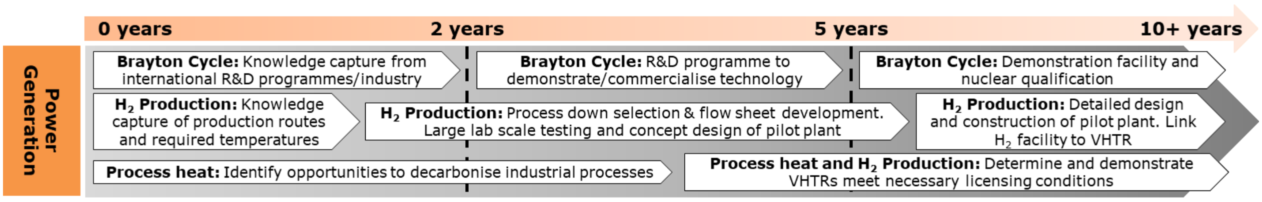

Figure 7: Roadmap of VHTR Power Generation needs

2.9. VHTR Fuel Cycle

Nuclear Fuel

VHTRs use coated particle fuel encased in an inert matrix fuel element. As such only the differences from HTGRs will be discussed. The HTTR in Japan uses UO_2 fuel kernels encased in a silicon carbide (SiC) TRISO, which are then encased in a graphite matrix due to the prismatic modular core. VHTRs may require the use of uranium oxycarbide (UCO) and an advanced coated particle fuel, involving zirconium carbide (ZrC) for long term operation at 950°C. VHTRs could operate on a thorium-uranium fuel cycle and have also been proposed as plutonium burners; yet further work is required to confirm this.

Studies have indicated that uranium oxycarbide (UCO) reduces the build-up of CO in the fuel particle and has improved robustness at temperatures up to 1800°C. Coating strategies for VHTRs include encasing the fuel kernel in a thin zirconium carbide (ZrC) coating prior to adding the porous carbon, pyrolytic carbon (PyC), SiC and PyC layers; to produce a so called QUADRISO particle. Dispersion of ZrC throughout the inner PyC layer of an TRISO particle as well as replacing the SiC in a TRISO particle with ZrC have also been proposed. Incorporation of ZrC is viewed as advantageous for VHTR fuel due to the higher thermal resilience (melting point of ZrC is 2876°C whereas SiC decomposes above 2000°C) and enhanced resilience to fission product attack compared to SiC. However, the manufacture and incorporation of ZrC is an outstanding R&D challenge that has yet to be overcome. To advance understanding of these processes further research is required. Research infrastructure in the UK is currently being developed for coated particle fuel research. Should one of the fuel concepts above be used for VHTRs, an irradiation programme in a materials test reactor (MTR) will be required. The lower research state and more limited international irradiation experience means that VHTR fuel qualification, especially for coated particle fuels containing ZrC is a longer-term activity than for HTGRs. The international and commercial manufacture of coated particle fuel suitable for continuous and long-term use in VHTRs is not clear.

A domestic research programme could utilise existing facilities developed as part of Nuclear Innovation Programmes (NIP). This includes facilities for the coating of fuel kernels to produce at the University of Manchester (UoM). In addition, the National Nuclear Labs (NNLs) Preston facility is developing the capability to produce fuel kernels on a lab-scale as well as researching the production of advanced ceramic (uranium silicide and uranium nitride) fuels.

VHTRs are expected to require enrichments >8% and up to 19.9%. As with HTGRs, several licensing gaps exist, in terms of: i) enrich fissile material to this level; ii) transport of fissile material or fuel; and iii) manufacture fuel for the reasons discussed for HTGRs, see page 20.

To note, the HTTR, a test VHTR in Japan is understood to require fuel enrichments that range from 3% to 10% in its core. The use of multiple enrichments is a potential error trap, which would require the development of safeguards and processes to mitigate.

Reprocessing and Spent Fuel Disposal

VHTRs, like HTGRs intend to operate an open fuel cycle, with spent fuel storage prior to disposal in a suitable facility. Significant research programmes, involving leach tests, are required to determine the long-term suitability of the coatings; given the differences in thermal environment and potential coating composition. Multi-years tests, and ideally long term (>10 years) could help validate current disposal assumptions and support licensing activities. Such studies on non-active coated particle fuel could be undertaken at the existing MIDAS (Materials for Innovative Disposition from Advanced Separations) facility, at the University of Sheffield, utilising coated particle fuel produced at the University of Manchester. These would need to be undertaken prior to reactor development, to confirm the models are consistent with experimental results. The VHTR reprocessing needs are analogous to those for HTGRs and will not be repeated, see page 21.

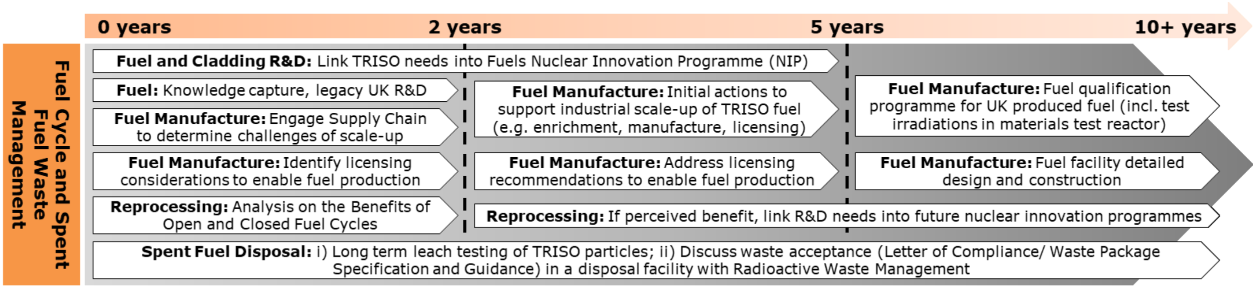

Figure 8: Roadmap of VHTR Fuel Cycle and Spent Fuel Waste Management needs

2.10. Gas-cooled Reactor Technology and Supply Chain Summary

A significant volume of R&D, leading to the operation of seven helium-cooled reactors has been focused upon High Temperature Gas-cooled Reactors (HTGRs) and Very High Temperature gas-cooled Reactors (VHTRs). Especially when compared to other thermal neutron spectrum AMRs. Operational experience gained from lower temperature CO_2-cooled and commercial gas-cooled reactor fleets, such as the UK's MAGNOX and AGRs, has some overlap with HTGRs. This wealth of experience has resulted in this study assessing HTGRs as having an international TRL of 7 (Figure 9). However, R&D challenges exist that must be overcome prior to widespread commercial deployment; these are:

- **Modelling and Simulation:** all AMRs require modelling and simulation support for licensing and experimental programme validation. The exact requirements will vary between vendors.
- **Fuel Cycle and Waste Management:** Coated Particle Fuels (CPFs) have been made across the globe in limited quantities. R&D is required for process improvements, fuel qualification and to investigate the long-term ability of the coatings to contain fission products for extended periods of time. As direct disposal of spent CPF is intended in a suitable geological facility.
- **Instrumentation and Control:** the high temperatures of HTGRs raise challenges for reactor monitoring, requiring the development and demonstration of suitable sensors and equipment.
- **Provision of high temperature heat:** while not required for initial reactor deployment, enabling work to support the siting of HTGRs close to industrial areas or a H_2 production facility are required.

The reduced operational experience of VHTRs, and the fact that the necessary high thermal conditions (950°C) have only been achieved for short periods of time means that additional R&D challenges exist for VHTRs compared to HTGRs. This has resulted in this study assessing VHTR as having an international TRL of 5 (Figure 9). Development needs prior to commercial VHTR deployment include those already discussed for HTGRs, as well as:

- **Materials:** Existing nuclear qualified materials are not licensed to the temperatures required for VHTRs, requiring their development, and nuclear qualification.
- **Reactor Equipment:** Reactor equipment, will require demonstrating at the enhanced temperatures required in VHTRs.
- **Fuel Cycle and Waste Management:** as for HTGRs, with significant additional R&D required if Zirconium Carbide (ZrC) is used.
- **Power Generation:** to benefit from the high coolant outlet temperatures and realise the enhanced thermal efficiencies possible, a Brayton power conversion cycle is required for VHTR deployment.

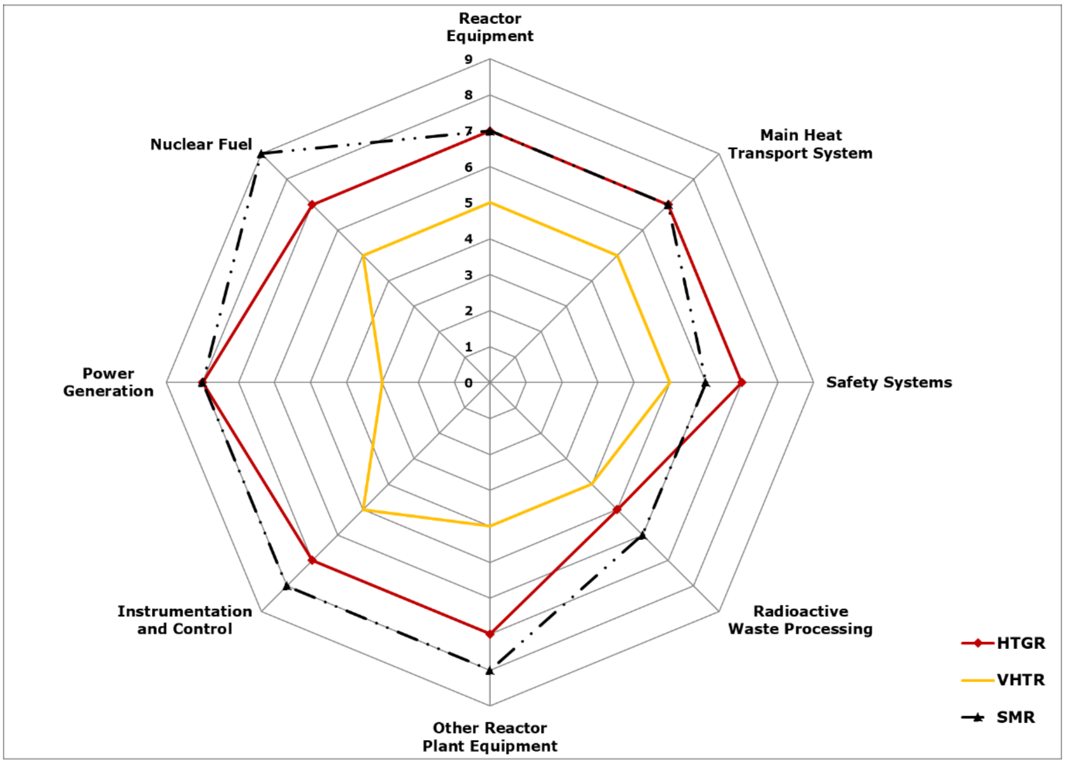

Figure 9: Comparison of HTGR, VHTR and SMR TRLs

Existing nuclear codes and standards are expected to be suitable for HTGR deployment, given the expected temperatures and materials. This is not the case for VHTRs, which will require the development and implementation of new nuclear codes and design standards. In terms of fuel regulation, HTGRs and VHTRs could require uranium enrichments up to 19.9%; this is beyond existing regulations for enrichment, fuel manufacture and transport. A licensing gap also exists for the direct disposal of spent coated particle fuel. If the deployment of HTGRs or VHTRs is based upon the supply of heat to decarbonise industrial processes, it will require siting GCRs close to heavy industrial areas. In the UK, this is a significant licensing gap, as nuclear facilities are typically located away from the industrial areas that could most benefit from decarbonisation.

The UK supply chain historically had the capability to manufacture a significant number of the components necessary for HTGR deployment, but this is no longer thought to be the case. This is in part due to: i) the amount of time since the UK last constructed a new nuclear reactor; and ii) the relative immaturity of AMR concepts, (with many yet to demonstrate feasibility at the concept design stage) resulting in a lack of clear vendor requirements. To address the capability and capacity gap, support and development of targeted areas of the UK supply chain is required. This challenge is not unique to HTGRs and is faced by all AMRs.

For HTGRs, the UK nuclear supply chain is believed to be unable to meet the capacity and capability (Red) to produce approx. 16% of the components assessed by this study and deemed necessary for a future HTGR (Figure 10). This includes: **core moderators**, **reflectors**, **control rods**, **shutdown assemblies** and their **drive mechanisms**; established international supply chains exist for these components. Targeted development to advance existing capability could enable UK manufacture of ~64% of the components assessed in this study. To achieve this would require minor (Green) or significant development (Amber) in either supply chain capability or facilities. Approximately 20% of assessed reactor components could currently be manufactured (Blue). This includes: **pipework**, **electrical panels** and **cables**, **emergency generators**, **waste containers** and **spent fuel transport containers** and is due to: i) UK operation of the MAGNOX and AGR commercial fleets; ii) legacy information and experience from the "Dragon" reactor (HTGR); and iii) the UK's advanced aerospace sector, where similar temperatures are experienced.

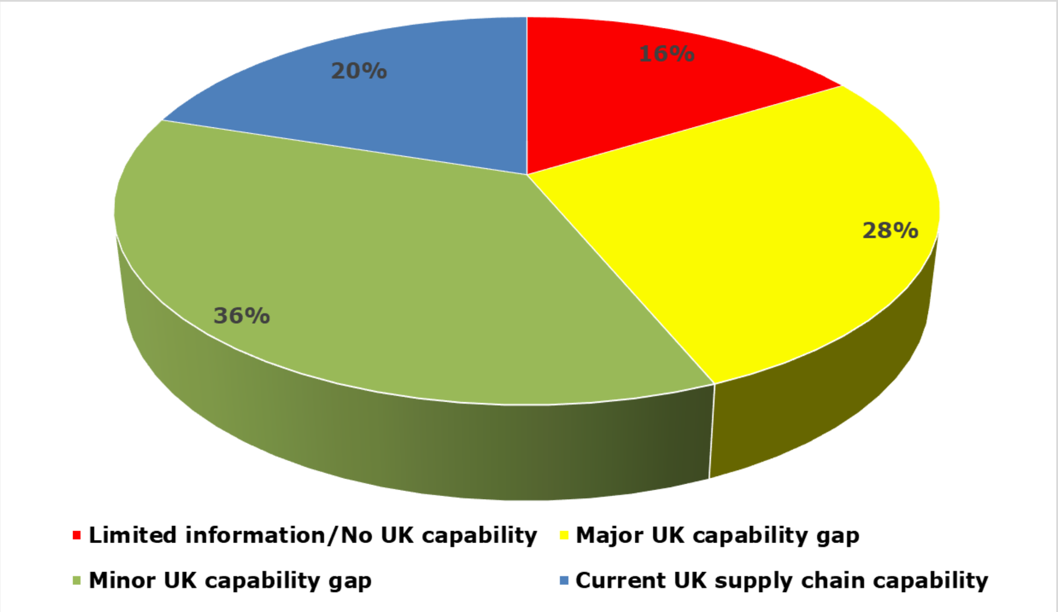

Figure 10: Summary of UK supply chain capability for HTGRs

3. Sodium-cooled Fast Reactors (SFRs): summary of current state and development needs

3.1. Sodium-cooled Fast Reactor Key Points

Liquid sodium-cooled reactors operate at ~550°C and are low pressure systems. 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.

3.2. Overview of SFR systems

SFRs are the most mature fast reactor technology, with more than 400 reactor operating years of experience. It is important to note that the UK has ~40 reactor operating years' experience with SFRs, from the Dounreay Fast Reactor (DFR) and Prototype Fast Reactor (PFR), both at Dounreay. In addition, SFRs have operated in France, the USA and Japan; are operating in Russia; and more recently China and India have started operating SFRs. The UK fast reactor programme (1950s-1994), resulted in a significant volume of knowledge and experience with SFRs. However, documenting the experience and knowledge generated by the UK fast reactor programme was not widely undertaken upon its cessation. The BEIS funded Nuclear Innovation Programme (NIP) included a package of work to capture this historic knowledge and experience to ensure it was not lost to future generations. However, the volume of work undertaken by approx. 1000 scientists over 40 years is significant and beyond the current scope.

Sodium-cooled Fast Reactors (SFRs) operate in the fast neutron spectrum with maximum reactor outlet temperatures between 500°C and 550°C. An inert atmosphere, typically of

Argon, is maintained above the liquid sodium or sodium alloy (e.g. NaK). The use of liquid sodium allows high coolant outlet temperatures at atmospheric pressure and provides a large thermal inertia (a coolant with high boiling point, thermal capacity and thermal conductivity) in the event of reactor transients [10]. Reactor vessel and equipment, pipework and heat exchangers can be fabricated from austenitic or ferritic-martensitic stainless steels due to the limited materials corrosion induced by molten sodium. There are typically two main classes of Gen. IV SFR designs [11]:

i) Pool-type designs that contain the key reactor components (e.g. intermediate heat exchanger and pumps) in the reactor vessel (see Figure 11) [1]; and
ii) Loop-type designs that have smaller reactor vessels with the intermediate heat exchanger and coolant pumps external to the vessel.

The fissile material content of fast spectrum reactors requires fuel with higher fissile material contents than thermal spectrum fuels (20-30% versus <5%). As the core physics dictates greater fissile material is required to sustain the chain reaction. SFRs have operated with metallic or ceramic fuels encased in metallic (stainless steel) fuel pins and this is thought to be the intention for initial SFR-AMR deployment. Overtime, SFRs could transition to the use of advanced ceramics (mononitrides or carbides) or ceramic cladding to provide operational benefits. To realise the potential advantage of fast spectrum reactors (e.g. fuel sustainability, MA burning and waste minimisation), a closed fuel cycle is required that involves spent fuel reprocessing and its fabrication into new fuel.

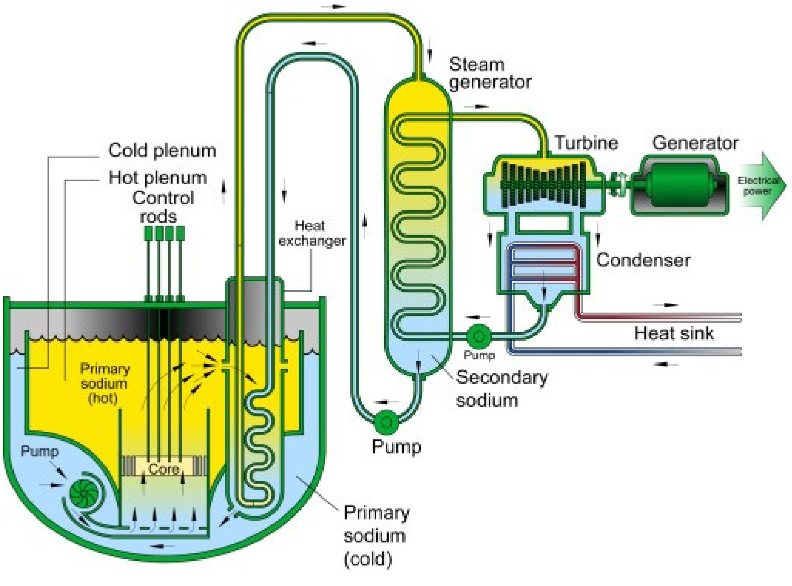

Figure 11: Generic Gen. IV (pool-type), Sodium-cooled Fast Reactor

Power generation has been achieved with SFRs, including in the UK (with both DFR and PFR), using steam (Rankine) cycles. To mitigate the potential reaction between water and the primary sodium circuit, an intermediate sodium loop is typically incorporated. Such 3-loop systems require intermediate heat exchangers between the primary and secondary sodium loops (as displayed in Figure 11). However, multiple heat exchangers reduce the thermal efficiency and increase the reactor footprint. To overcome this, Brayton power conversion cycles are being researched, as part of long-term deployment strategies. These power cycles remove the potential for sodium-water interactions, may negate the need for a secondary coolant loop (improving efficiency and reducing the reactor footprint) and offering higher thermal efficiencies.

3.3. SFR Nuclear Island Discussion

For SFRs, the 400 reactor years of operational experience and fundamental R&D to support this has identified and overcome various R&D challenges. Yet, until the remaining R&D needs are surmounted, widespread SFR-AMR deployment is unlikely. The focus of current SFR research is the development and implementation of economic, safety or efficiency benefits.

Reactor Vessel Equipment

Sodium-cooled fast reactor (SFR) vessels and core equipment have typically been made from austenitic or ferritic-martensitic stainless steels. To mitigate the potential of a molten sodium leak, SFR vessels are typically double skinned. While these materials have been operationally proved across research and prototype reactors; a gap is thought to exist in current nuclear codes and standards for commercial SFRs. As such, nuclear codes and standards will require updating prior to deployment. Such an update would benefit from first developing a strategy to qualify the materials and is unlikely to be a UK only endeavour, with opportunities for international partnership (e.g. US for ASME and France for AFCEN) whilst engaging with international bodies (e.g. IAEA, EURATOM and GIF) and technology vendors. This would be followed by studies to develop and implement tests to qualify the materials and could benefit from access to a zero-power research reactor; to provide additional data. However, it may not be necessary, given the historic reactor experience and data generated as part of the historic UK and international Fast Reactor Programmes. It is important to note that a review of the state of nuclear codes and standards for advanced reactors, including sodium-cooled reactors is within the scope of Phase 1 of the Nuclear Innovation Programme (NIP).

Development needs for SFR vessels and reactor materials are focused upon addressing design specific issues. Such as the effects of vessel geometry and size and the effects this has on thermal cycling (e.g. structural integrity, stress cracking, creep and strain). All SFR-AMR designs require creation of unique models of the core and vessel geometry. Access to a suitable test rig (heated flow loop/ thermal hydraulics) would be required for validation purposes. Model development will also be required for optimising the Inspection and Maintenance requirements and which could influence the layout of the reactor internals. Such studies were regularly undertaken as part of the UK's historic Fast Reactor Programme. Access and use of this valuable historic knowledge and data could rapidly advance current understanding. Additional and design specific modelling encompassing core physics will influence the design of control and instrumentation as well as impact on fuel cycle studies.

The construction and operation of DFR and PFR led to the development of knowledge and experience of SFRs in the domestic supply chain to the mid-1990s. It is noted that many of the individuals involved at with these programmes at the time may be approaching or already have retired. As such, it is important to capture this knowledge and experience as a means of domestic upskilling and avoiding the costly repeating of work. Even considering the intervening time, the ability of the domestic supply chain to produce the materials required for an SFR vessel is viewed as high. However, a potential capacity (facilities) gap may exist for vessel manufacture, due to the lack of clarity regarding vessel dimensions.

In the longer term, SFRs have the potential to use novel material grades such as advanced alloys or ceramics that could provide an operational, economical or safety related benefit. The R&D needed to develop advanced materials for SFRs will not be discussed in this summary as such alloys are not required for initial deployment; however, knowledge capture of historic experience to define materials needs and understand the effect of irradiation induced material damage and swelling could be beneficial. The development of advanced manufacturing, joining and inspection techniques applicable to SFR-AMRs could be incorporated into existing research programmes, such as the Nuclear Innovation Programme.

Domestic supply of reactor shielding, in the form of lead-based components or shield doors/gamma gates for spent fuel handling/storage are well within the capabilities and capacities of the UK supply chain. Due to the extensive experience gained with ongoing decommissioning programmes across the UK's nuclear facilities. Supporting studies could better define the expected fission products that shielding would be required for, requiring clarity as to the reactor fuel, fuel burnup and core physics of the AMR. This manufacturing experience could also contribute to the domestic supply of metallic reflectors for SFRs. Domestic supply chain needs are for engagement with vendors to better understand their manufacturing needs.

Main Heat Transport

The violent reaction between sodium and water has typically resulted in SFRs being 2-loop systems, requiring intermediate heat exchangers (IHXs) to transfer heat between the primary and secondary circuit. Previously, mechanical pumps have been used in SFRs and using equipment that has previously been demonstrated during hundreds of reactor operating years in SFRs means that limited research of such technology is required. Potential research topics are focused upon substantiating evolutionary designs or novel materials (e.g. advanced alloys) to provide an efficiency improvement. The use of electromagnetic pumps, in place of mechanical pumps could provide an advantage – yet requires additional R&D and demonstration. Electromagnetic pumps have operated in the UK's DFR, but in general have gained less operational experience than mechanical pumps. Capturing knowledge and experience from DFR on electromagnetic pumps could support UK upskilling and pump development. A heated flow loop (liquid sodium) would be required to demonstrate and qualify the equipment, infrastructure the UK lacks but that may be available internationally, such as those involved in the SFR system arrangement of the Generation. IV International Forum (GIF).

Safety Systems

Passive safety of SFR-AMRs, such as the ability to remove excess decay heat to the surrounding environment without the need for active intervention has been demonstrated on research reactors at full operational power. Active features, such as control and shutdown rods have been demonstrated to effectively control SFR reactivity. A need exists for fault definition of vendor specific designs, to ensure suitable monitoring, intervention or passive features exist. Work to determine if the passive safety features of SFR-AMRs are sufficient to remove the need for multiple independent active safety systems (an ONR requirement). This would require initial discussions between the regulator and SFR-AMR vendors, followed by focused R&D research to potentially substantiate the passive safety claims.

A domestic supply chain gap, in terms of the civil nuclear supply chain has been identified for the manufacture of control rods, shut down assemblies and their drive mechanisms. Control rods and drive mechanisms are required across all reactors, irrespective of coolant and are available from an established international supply chain. Control rods typically have a 6-year operating life, as such SFR designs with cores of 10-, or even 20-years will still require regular replacement or the development and licensing of control rods with a suitable design life.

Waste

Purification of the molten sodium loops in SFRs is required, due to the ingress of oxygen and hydrogen which can affect safety monitoring and lead to corrosion. "Cold traps" have been demonstrated in SFR operations across the globe and limited R&D is required for these. However, one activity could be to undertake a historic knowledge exercise to ensure the data and experience from legacy R&D programmes is not lost and to develop addition domestic capability. "Hot traps" have been the focus of recent international studies that have demonstrated their ability to significantly reduce oxygen levels in SFRs. This technology requires further development and long-term testing (in sodium flow loops) at reactor temperatures to confirm suitability and could form part of a 5-year R&D programme.

The decommissioning of SFRs is an ongoing international and domestic activity, with limited need for further R&D. A key task will be to ensure that the processes, data and experiences are captured and made available to SFR-AMR vendors to consider during the design phase and for eventual decommissioning, should sodium-cooled reactors be deployed. Given the domestic experience with SFRs, a strategy to undertake post-irradiation examination (PIE) of reactor core and vessel materials would provide a detailed understanding of the effects of fast neutrons on materials and could be incorporated into decommissioning plans. In addition, the UK is a global leader in SFR decommissioning and opportunities to export domestic capability gained from decommissioning DFR and PFR should be investigated.

Instrumentation and Control

Instrumentation & Control systems have been demonstrated on multiple research and prototype SFRs. In-reactor monitoring is complicated by the liquid metal coolant which is both optically and electromagnetically opaque. Further challenges are faced due to the increased thermal conditions (compared to PWRs) and reactivity of the coolant with air and moisture. Since deployment of the Prototype Fast Reactor (PFR) in the UK, significant advances in ultrasonic imaging and core monitoring have occurred that will require substantiating and incorporation into future domestically deployed SFR-AMR.

Online monitoring and digital control systems have been developed and demonstrated across multiple non-nuclear sectors. A review to ascertain the potential compatibility of such systems with all AMRs is required and would require initial definition of the monitoring and data needs for SFRs. The domestic supply chain is viewed as requiring support to compete for the manufacture of sensors suitable for SFR-AMRs (e.g. temperature, neutron flux and flow-rate), yet is well placed to manufacture cabling and control panels.

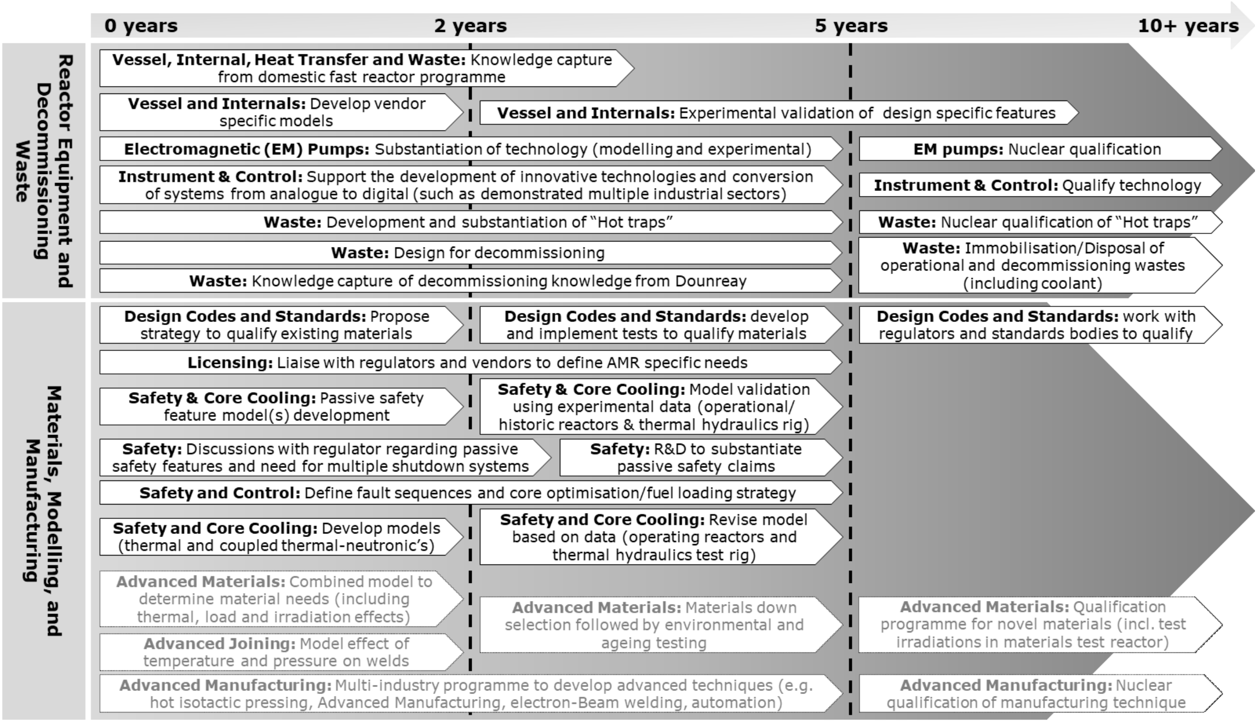

Figure 12: Roadmap of SFR Nuclear Island needs

3.4. SFR Power Generation Discussion

Rankine Cycle

Numerous SFRs have operated with various steam generator, reheater and superheater designs. R&D to support these double walled and straight tubed designs has already been undertaken and as such is not required. Limited support of the UK nuclear supply chain is required, given historic manufacturing experience (DFR and PFR) and the continued manufacture heat exchangers to a wide range of sectors. Design improvements to enhance performance and reduce the component footprint, such as helical coiled designs require nuclear qualification and a licence to manufacture due to IP constraints. The domestic manufacture of advanced steam generator designs is a capability gap, due to a domestic lack of manufacturing licences.

Brayton Cycle

Nitrogen (N_2) or supercritical carbon dioxide (s-CO_2) power conversion cycles can remove the need for a secondary sodium loop and avoid any potential interaction between hot sodium and water or steam. This has led to a significant volume of global R&D, particularly in France (ASTRID), however outstanding technology challenges persist. This includes heat exchanger design, system modelling; development of the turbine system; and the development of compatible materials and joining processes. The domestic High Temperature Facility (HTF), Advanced Manufacturing Research Centres (AMRCs), or Catapults (Manufacturing Technology Centre) could support the development and qualification of various aspects of a Brayton cycle as well as identify opportunities for domestic manufacture. The similarity between a N_2

Brayton Cycle and the aerospace sector (i.e. temperatures and composition of atmosphere) indicate that less support of the UK supply chain may be required to manufacture components for an N_2 cycle than an s-CO_2 cycle. Providing an opportunity for technology transfer from aerospace where turbines are manufactured from advanced alloys (e.g. Ni-based alloys rich in Cr) for use in high temperature environments.

H_2 Production/ Process Heat

Multiple processes to produce H_2 via thermochemical water splitting are undergoing internationally R&D. This includes the copper chloride process that requires temperatures of circa 550°C that may be possible to achieve with SFR-AMRs. To support this, additional R&D is required. This includes into the fundamental water-splitting reaction to produce H_2, which could be carried out at universities or national research centres. Following this, large scale trials would require the construction of suitable facilities to investigate the robustness and scalability of the process and that do not domestically exist.

Decarbonising industrial facilities, through the provision of process heat in the form of steam from SFR-AMRs requires limited R&D to overcome technical challenges. For Brayton cycles, the R&D requirements would align with those discussed in Brayton Cycle (page 34) to transfer heat from the molten sodium-to-gas (e.g. N_2) and to avoid the potential "nitriding" of the heat transfer network.

Common to both process heat and hydrogen production applications are the need to overcome licensing and safety challenges associated with siting such a facility near a reactor.

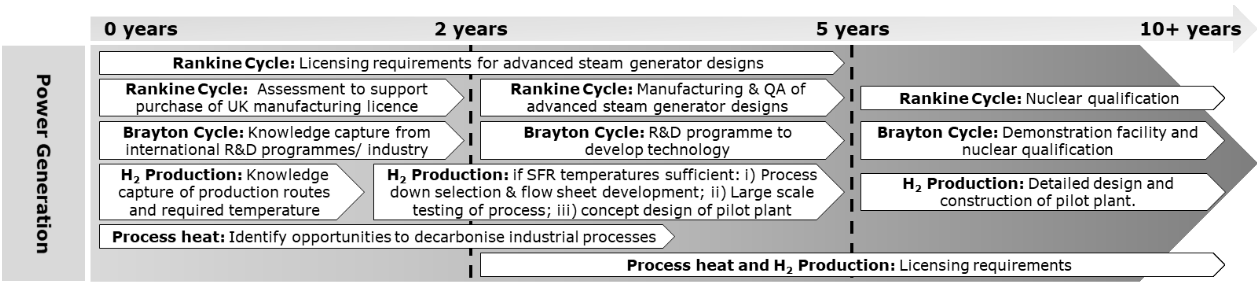

Figure 13: Roadmap of SFR Power Generation needs

3.5. SFR Fuel Cycle Discussion

Nuclear Fuel

Fast reactors are expected to have fissile material (e.g. Pu-239 or U-235) contents approaching 20%-30%. These have been produced in the past, so from a technical perspective it is achievable, but not at existing facilities due to licensing requires and criticality concerns. Existing safety and licensing requirements, for fuel manufacture and fuel transport are also not suitable for fuel transport (LWR fuel <5% enrichment). As such, this is a critical area that will require work to overcome and is applicable to all AMRs.

For initial SFR-AMR deployment the fuel is expected to be either Mixed Oxide (MOx) fuel - a combination of UO_2 and PuO_2; or metal alloy fuel - such as a U-Pu-Zr alloy – both encased in a metallic cladding. MOx and metal alloy fuel have been demonstrated in fast reactors across the globe. Metal alloy fuels are planned for SFRs in China, South Korea and the US whereas France and Russia both favour ceramic fuels (oxide and mononitride respectively). The UK has limited current facilities to make Pu- or MA-bearing fast reactor fuel on an R&D scale. Domestic fuel R&D has been limited to UO_2, in support of the operating reactor fleet.

Advanced fuels, including carbides or mononitrides (ceramics) and novel claddings (e.g. ceramics) are also proposed for SFRs. These are not required prior to SFR deployment and instead could provide an economic, safety or performance benefit during a reactor's life; as such the R&D to realise these have not been discussed here.

Minor Actinide (MA) bearing metal or oxide fuels have previously been manufactured and irradiated in SFRs. The ability to burn MA-bearing fuel, offers a means to reduce the waste from nuclear reactors. MA-bearing fuel links spent fuel reprocessing with fuel fabrication and benefits from the co-location of suitable facilities for both. Prior to undertaking experimental studies into MA-bearing fuels, an economic and technical assessment (including from historic reactor operations) is suggested. Following this, an experimental programme to optimise fuel production is required, ultimately requiring fuel qualification in a suitable fast spectrum materials test reactor. As such it can be viewed as a long-term endeavour with a need for significant R&D to achieve.

R&D to support SFR-AMR fuels would be best achieved through inclusion in an existing or future Nuclear Innovation Programme. This could include capture of the historic knowledge and experience gained during the UK and international Fast Reactor Programmes and support the design, development and installation of an R&D scale Pu-bearing fuel facility in the UK. NNL has existing facilities and experience to handle Pu or U materials. The Dalton Nuclear Institutes (part of the University of Manchester) is actively involved in nuclear R&D, while the Royce Institute (a partnership between the Universities of Cambridge, Imperial College London, Leeds, Liverpool, Manchester, Oxford and Sheffield as well as NNL and UKAEA) will focus upon the development of new materials.

Following facilities development, a fuels R&D programme would aim to determine if suitable Pu-bearing fuel can be produced from the UK's Pu stockpile and to optimise the process. A fuel irradiation programme would follow and due to a UK facilities gap (no UK materials test reactor) would require partnering or engagement with another country. Thermal spectrum facilities exist in the Netherlands (Petten), Belgium (BR1 and BR2), France (the future Jules Horowitz Reactor); currently Russia is the sole nation with a fast neutron MTR (BOR-60). Russia are constructing a replacement (MBIR) to the near 60-year old fast neutron materials test reactor; the US are in the process of designing a similar facility (Versatile Test Reactor).

Reprocessing

A strategy for waste minimisation and the reduction of heat in a future disposal facility (through the burning of plutonium and minor actinides) may contribute to the decision to deploy fast reactors. Technically, it is not necessary to have overcome all the R&D challenges associated with spent fast reactor fuel reprocessing prior to initial SFR deployment, however it is good practise and may ultimately support SFR-AMR deployment. Closed fuel cycles have been demonstrated at Dounreay, as part of the UK's Fast Reactor Programme as well as internationally (including in France and Russia). This requires the cooling and reprocessing of spent SFR fuel and its subsequent formation into new fuel that is itself irradiated. In the UK, an aqueous reprocessing flowsheet, similar to the PUREX (Plutonium Uranium Redox EXtraction) process employed on an industrial scale in the UK (THORP) and France.

Advanced reprocessing, either aqueous or pyrochemical offers many advantages over the current PUREX process developed in the 1950s and first commercially deployed in the 1970s. Currently advanced processes are limited to laboratory scale and require additional R&D prior to commercial scale deployment (Figure 14). An existing Recycle Nuclear Innovation Programme (NIP) has focused upon an advanced aqueous (solvent extraction) process for PWR fuel. Inclusion of a fast reactor reprocessing activity, in a future phase of a NIP, will leverage learning from existing programmes and support development of the necessary and fundamental science to enhance understanding of both advanced aqueous and advanced pyrochemical reprocessing. An initial activity of this could include the knowledge capture of the R&D undertaken as part of historic UK and international programmes (UK Fast Reactor Programme at Dounreay and UK research into molten salts for pyrochemical reprocessing) and international programmes. This information would feed into the development of a fuel cycle strategy, which would require significant addition nuclear data including vendor specific information (e.g. fuel and core information to determine fission product inventory). In parallel, it may be important to undertake an assessment as to the benefit/ disbenefit of operating a closed fuel cycle. A longer-term programme would look to develop a process flow sheet and include a forward experimental programme. Following this, an experimental programme using actual fuel, initially unirradiated and eventually spent fuel would need to occur. Existing facilities at the National Nuclear Labs (NNLs) Central Lab are suitable for initial development of an advanced aqueous recycle process (i.e. multi-gram quantities of transuranics); the UTGARD laboratory at the University of Lancaster (applied chemistry and engineering data needs); the University of Manchester's Dalton Cumbria Facility and Centre for Radiochemistry Research; and the University of Leeds, which has a 3-stage engineering scale centrifugal contactor rig developed to investigate solvent extraction in an advanced aqueous processing. The MIDAS laboratory (University of Sheffield) could also support the investigation of waste immobilisation from a future advanced reprocessing cycle. Pyrochemical reprocessing facilities exist at the University of Edinburgh (Pyro-Reprocessing Laboratory) for non-active molten salt experiments. Largescale trials on surrogates and spent fuel are beyond the scope of current facilities and require developing.

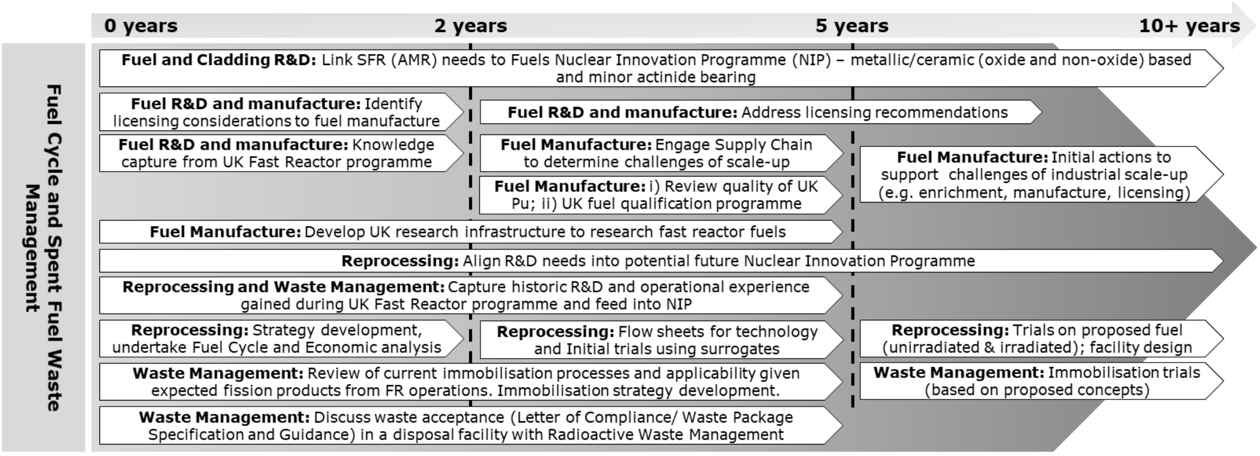

Figure 14: Roadmap of SFR Fuel Cycle and Spent Fuel Waste Management needs

3.6. Sodium-cooled Fast Reactor Technology and Supply Chain Summary

Sodium-cooled Fast Reactors (SFRs) have been the R&D focus of a significant number of countries since the 1950s; especially when the R&D efforts are compared to other fast neutron spectrum AMR concepts. This has resulted in multiple operational reactors, ranging in power from 10 MWe to near 800 MWe, and more than 400 reactor operating years of experience. This experience has led to this assessment concluding that SFRs have an international TRL of 7 (Figure 15). However, research activities are ongoing into potential R&D challenges that could hinder commercial deployment, that include:

- **Modelling and Simulation:** all AMRs require modelling and simulation support for licensing and experimental programme validation. The exact requirements are likely to vary between vendors.
- **Instrumentation and Control:** the high temperatures (compared to PWRs) as well as the optically and electromagnetically opaque liquid sodium coolant are challenges for core monitoring. Requiring development and demonstration of suitable equipment.
- **Reactor Equipment:** materials suitable for 60-year operating lives need to be demonstrated given the environment in SFRs.
- **Fuel Cycle and Waste Management:** fast reactor fuels have been made in many countries but only on a scale necessary to support reactor operations. R&D is required to identify process improvements in fuel manufacture, fuel qualification and into Minor Actinide (MA)-bearing fuels (to reduce heat load in a geological disposal facility). The development and demonstration of advanced reprocessing methods are also required (to close the fuel cycle) reducing the volume of operational waste.
- **Power Generation:** Advanced steam generator designs or Brayton power conversion cycles are required to minimise the potential for water-sodium interactions.

Existing Nuclear Codes and Design Standards are not viewed as being applicable to SFRs, and as such the development of new codes and standards are required prior to commercial reactor deployment. Due to reactor neutronics, fast reactors require significantly higher fissile material contents in fuels than existing commercial reactors and above those allowed by existing regulations for both fuel manufacture and transportation in many countries. The licensing of a suitable spent fuel reprocessing facility, at or close to a fuel manufacturing facility is also required to support "closure" of the fuel cycle and realise the potential benefits of fast reactors. If SFRs are intended to support the decarbonisation of industrial processes, it will require their siting close to industrial areas. In the UK, nuclear facilities are typically located away from the industrial areas that could benefit most from decarbonisation. As such, a significant licensing gap would need to be overcome to enable this that is applicable to all AMRs.

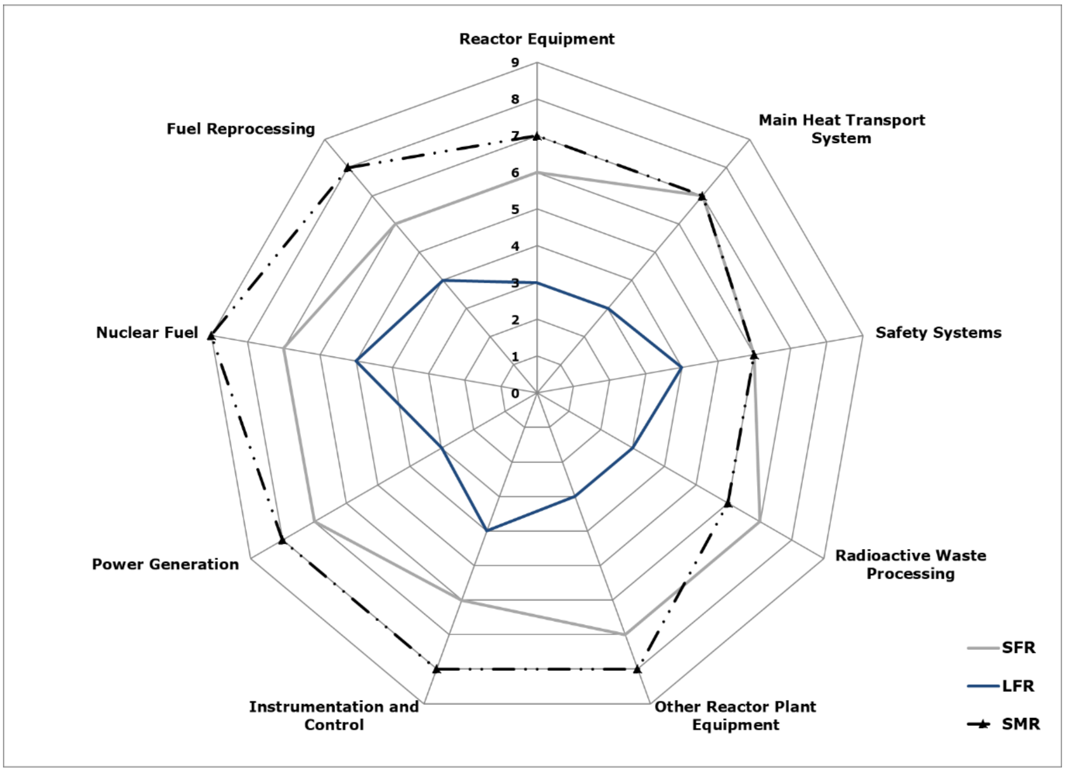

Figure 15: Comparison of SFR, LFR and SMR TRLs

The UK nuclear supply chain historically had the capability and capacity to manufacture a significant proportion of the components necessary to support SFR deployment; yet this is no longer viewed as the case. This is primarily due to the amount of time since the UK last constructed a new nuclear power station or fast reactor. In addition, the relative immaturity of many AMR concepts results in a lack of clear vendor requirements. To address the gaps, support and development of targeted areas of the UK supply chain are required. This is not unique to SFRs, with support required for all AMRs.

For SFRs, the UK nuclear supply chain is viewed as having the current capacity and capability (Blue) to produce approx. 17% of the components assessed by this study and deemed necessary for a future SFR-AMR (Figure 16). These include **reactor vessel materials**, **pipework**, **emergency generators**, **electrical panels**, **cabling**, **waste containers** and **spent fuel casks**. Targeted development to advance existing capability could enable UK manufacture of ~73% of the components assessed in this study. To achieve this would require minor (Green) or significant development (Amber) in either supply chain capability or facilities. A capability and capacity gap (Red) for a component is based on an inability to find information, or an assessment resulting in the determination of a lack of capability. This equates to circa 10% of SFR components and is primarily due to the existence of an internationally established supply chain for **control** and **shutdown rods**, and their relevant **drive mechanisms**. UK ability to support SFR manufacturing is supported by the legacy of the UK Fast Reactor programme and involved the operation of two SFRs (DFR and PFR) in addition to various additional infrastructure.

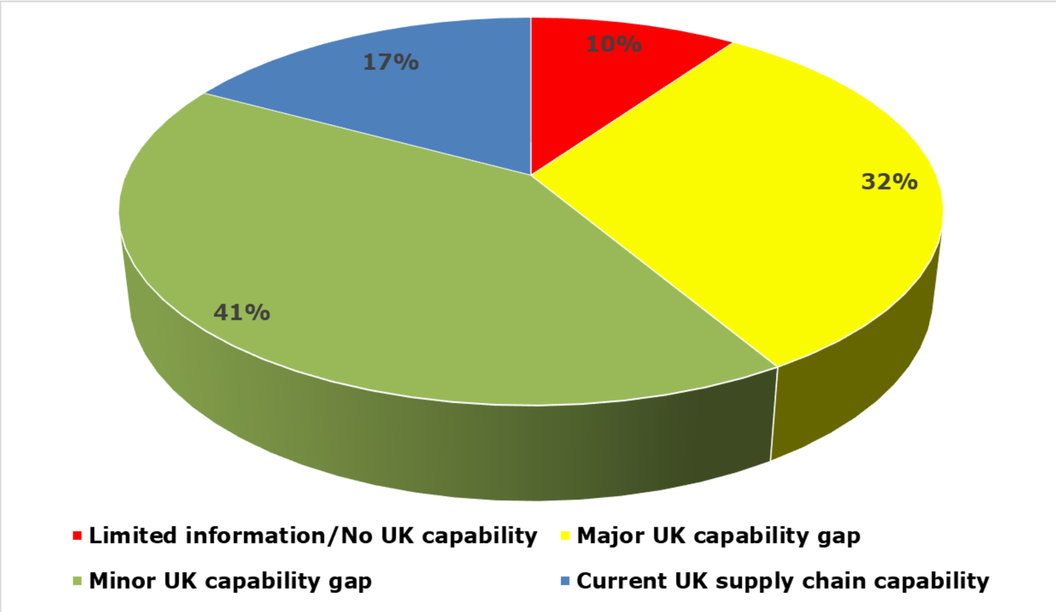

Figure 16: Summary of UK supply chain capability for SFRs

4. Lead-cooled Reactors (LFRs): summary of current state and development needs

4.1. Lead-cooled Fast Reactor Key Points

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 exists 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 a lack of awareness of opportunities – due to limited experience with the technology; and supply chain facilities gaps. 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.

4.2. Overview of LFR systems

The term, Lead-cooled Fast Reactor (LFR) can encompass two coolants, Lead or Lead-Bismuth Eutectic (LBE). LBE systems have a lower melting point (between 150°C and 200°C) than those of pure Lead (327°C). However, Bismuth can undergo transmutation during reactor operation to produce the highly volatile and radiotoxic (α-emitter) Polonium-210. Lead is a significantly more abundant element in the Earth's crust than Bismuth, and insufficient Bismuth may exist to enable commercial LBE-cooled reactor deployment. As such, only lead-cooled and not LBEs-cooled reactors are discussed in this study.

LFRs are expected to be fast neutron reactors, with no core moderator present. Lead has a very high boiling point (1745°C) offering the potential for outlet temperatures that could help to decarbonise energy intensive processes through the provision of process heat as well as enabling greater thermal efficiencies to be achieved than is possible with PWRs. Initial LFR coolant outlet temperatures are expected to be limited to between 500°C and 550°C due to materials corrosion. These corrosion challenges will require the use of advanced materials, such as exotic alloys or the ceramic over coating of metals, which have yet to be defined or qualified. Both pool- and loop-type LFRs are possible [1]. The key difference is that pool-type reactor (Figure 17) designs contain the key reactor components (e.g. intermediate heat exchanger/steam generator and pumps) in the reactor vessel, while loop-type designs have the intermediate heat exchanger/steam generator and coolant pumps external to the vessel.

LFRs have never operated, however up to 80 reactor operating years of experience with Lead-Bismuth Eutectic (LBE)-cooled reactors has been achieved by the Russian Navy. Epithermal (i.e. not fast) neutron spectrum LBE-cooled reactors were used in Russian "Alfa class" submarines; however, these operated with lower capacity factors (usage) and temperatures than the proposed Gen IV systems [11], [12]. It should be noted that a lot of the international experience gained with SFRs will be directly applicable to the future deployment of LFRs. Including the UK's experience at Dounreay. LFRs are viewed as passively safe, with the significant volume of lead providing a large heat capacity. As well as the high boiling point of the coolant compared to the operational temperature which ensures core voiding via coolant boiling is not possible (ΔT ~1200°C). Ceramic (mononitride or oxide) fuel, encased in metal or ceramic cladding (e.g. SiC) is intended for LFR-AMR deployment. A closed-fuel cycle, involving the reprocessing of spent fuel is needed to realise the resource and waste minimisation benefits of fast reactors.

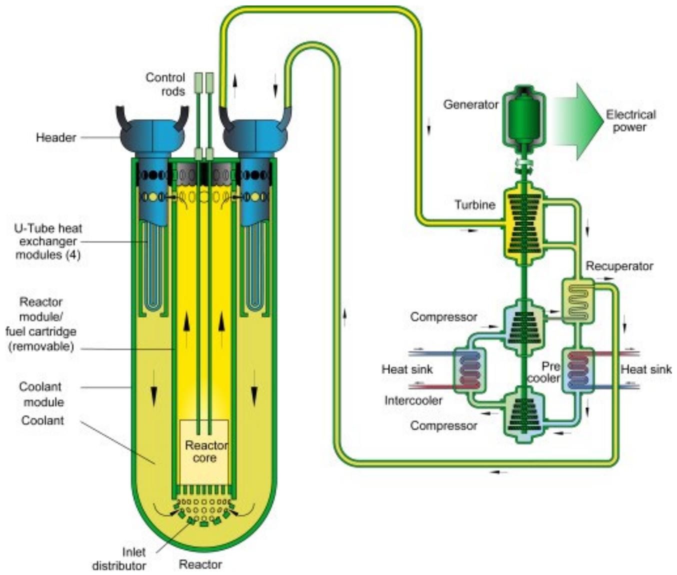

Figure 17: Generic Gen. IV Lead-cooled Fast Reactor

Power generation for LFRs is expected to use a steam (Rankine) cycle, with heat exchangers/steam generators either in the reactor vessel (pool-type) or outside the reactor (loop-type). The more subdued reaction between molten lead and water, compared to that between sodium and water removes the need for an intermediate circuit for LFRs. In the long-term, LFRs could use a Brayton (gas or supercritical fluid) power conversion cycle to increase reactor efficiency.

4.3. LFR Nuclear Island Discussion

Reactor Equipment

The mechanism of materials induced corrosion and erosion caused by contact with molten lead is an ongoing R&D topic (including through the Generation IV International Forum). A greater understanding of the various processes could aid in the identification and development of materials suitable for long-term (60-year) reactor operations. Coolant research is focusing on identifying and removing impurities (e.g. Oxygen) to maintain high coolant purity to minimising materials degradation. Initial domestic studies to overcome this would involve the development of suitable models. Followed by experimental programmes on environmental test loops to validate and refine the models (Figure 18). LFRs may require an online corrosion/erosion monitoring system, depending on the materials chosen for LFR construction. A focused programme of work would be required to achieve this; as no such system is known to exist. In addition, LFR sensors will have to overcome various challenges given the opaque nature (optical and electromagnetic) of molten lead.

The outputs of a coolant chemistry research programme would be expected to act as inputs to an LFR materials development programme. To enable an LFR with an economically competitive operating life, materials must undergo minimal degradation in contact with the reactor coolant. Studies have indicated that existing nuclear qualified grades, (e.g. stainless steels) undergo unacceptable materials corrosion, requiring the use of advanced alloys, composites or ceramics, including the ceramic coating of metals. Such materials or coating processes are not nuclear qualified and are not covered by existing nuclear design codes and standards. The developments needed to address these gaps are discussed in the following paragraphs and are applicable for all LFR material needs. To aid the development of the necessary materials, a fundamental materials R&D programme is required. This will require development of a combined model (including thermal, load and irradiation) to determine material properties. Initial materials screening and modelling would enable the down selection of materials for further testing. The modelling of a generic LFR-AMR would influence the specification and design of an environmental test facility and ultimately aid in material development. In tandem, a material qualification strategy would need to be developed.

Initial LFR materials development, could be undertaken using existing or planned domestic facilities. These include The High Temperature Facility, able to test materials at temperatures up to 1000°C and the Royce Institute (a partnership between the Universities of Cambridge, Imperial College London, Leeds, Liverpool, Sheffield, Manchester and Oxford as well as NNL and UKAEA) that will undertake interdisciplinary materials research. The UK does not have the necessary infrastructure to undertake long-term environmental testing; however, the use of internationally hosted test facilities, such as but not limited to those in Belgium, Germany, the US, India and Russia could avoid the need for domestic development. For materials qualification, a materials test reactor is required – a facility that the UK lacks. International MTRs, such as those hosted by Belgium (BR1 and BR2), France (Jules Horowitz Reactor), the

Netherlands (Petten) or US National Labs may, depending on the requirements, be suitable. Internationally, a facilities gap exists for an MTR able to test lead. A multi-loop test reactor, able to test lead, lead-bismuth, sodium and gas coolants is under construction in Russia (MBIR) [13]; with a similar facility proposed by the US (VTR). It is important to note that the UK does host post-irradiation examination facilities, which support the existing gas-cooled reactor fleet, and are, required to analyse the irradiated samples.

Significant differences exist between LFRs and water-cooled systems for which the codes and standards were developed; requiring the development of new codes and standards prior to commercial LFR-AMR deployment. To develop new codes and standards, it is important to first identify a strategy to qualify new materials. This would be followed by a structured programme to identify and develop the tests to qualify materials. Infrastructure necessary to develop codes and standards include a zero-power research reactor, thermal hydraulics facility and environmental test loop, all of which the UK does not currently host. The amount of time since the UK last hosted civil research reactors or thermal hydraulic facilities means that limited suitably qualified and experienced personal (SQEP) exist to operate these facilities. Updating nuclear codes and standards to enable LFR-AMR deployment will be best achieved through partnership opportunities with nations (e.g. US for updating ASME codes and France for AFCEN), engagement with technology vendors, international organisations (e.g. IAEA) or multinational research activities (e.g.GIF and EURATOM). The "Advanced Manufacturing and Materials" Nuclear Innovation Programme (NIP) includes funding to identify the needs to update nuclear codes and standards for advanced reactors, including lead-cooled systems. The use of advanced materials may require the use of advanced manufacturing, assembly or joining techniques. To include these processes in an update of the codes and standards, development programmes, to model and experimentally validate the effect of temperature, coolant and load would be required.

Due to the density of lead, further unique studies are required. These require the development of suitable models and experimental facilities to investigate: fuel element movement and fatigue, induced by the flow of lead through the core that could resulting in vibrations which could move or damage the fuel pins; and fuel floating, with a need to fix the elements to the base of the reactor, due to the density of the fuel compared to lead. Domestic experimental facilities to validate the models do not exist.

The domestic supply of reactor shielding, in the form of lead-based components or shield doors/gamma gates are currently available from the UK supply chain. Due to the significant decommissioning experience gained from the UK's legacy domestic nuclear facilities. For LFRs, the widespread use of shielding may not be required as the reactor coolant will act to shield much of the core reactivity. Studies to define the expected fission products, will require information on the reactor core, fuel composition and burn-up. A lack of clarity exists as to the material needs for metallic LFR reflectors, however the challenges previously discussed regarding material corrosion and erosion will be present.

Main Heat Transport

The reaction between molten lead (primary loop) and water (power conversion loop) is governed by the temperature difference between the two, unlike for SFRs. This offers the potential for LFRs to operate without a secondary loop minimising the reactor footprint and avoiding the need for an intermediate heat exchanger. Should vendor designs require an intermediate heat exchanger, the development challenges faced will be similar to the reactor vessel in terms of material selection and qualification. The development of a validated thermal and core physics model to optimise heat exchanger design will be required to ensure efficient heat transfer. The historic R&D and operational experience with SFRs could aid in this, providing a starting point for further studies. Access to a thermal test loop will be required to validate the model and aid with nuclear qualification. No such infrastructure exists in the UK; however, nations such as the US, Belgium, India, and Germany are thought to have constructed Lead or Lead-Bismuth Eutectic research facilities. A lack of clarity as to the dimensions, design and heat exchanger/steam generator material needs exists for LFRs; as such it has not been possible to confirm if current manufacturing capability is suitable.

Studies have indicated that for LFRs, mechanical pumps are required due to the density of the Lead (~11 times that of water). Pumps will need to be constructed from advanced alloys or have ceramic coatings as significant materials corrosion has been shown to occur with stainless steel pumps. Long-term testing, on heated flow loops (a domestic infrastructure gap) will be required to provide confidence that the equipment is suitable for use and confirm reliability. Materials selection will align with the broader LFR materials development programme discussed for **Reactor Vessel Materials**. Domestically manufactured, nuclear qualified pumps are available for water-cooled reactors; however, these are not compatible with LFRs. The domestic manufacture of pumps for LFRs could require supply chain support. Through early involvement in materials development programmes, providing information on potential manufacturability challenges present as a part of materials down selection.

Pipework and seals in the primary loop (in contact with lead) require focused materials R&D, as discussed in **Reactor Vessel Materials**. Domestic capability to produce the necessary components is viewed as a gap, due to the expectation that advanced materials or coated components will be required. Areas that the domestic nuclear supply chain may have limited experience of; and on materials/processes that have yet to be determined or qualified.

Waste

Decommissioning challenges of LFR reactor vessels and equipment will share many of the challenges as SFRs and may allow the use of techniques and technologies that have been developed and demonstrated both internationally and domestically (i.e. Dounreay). To aid the “design for decommissioning” of a future LFR-AMR fleet, it will be important to identify the sources of waste at an early; this will enable development of a waste management strategy for the entire lifecycle of an LFR-AMR. A key challenge for LFR waste relates to the coolant. Lead is a highly toxic element that will require secure containment follow reactor closure. During reactor shut down/decommissioning, active heating will be required to avoid solidification of the coolant prior to its removal. The manufacture of flasks to contain waste arising from decommissioning activities is well known in the UK. To enable UK manufacture of LFR waste flasks, clarity as to the material requirements are required; however, this is reliant on the outputs of the wider materials development programme.

Safety Systems

Metal-cooled reactors, especially LFRs have several advantageous properties. Core voiding due to coolant boiling is almost impossible, given the boiling point of lead (>1745°C) and the operating temperature (<550°C) and LFRs have unpressurised reactor vessels. The core physics in LFRs also enable increasing the spacing between the fuel elements; enabling more coolant to flow between the fuel elements and potentially facilitating cooling via natural circulation. A negative temperature coefficient of reactivity (i.e. increasing temperature decreases reactivity) is expected for LFRs. All these passive safety features have yet to be demonstrated and are based on theoretical studies. To validate such models requires facilities (e.g. thermal hydraulics rig and zero-power research reactor) that the UK lacks. In addition, a small-scale prototype/ demonstrator reactor would be beneficial to investigate passive safety, prior to LFR-AMR licensing and commercial deployment (Figure 18). LFRs are being investigated internationally by national programmes (including in Belgium, Russia and China) and multi-national organisations (EUTRAOM and GIF) that has led to the construction of flow loops in various countries. Vitally important to LFRs, is a need to develop back-up systems to ensure the reactor coolant remains liquid during loss of power or reactor SCRAM incidents. If the core drops below 327°C, it is likely the lead will solidify, encasing the fuel and control rods and potentially damaging the reactor.

Instrumentation and Control

Molten lead is optically and electromagnetically opaque. Negating the use of technologies developed and deployed on existing nuclear systems, (e.g. PWRs and BWRs). To avoid a significant volume of fundamental research it may be possible to build upon the experience gained on SFRs, especially for (ultrasonic) core monitoring given the similar thermal (500°C-550°C) and liquid metal (i.e. opaque) environment. For LFRs, it will also be necessary to identify and understand local fault scenarios as a means of defining monitoring requirements. This will enable the development of a coupled reactor physics and thermal hydraulics model and determination of the specification of a suitable test rig to validate the model. Model validation would enable further studies that would provide information to optimise core geometry and a fuel loading strategy. However, it could take 10+ years and would require construction of test rig infrastructure. Internationally, the VENUS test facility in Belgium could mitigate the need for a domestic facility. However, the VENUS facility is understood to be supporting development of MYRRHA (Multipurpose Hybrid Research Reactor for High-tech Applications), an accelerator driven Lead-Bismuth Eutectic cooled Fast Reactor System funded by the Belgium government and intended for operation from 2027.

The development, testing and qualification of instrumentation and control equipment for LFRs is a long-term activity, given the R&D needs and lack of operational precedence. This would include a significant and multiyear environmental testing programme to confirm compatibility of the equipment in the operating environment. As for all AMRs, an opportunity exists to incorporate digital control systems into a future LFR fleet. Domestic manufacture of cabling and control panels is ongoing for existing operation reactors and thought to be applicable to LFRs. However, supply chain support may be required for sensor (e.g. temperature, neutron flux and flow-rate) and the monitoring needs of LFRs are still to be defined.

Active control measures, control rods and shut down assemblies, are intended for use with LFRs. Due to the high density of the coolant, these are expected to have to be fixed to the base of the reactor. Such a unique location requires demonstration of the concept and technology, especially for deployment in emergencies. The supply of components (i.e. control rods and shut down assemblies and their drive mechanisms) are a domestic supply chain gap due to an established internationally supply chain and are a supply chain gap for all AMRs, irrespective of coolant.

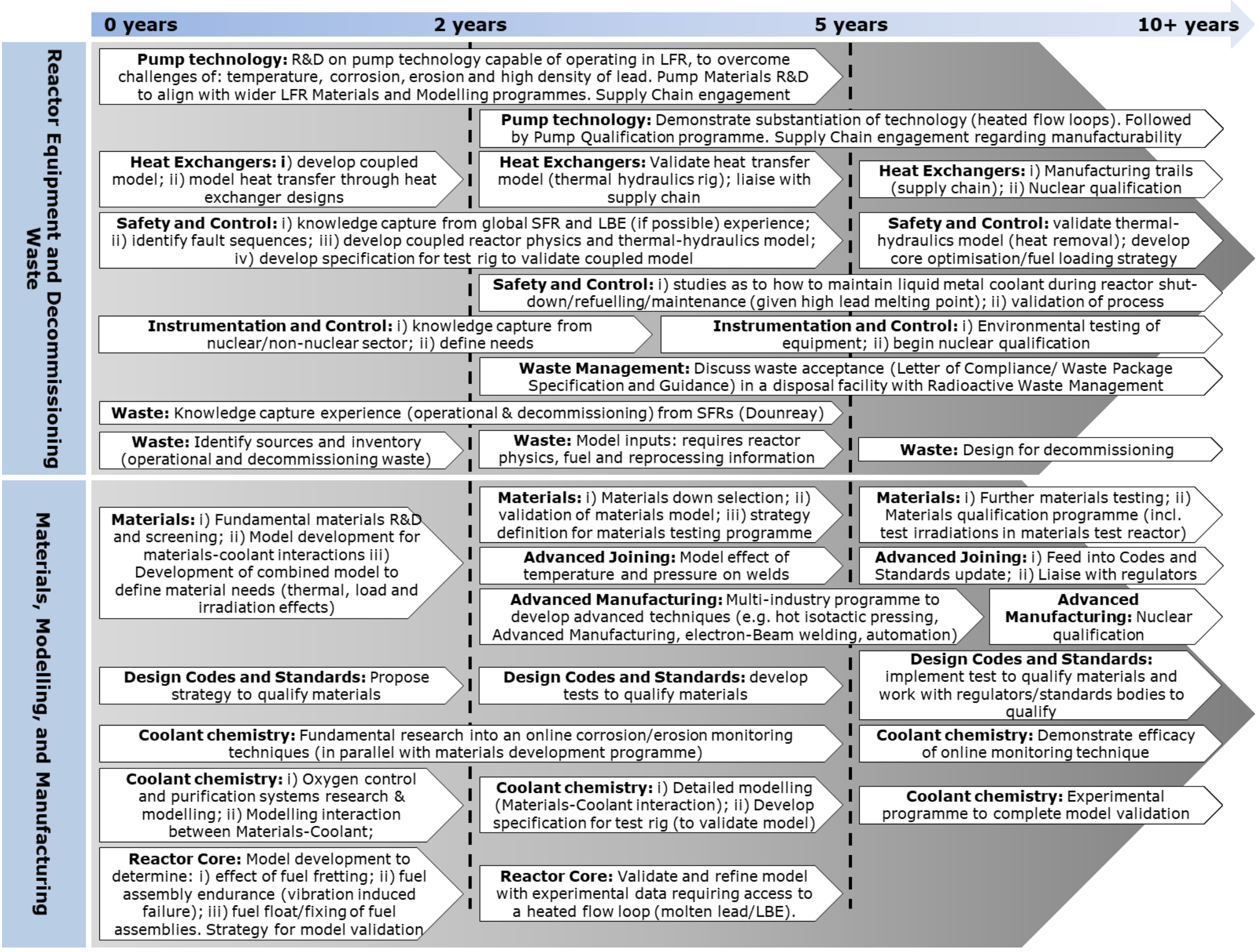

Figure 18: Roadmap of LFR Nuclear Island needs

4.4. LFR Power Generation Discussion

Rankine Cycle

Initial LFR-AMR deployment is anticipated to use a Rankine (steam) cycle for electricity generation. Aside from the heat exchanger technology, (i.e. steam generator, reheater and/or super heater) the steam turbine, condenser and pipework are viewed as standard across the energy sector and will not be discussed. The Russian Navy's Lead-Bismuth Eutectic (LBE) reactors are assumed to have used a Rankine Cycle, limited information exists regarding this.

An LFR-AMR Rankine Cycle R&D programme would have a significant materials selection focus, given the challenges of operating with molten lead on one side and steam on the other. Such a development need would align with the broader materials programme discussed in on page 43. Knowledge capture of domestic and global liquid metal-cooled reactor programmes (i.e. SFRs) could be beneficial and identify the operational challenges that LFRs may also face. Supporting the upskilling of the UK R&D workforce; quickly identifying challenges that steam generators/reheaters will face; and helping to define additional R&D, such as modelling studies to influence steam generator designs. Theoretical studies would need to be validated by experimental trials, on a heated flow loop (a UK facilities gap but internationally available) prior to nuclear qualification of the components.

The outstanding R&D needs and the lack of clarity as to component requirements (design and materials) has resulted in a major UK capability gap being assessed for LFR-AMR steam generators. Clarity as to vendor needs (design and materials) could enable the experienced domestic supply chain to manufacture the necessary heat exchangers – due to the precedent of supplying such designs to many non-nuclear sectors. Should an advanced heat exchanger design (e.g. helical coil) be required for LFRs, then a domestic capability gap, as identified for SFRs, would exist. AS UK companies are not understood to own the necessary production licences or be experienced in their manufacture.

Brayton Cycle

Nitrogen (N_2) or supercritical carbon dioxide (s-CO_2) power conversion cycles offer the potential to improve on the thermal efficiency of LFR-AMRs. They also avoid the potential interaction between molten metal and water/steam. Internationally, countries such as France and Japan are researching Brayton cycles for SFRs and VHTRs respectively. This shows the wide-ranging applicability of the technology. Further R&D is required prior to commercial deployment of the technology. A key outstanding task regards heat exchanger materials and design, which for LFRs is further complicated given the density, vibrational, erosive and corrosive effects of the coolant. Research needs for pipework; turbine system; and heat transfer systems are similar across all AMRs and will not be repeated – see page 34.

The lack of clarity regarding material needs for a lead-to-N_2/s-CO_2 heat exchanger resulted in a major domestic supply chain gap being identified, based on the perceived need for advanced materials. A domestic aerospace supply chain has been taken to imply the UK is currently well placed to produce the necessary turbines and compressors for an N_2 system.

H_2 Production/ Process Heat

The production of H_2 via thermochemical water splitting is an active area of international research. This includes the Copper Chloride process which requires temperatures of circa 550°C – approaching those possible with LFR-AMRs. Should the materials corrosion challenges can be overcome, LFRs may be able to operate at higher outlet temperatures enabling the use of alternative processes such as the Iodine-Sulphur (IS) process which requires temperatures above 950°C. The UK could carry out initial, lab scale R&D in academia or national research centres; large scale trials to demonstrate process robustness and scalability facilities that the UK does not have. Nations such as Canada and Japan that are actively researching "green" H_2 production processes, host many of the necessary facilities.

The supply of process heat using high temperature steam from LFRs shares several R&D needs to those identified for **Rankine Cycle**. If a secondary gas, such as N_2 was to be used, the R&D requirements would align with those necessary to develop a **Brayton Cycle** – heat transfer from the molten lead to gas and how to minimise the potential for "nitriding".

Common to both process heat and hydrogen production applications are the need to overcome licensing and safety challenges associated with siting such a facility near a reactor.

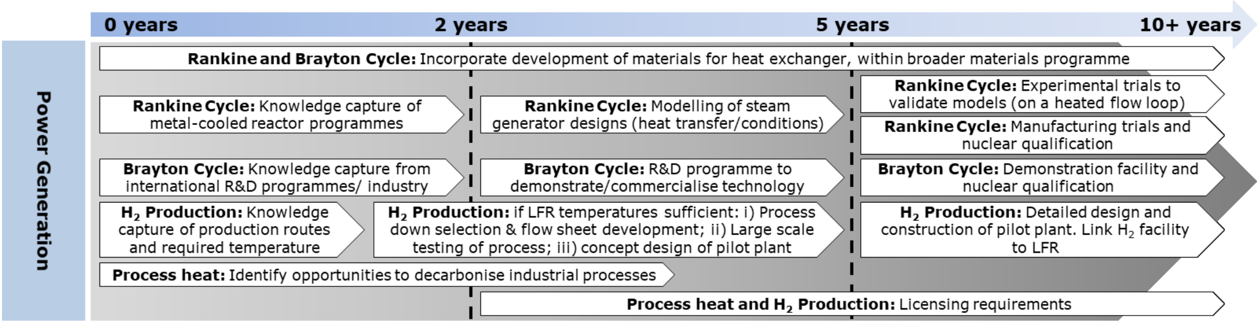

Figure 19: Roadmap of LFR Power Generation needs

4.5. LFR Fuel Cycle Discussion

Nuclear Fuel

Fast reactors are expected to have fissile material (e.g. Pu-239 or U-235) contents approaching 20%-30%. These have been produced in the past, so from a technical perspective it is achievable, but not at existing facilities due to licensing requires and criticality concerns. Existing safety and licensing requirements, for fuel manufacture and fuel transport are also not suitable for fuel transport (LWR fuel <5% enrichment). As such, this is a critical area that will require work to overcome and is applicable to all AMRs.

LFR-AMRs are expected to use a ceramic fuel encased in a metal cladding. Initial fuels are expected to be mixed oxide (MOx), a combination of UO_2 and PuO_2 or uranium mononitride (UN). The experience and knowledge of MOx production for SFRs is applicable to LFR-AMRs. Mononitride fuel research is thought to be most advanced in Russia. Yet, several technical challenges still exist, due to: the pyrophoric nature of powders; processing challenges due to reduced green strength and flow; need for higher sintering temperatures (than oxide); and the generation of radioactive C-14 unless isotopically enriched N-15 is used. Claddings suitable for LFRs require development, testing and nuclear qualification. Fundamental materials development needs are discussed on page 43 and will not be repeated – additional fuel cladding specific activities will be needed to understand the effect of fast neutrons and the fuel pellet on the cladding during reactor operations and transients. Requiring coolant and irradiation testing to support the development of and nuclear qualification of cladding.

Minor Actinide (MA) bearing oxide fuels have previously been manufactured and irradiated, but only in SFRs. The ability to burn MA-bearing fuel, offers a means to reduce the waste from nuclear reactors. MA-bearing fuel links spent fuel reprocessing with fuel fabrication and benefits from the co-location of suitable facilities for both. Prior to undertaking experimental studies into MA-bearing fuels, an economic and technical assessment (including from historic reactor operations) is suggested. Following this, an experimental programme to optimise fuel production is required, ultimately requiring fuel qualification in a suitable fast spectrum materials test reactor. As such it can be viewed as a long-term endeavour with a need for significant R&D to achieve.

LFR-AMR fuel R&D would be best achieved through incorporating into an ongoing or future Fuels Nuclear Innovation Programme. Knowledge capture of historic metal-cooled fast reactor fuels R&D, (both domestic and international) could support UK capability development and identify aspects of a forward experimental programme. The National Nuclear Lab (NNL) has existing infrastructure to handle Pu or U fuels but would require support to develop and commission a fuel line able to develop fast reactor fuels containing Pu. Domestic facilities, such as the Dalton Nuclear Institutes (part of the University of Manchester) are actively involved in nuclear R&D while the Royce Institute (a partnership between the Universities of Cambridge, Imperial College London, Liverpool, Manchester, Leeds, Oxford and Sheffield as well as NNL and UKAEA) focuses on material development.

Existing uranium active facilities at National Nuclear Lab Preston are also focused towards UO_2 research or the development of accident tolerant uranium silicide (U_3Si_2) fuel. The installation and commissioning of inert facilities would be required to enable research into pyrophoric mononitride fuels to be carried out. Experimental programmes to develop potential fuels are multiple year endeavours – especially given the time and availability of suitably qualified and experienced personal (SQEP) to support this. A fuel qualification programme in a materials test reactor (MTR) would also be required for LFR-AMR fuel. The UK has the facilities to undertake pre- and post-irradiation examination of fuels but lacks the necessary infrastructure to undertake an irradiation programme. International thermal spectrum MTRs exist, such as those in Netherlands (Petten), Belgium (BR1 and BR2), France (the future Jules Horowitz Reactor). Russia hosts the only fast spectrum MTR, the BOR-60 which was commissioned in 1969 and is due for closure – the replacement (MBIR) is under construction and the US are developing their own facility (Versatile Test Reactor). However, an international gap may exist if projects are delayed or cancelled.

Reprocessing

As discussed for SFRs (see page 35 for more detail), a waste minimisation strategy and reduction in heat load in a geological disposal facility, through spent fuel reprocessing and MA burning may contribute to the decision to deploy fast reactors. Closed fuel cycles for fast reactors (SFRs) have been globally demonstrated. The commercial reprocessing of thermal spectrum reactor fuel is via the PUREX (Plutonium Uranium Redox EXtraction) process.

For LFR-AMRs, advanced aqueous or pyrochemical reprocessing techniques are being developed on the lab scale. These offer advantages over PUREX, which was developed in the 1950s. Advancement of the fundamental science to better understand and develop these processes could be best achieved through incorporation into an ongoing or future Nuclear Innovation Programme (NIP). Domestic upskilling could be supported through knowledge capture of R&D as part of historic domestic (i.e. UK Fast Reactor Programme and research into molten salts for pyrochemical reprocessing) and international programmes. Vendor specific information (e.g. fuel and core details to determine fission product inventory) would be required to aid the development of a fuel cycle strategy. This would be followed in the longer-term by the development of a process flowsheet and its demonstration on non-active surrogates. Following this, an experimental programme using fuel, initially unirradiated and eventually spent fuel would be carried out. Existing facilities at the National Nuclear Labs Central Lab are suitable for initial development of an advanced aqueous recycle process (i.e. multigram quantities of transuranics) – supported by the UTGARD laboratory at the

University of Lancaster (applied chemistry and engineering data needs); the University of Manchester's Dalton Cumbria Facility and Centre for Radiochemistry Research; and the University of Leeds, (engineering scale centrifugal contactor rig). The MIDAS laboratory (University of Sheffield) could support studies into waste immobilisation. Non-active pyrochemical reprocessing studies could be undertaken at the Pyro-Reprocessing Laboratory at the University of Edinburgh. Largescale trials on surrogates and spent fuel are beyond the scope of all current facilities and support would be required to develop these.

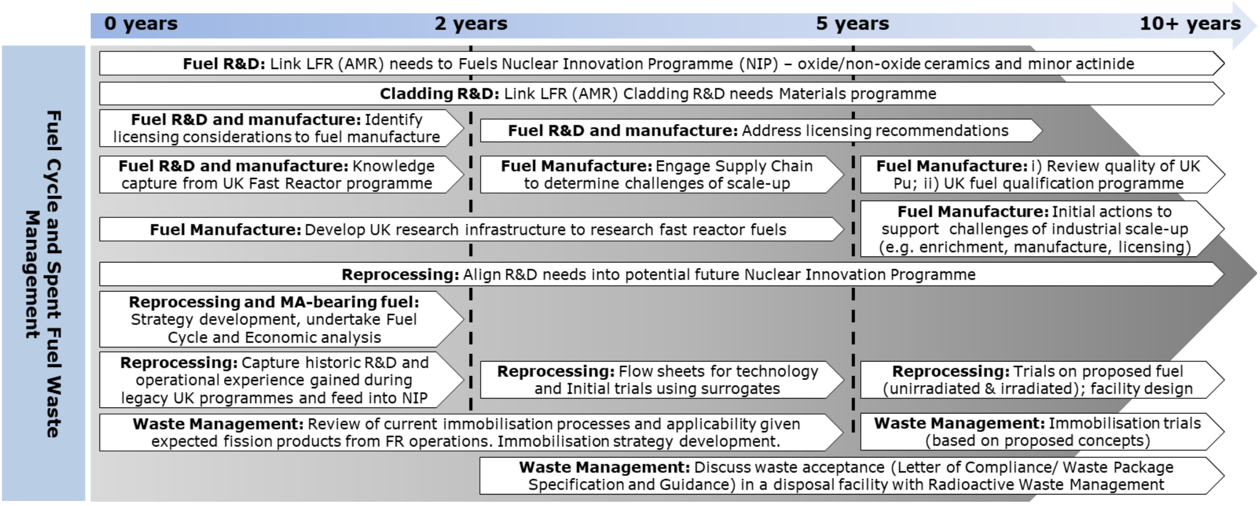

Figure 20: Roadmap of LFR Fuel Cycle and Spent Fuel Waste Management needs

4.6. Lead-cooled Fast Reactor Technology and Supply Chain Summary

To date, no Lead-cooled Fast Reactor (LFR) has operated. Lead-bismuth eutectic (LBE) cooled reactors have been operated by the Russia navy, yet these were epithermal neutron spectrum reactors. Historically, Russia was the main proponent of LFRs. More recently, there is now global interest in LFRs including the hosting of multiple lead test loops and a zero-power reactor in China. Such R&D activities has led to this assessment concluding that LFRs have an international TRL of 4 (Figure 21). This is because multiple R&D challenges still exist that could cause a long delay to, or potentially inhibit, commercial deployment due. Topics for further R&D include:

- **Modelling and Simulation:** all AMRs require support for licensing and experimental programme validation. Exact requirements are vendor specific.
- **Coolant:** an understanding of fundamental coolant chemistry is necessary to support other R&D activities.
- **Materials:** suitable for 60-year operating lives in LFRs need to be developed, tested and qualified. Especially given the corrosive and erosion properties of the coolant.
- **Reactor equipment:** such as pumps and heat exchangers require developing and qualifying, due to the density of the coolant and lack of operational precedent.

- **Instrumentation and Control:** LFR operational conditions and coolant properties (optically and electromagnetically opaque) are challenges for core monitoring - requiring development and demonstration of suitable equipment.
- **Fuel Cycle and Waste Management:** R&D is required to identify process improvements in fuel manufacture, fuel qualification and into Minor Actinide (MA) bearing fuels (for waste minimisation). The development and demonstration of advanced processes for reprocessing of spent nuclear fuel are also required (to close the fuel cycle) reducing the volume of operational waste.
- **Waste Management:** containers for the disposal of reactor coolant and vessel materials will be unique to LFRs and require developing and qualifying.

A gap in the Nuclear Codes and Design Standards exists for materials necessary for LFRs. Requiring the development and implementation of new codes and standards prior to commercial LFR deployment. Due to reactor neutronics, fast reactors require significantly higher fissile material contents in fuels than existing commercial reactors and are above those allowed by existing regulations for both fuel manufacture and transportation in many countries. The licensing of a suitable spent fuel reprocessing facility, at or close to a fuel manufacturing facility is also required to enable "closure" of the fuel cycle and realise the potential waste minimisation benefits of fast reactors. If LFRs are intended to support the decarbonisation of industrial processes, it will require their siting close to heavy industrial areas. In the UK, nuclear facilities are typically located away from the industrial areas that could benefit most from decarbonisation. As such, a significant licensing gap would need to be overcome to enable this that is applicable to all AMRs.

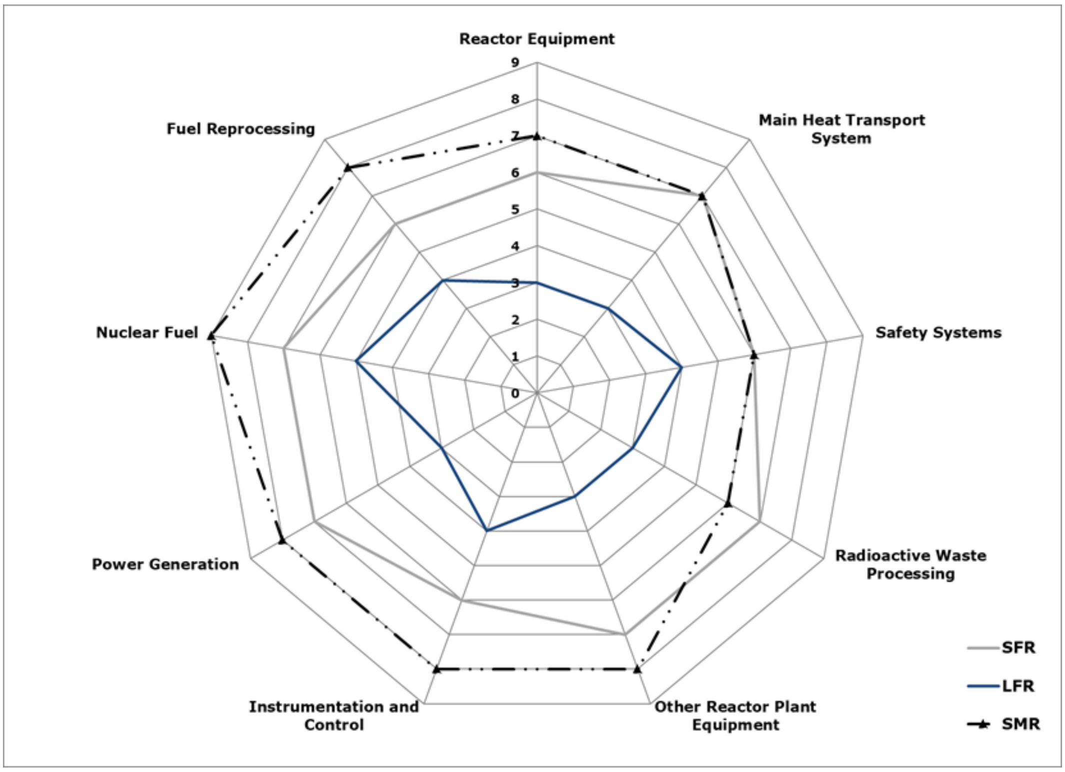

Figure 21: Comparison of LFR, SFR and SMR TRLs

During the UK Fast Reactor Programme, the UK nuclear supply chain had the capability and capacity to support advanced reactor development; yet this is no longer viewed to be the case. In addition to the time since the UK last constructed a new nuclear power station or fast reactor, the relative immaturity of many LFR-AMR concepts results in a lack of clear vendor requirements. This lack of clarity is hindering supply chain development. To address the gaps, support and development of targeted areas of the UK supply chain are required. This could include the implementation of novel manufacturing technologies. This is not unique to LFRs, with support required for all AMRs.

The UK nuclear supply chain is viewed as having the current capacity and capability (Blue) to produce approx. 7% of the components assessed by this study and deemed necessary for a future LFR-AMR (Figure 22). This is predominantly limited to **electrical panels**, **cabling**, **insulation**, and **emergency generators**. Targeted development to advance existing capability could enable UK manufacture of ~59% of the components assessed in this study. To achieve this would require minor (Green) or significant development (Amber) in either supply chain capability or facilities. The UK supply chain is viewed as having either a capability or capacity gap (Red) for the manufacture of circa 34% of the components assessed in this study. This is partly due to the existence of international supply chains for **control** and **shutdown rods**, and their relevant **drive mechanisms**. Limited domestic experience for the manufacture of the necessary coated or advanced **materials** necessary for **reactor vessels**, **manifolds**, **piping**, **pumps**, **valves**, **waste containers**, **heat exchangers**, **sensors**, **reactor control systems** and **inspection equipment** due to the need for advanced materials or coated materials that are novel to nuclear.

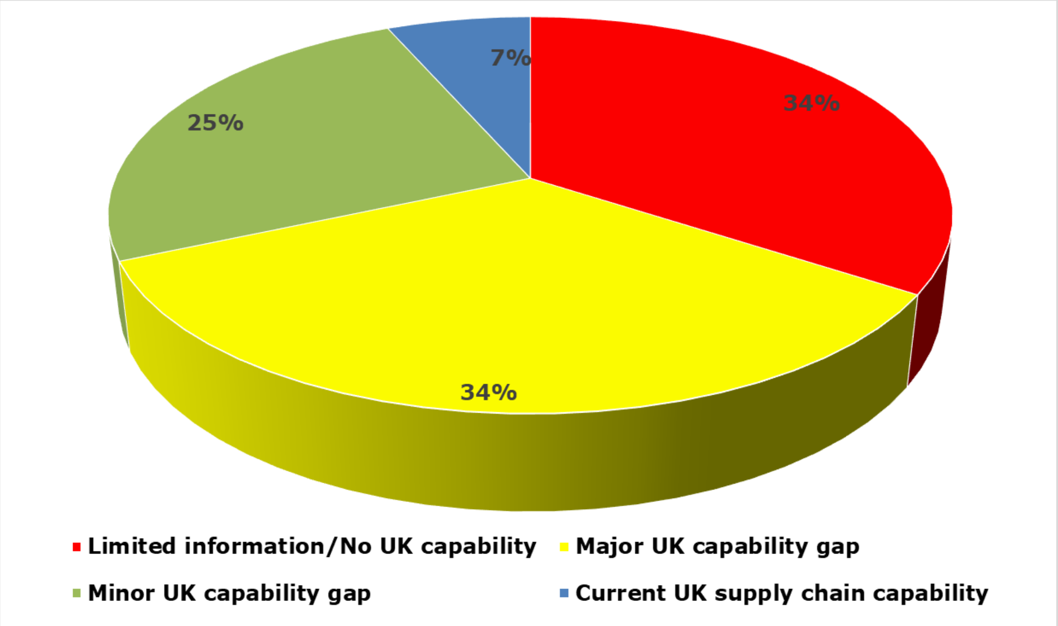

Figure 22: Summary of UK supply chain capability for LFRs

5. Molten Salt-fuelled Reactors (MSRs): summary of current state and development needs

5.1. Molten Salt-fuelled Reactors Key Points

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** studies require 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 exists 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.

5.2. Overview of Molten Salt-fuelled Reactors (MSRs)

Due to the similarities between molten salt-fuelled thermal and fast spectrum reactors (MSThR and MSFR) the development needs covered apply to both. Where development needs are specific to a reactor type, these differences are highlighted. For the Technology Readiness Level (TRL) assessment, the systems were assessed individually.

MSRs are expected to operate with high coolant outlet temperatures (up to 700°C), at atmospheric pressures. Such operating temperatures offer the potential for cogeneration (heat and power) or thermochemical hydrogen production. In contrast to all the other AMRs considered, MSRs do not use solid fuels. Instead the fissile material is dissolved in the reactor coolant as a halide salt (e.g. UF_4). Uranium, plutonium or thorium fuel cycles are all theoretically possible with MSRs. Thermal and fast spectrum reactors are notionally able to operate in a breeder mode, producing more fuel than they consume. MSRs are expected to require continuous online reprocessing to maintain reactor efficiency by removing fission products. As the primary reactor coolant contains fuel, the entire primary reactor circuit, including: pumps, intermediate heat exchanger and reprocessing facility will need to be heavily shielded and/or- contained with a hot cell, due to the high radioactivity.

Power generation requires a minimum of a second and sometimes a third, clean salt loop prior to the power conversion cycle (Figure 23) [1]. Initial MSR-AMR deployment is expected to use a steam (Rankine) cycle as this technology has already been demonstrated in the concentrated solar sector. In the longer-term, a Brayton power generation cycle could be coupled to an MSR-AMR to improve the system thermal efficiency.

The fuel salt circulates through channels in the core of both MSThR (thermal) and the MSFR (fast). A key difference is that thermal spectrum reactors require a core moderator (graphite or zirconium hydride). To avoid the interaction of fuel salt with core moderator to potentially increase the life of the core moderator some vendor designs have the channels in the core clad in metal.

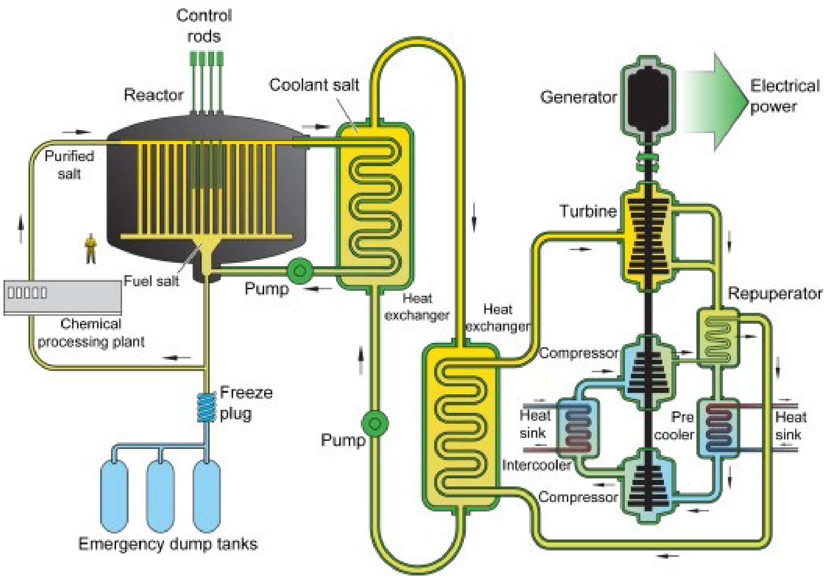

Figure 23: Generic Gen. IV Molten Salt-fuelled Reactor

Alternative designs of molten salt reactors have the fuel immobilised in either fuel pins or use TRISO fuel (see HTGR or VHTR) in-lieu of a liquid fuel. Both options offer the potential to remove the need for online reprocessing, lessening the shielding requirements and could reduce the complexity and size of the AMR by avoiding a secondary or tertiary salt circuit.

5.3. MSR Nuclear Island Discussion

Reactor Vessel Equipment

MSRs typically have a halide fuel salt, containing fissile material (U-233, U-235 or Pu-239) that is dissolved in the primary coolant and circulates throughout the reactor. As such, the reactor vessel has a dual purpose of providing containment for the coolant and acting as the fuel cladding. The reactor vessel is at the coolant inlet temperature, with the "cooled" coolant (at ~500°C) in contact with the vessel structure. To avoid molten halide salt induced materials corrosion, metallic components of the Molten Salt Reactor Experiment (MSRE) were made from a nickel-based alloy (Hastelloy-N). Subsequent environmental testing at temperatures up to 700°C and lasting for approx. 9 years resulted in modification of Hastelloy-N to avoid tellurium induced corrosion and irradiation induced embrittlement. Similar nickel-based alloys are proposed for the reactor vessel, primary circuit pipework (including coolant inlet manifolds) and intermediate heat exchangers for both thermal and fast spectrum molten salt reactors (MSThRs and MSFRs) – including AMR variants. This is due to the operational precedent and historic R&D which has been further augmented by recent studies. Advanced materials such as ceramics or composites (e.g. SiC or SiC fibres in a SiC matrix) have also been proposed for MSRs, as linings or coatings for pipes, reactor core structures and pumps.

Down selection of reactor materials and designs requires confirmation of the fuel and coolant salts because of the effects they have on reactor operations (e.g. materials corrosion, thermal conductivity, reactor physics, thermal hydraulics). Supporting studies will be required to capture the historic R&D and identify information gaps. As such, a short-term materials R&D programme would be expected to focus upon compiling existing data and development of a combined system model (thermal hydraulics, core physics, reprocessing and salt corrosion) to aid in determining the required material properties, once the fuel cycle and salt has been confirmed. In the longer term, materials development, testing and down selection would follow and require access to a heated flow loop, containing the relevant molten salt and suitable surrogates, to validate the simulations. Materials qualification would require an irradiation programme in a Materials Test Reactor (MTR) with a molten salt coolant loop. Currently this is a global facilities gap – Russia is constructing the MBIR with lead, lead-bismuth, sodium and gas coolants loops; and the US is designing the Versatile Test Reactor (VTR) that would have the capability to run with sodium, lead, lead-bismuth, gas and molten salt coolant loops.

A gap in nuclear design codes and standards exist for MSRs. Current material grades that are nuclear qualified materials are not compatible with the conditions found in MSRs; requiring code revision prior to MSR-AMR deployment. Such an update is unlikely to be a UK only endeavour, with opportunities to partner with nations (e.g. US for ASME and France for AFCEN), international bodies (GIF, EURATOM and IAEA) and private companies (technology vendors). Partnership with nations, such as the US (Oak Ridge National Lab) and other active members of the GIF, including the Czech Republic may allow access to molten salt test loops. In addition, the Concentrated Solar Power (CSP) sector uses molten salts as the heat transfer medium and may enable use of existing infrastructure (such as the molten salt test loop at Sandia National Lab) to aid in the codes and standards update. A review of current nuclear codes and standards to identify gaps that could hinder Generation IV reactor deployment, including molten salt-fuelled, is included as part of an ongoing domestic Nuclear Innovation Programme. Such an update would first require the development of a strategy to qualify new materials. Following this, tests would need to be developed that would be used to qualify materials. This would require multiple facilities, including: flow/thermal hydraulic loops and access to a zero-power research reactor – ideally one able to generate both thermal and fast spectrum neutrons; all infrastructure the UK lacks and has limited suitably qualified and experienced personal (SQEP) to operate. Coolant flow loops exist globally, but an international facility gap exists for a zero-power MSR.

The domestic nuclear supply chain is not understood to have experience in the production of large components, such are reactor vessels from nickel-based alloys. Existing domestic facilities are viewed as insufficient to meet AMR reactor vessel needs. In addition, Hastelloy grades are currently polished by hand to enhance the corrosion resistance properties of the materials. This requires the development of automated finishing processes for the UK to be able to compete internationally. In addition, support to develop automated manufacturing and joining of components would be especially beneficial for MSRs and the wider nuclear manufacturing industry. Globally, there are a limited number of manufacturers of advanced alloys, which includes nickel-based materials, exist. As such they may have little-to-no capacity to provide advanced alloys to enable AMR deployment in the short-term due to existing contractual commitments. To overcome this, early engagement of AMR vendors and the nuclear supply chain, to identify expected material needs, (i.e. grades, dimensions and volumes) would be beneficial. Industries such as the oil and gas, aerospace, petrochemical and electroplating sectors offer the potential for technology transfer, as they have developed processes to overcome challenges associated with manufacturing, joining and inspecting of nickel-based alloys, particularly Inconel's.

Thermal spectrum MSRs require a core moderator, this is expected to be graphite or zirconium hydride. This study has identified a single international source of nuclear graphite (IG110) from Japan and thus, a domestic manufacturing gap. Domestic companies such as Anglo Great Lakes Corporation Ltd. and Union Carbide have historically produced nuclear graphite for the UK's domestic gas-cooled reactor fleets. Sector support, initially to facility the discussion between technology vendors and domestic suppliers of graphite as to the suitability of existing grades (such as Pile Grade A, IM1-24 or GCMB) for MSR-AMRs could avoid the need to develop and qualify a new domestic grade. This may then require the development of infrastructure to enable manufacture; given the capability and assumed capacity gap. Should a novel domestic grade of graphite be preferred, its development could take more than 10 years. Requiring environmental testing to confirm compatibility of the grade with the coolant and fuel salts. This would culminate in a multiyear qualification programme in a Materials Test Reactor (MTR); infrastructure the UK doesn't host and if a molten salt loop is required – is not currently available globally. The pre- and post-irradiation examination could be undertaken in domestic facilities. This of course requires clarity as to the coolant and fuel first. A similar materials development and qualification programme, as discussed for graphite, is required for zirconium hydride.

Main Heat Transport

As the fuel is dissolved in the primary reactor circuit, MSRs will require at least one additional molten salt loop. This is to minimise the potential for activation of the power generation loop. Heat exchangers for the transfer of thermal power between two molten salt loops have yet to be demonstrated. Theoretical and experimental studies are required to overcome this. Simulations will require the development of a suitable thermal hydraulics model – that considers the effects of salt composition on heat transfer. Experimental validation will require access to a thermal hydraulic test rig; infrastructure not currently present in the UK and internationally limited. Molten salt test loops exist at US National Labs for concentrated solar power (CSP) research. The design of MSRs heat exchangers is ongoing internationally, using information from metal-cooled reactor research.

Heat exchangers (HXs), seals, valves and secondary circuit pipework are also expected to be made from nickel-based alloys or have ceramic coatings to overcome materials corrosion induced by contact with the molten salt. As such the material R&D needs are akin to those discussed on page 55 and will not be repeated. Domestic manufacture and supply of heat exchangers is understood to be ongoing to multiple non-nuclear industries. The UK previously manufacture heat exchangers for SFRs, as part of the UK Fast Reactor Programme. Heat exchanger designs, dimensions and to some extent materials (though expected to be nickel-based alloy) are not clear to the supply chain, with the supply chain unaware of the potential opportunities with MSR-AMRs. This requires engagement between technology vendors and the supply chain to enable an accurate assessment of domestic manufacturing ability. Valves and seals in contact with molten salts will also face the similar corrosion challenges as the reactor vessel and heat exchangers. The domestic nuclear supply chain is viewed as having little experience of their production. Non-nuclear sectors, such as the aerospace and the oil and gas sectors, utilise Ni- or Ni-Cr based alloys (e.g. Inconel's) and may provide an opportunity for technology transfer.

Nuclear qualified mechanical pumps have been designed for PWRs and are limited to approx. 260°C. Pumping technology developed and deployed in the concentrated solar power sector (CSP) for solar salts operates with coolant temperatures are approx. 300°C (inlet) to 500°C (outlet). CSP requires the pumping of molten salts from storage tanks at the base of towers to the top (to be heated). However, MSRs are expected to have coolant inlet temperatures of 400-500°C, above those used for CSP applications and of existing nuclear qualified pumps. To overcome this technological gap, R&D is required. An initial research programme could look to capture historic and ongoing pumping technology research for molten salts and liquid metal-cooled reactors. This would be followed by theoretical and experimental studies to confirm compatibility of pumps and materials to the operational environment (e.g. molten salt, fuel salt and temperature). Initially trials would confirm compatibility of the coolant salt up to operating temperatures. This could be followed by trials with surrogates in place of the fissile material and fission products prior to active trials and ultimately nuclear qualification. A long-term environmental testing programme would require suitable infrastructure (e.g. a heated molten salt flow loop) that could in the long-term handle fissile material (i.e. it would need to be located upon a nuclear licensed site). It is important to note that this would require confirmation of the fuel and coolant salt. Salt selection will also ultimately impact upon the choice of materials for pump construction and affecting the manufacturing ability of the domestic supply chain.

As the fuel will be dissolved within the circulating primary coolant, the entire primary circuit will require shielding. This could require lead-based components around the primary circuit or involve constructing the entire reactor and reprocessing facility within a shielded "hot-cell". The domestic supply chain is experienced in the supply of shielding or hot cells. However, a need for vendor clarity as to the shielding strategy and the predicted dose, which will depend of the fuel, neutron spectrum and core physics, is required.

Waste

An AMR fleet of molten salt-fuelled thermal neutron spectrum reactors (MSThRs) could increase the UK's already significant volume of graphite waste, (from the gas-cooled reactor fleets). Global R&D programmes have investigated the properties of graphite waste; with a need for follow-on projects to identify decommissioning activities and strategies to reduce future volumes of graphite waste. One outcome was confirmation of the need to produce nuclear graphite in a process that results in it being free from both chlorine and nitrogen, which form long-lived radioisotopes (such as carbon-14) during reactor operation.

R&D, to understand if High Level Waste (HLW) arising from MSR operations can be immobilised using techniques already deployed or under development is required – given the different waste streams from MSRs compared to gas-, water- and sodium-cooled reactors. The MIDAS Laboratory at the University of Sheffield was set up to develop capabilities for molten salt waste research and can support these activities. Existing facilities for waste immobilisation at Sellafield and Dounreay may also be able to support future MSR-AMR R&D or active demonstration. It is important to note, that continuation of waste management and decommissioning activities is recommended to maintain domestic skills, facilities and suitably qualified experienced personal (SQEP).

Salt choice may also influence the volume and classification of waste generated by MSRs. Studies to minimise the volume of salt waste first require clarity to as to the coolant salt. Fluoride salts do not result in long-lived radioisotopes. AMRs using chloride salts may result in the generation of significant amounts of the long-lived (half-life of 380,000 years) radioisotope Chlorine-36 (produced from neutron capture of Cl-35). An investigation into the potential volumes of Cl-36 that could be generated and the practicalities (including economics) of enriching the salt in Cl-37 would be beneficial.

Safety Systems

Molten salt Reactors (MSRs) are designed to have several passive safety features, including: a negative temperature coefficient of reactivity (increasing temperature reduces reactivity); MSRs are not pressurised; core voiding through coolant boiling is difficult given the very high boiling points (>1400°C); and reactor (fuel) meltdowns are not possible as the fuel is already molten. The negative temperature of reactivity was demonstrated in the 1960s; focused R&D to support validation of passive safety features are required for licensing. From a domestic perspective, the Office for Nuclear Regulation (ONR) will expect the demonstration of two independent shutdown mechanisms to take the reactor sub-critical. Removal of decay heat is purported to be through natural circulation. However, it is important to ensure cooling does not reduce the coolant below its freezing point, otherwise coolant heating will be required. Active safety features of molten salts, such as the ability to drain the primary coolant from the reactor, through a freeze plug, in the event of reactor damage or loss of power requires further R&D to substantiate. R&D to address and validate the safety features are being undertaken as part of pan-European studies through EURATOM (e.g. EVOL and SAMOFAR as part of Horizon 202), the Generation IV International Forum and national programmes in France, Russia and the US. The licensing of MSR-AMRs will be unique among AMRs, due to the liquid fuel. A gap exists in the licensing process, as well as nuclear codes and standards for liquid fuelled reactors, especially given the need for online reprocessing.

Instrumentation & Control

Molten salts are optically transparent and published studies have indicated that technology transfer of instrumentation from other sectors may be applicable for use on MSRs. Yet, the monitoring needs of MSRs require defining and a detailed assessment as to the potential for technology transfer carried out. All systems will need testing to confirm suitability with the operational conditions – as for materials. Key needs and opportunity areas for MSR-AMRs are the development of online corrosion monitoring processes for key reactor components and digital control systems.

A domestic supply chain gap has been identified for the manufacture of control rods and shut down assemblies as well as their respective drive mechanisms. However, it should be noted that control rods and drive mechanisms are required across all reactors, irrespective of coolant.

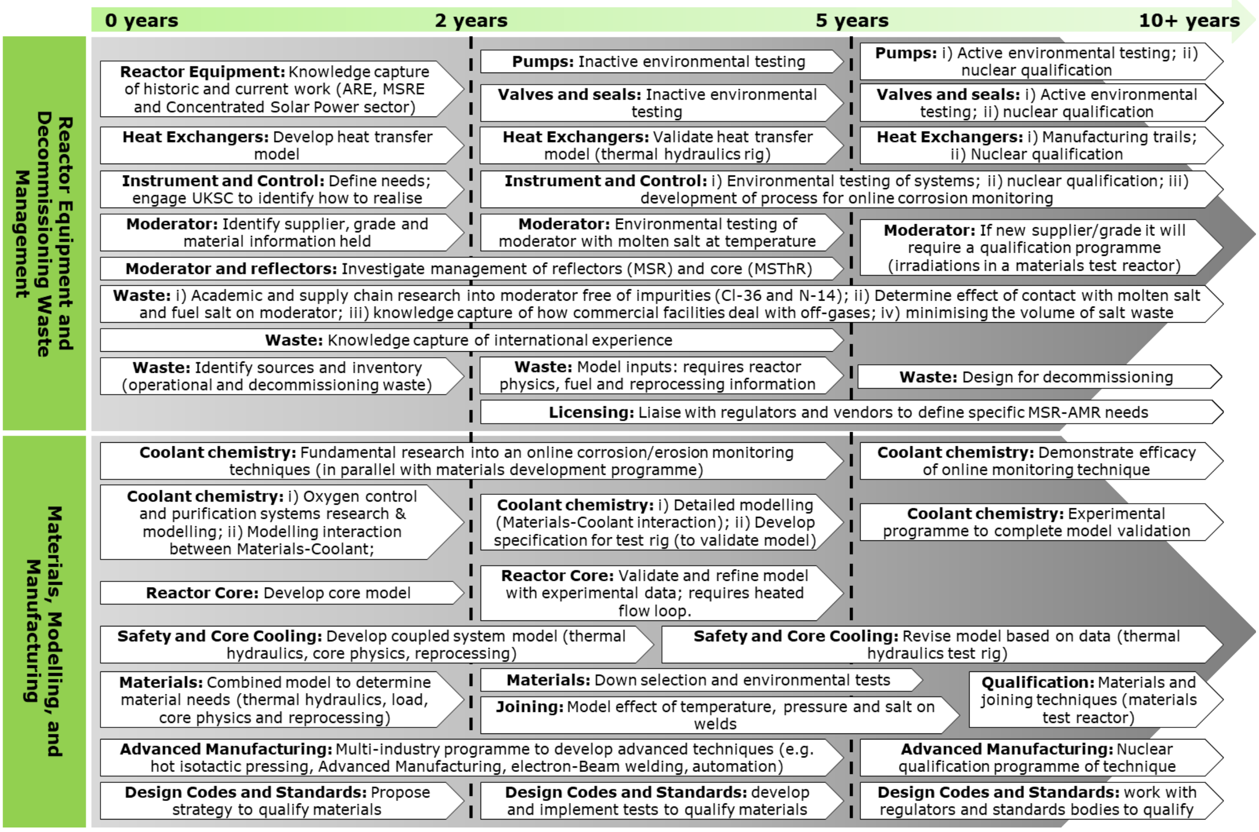

Figure 24: Roadmap of MSR Nuclear Island needs

5.4. MSR Power Generation Discussion

Rankine Cycle

The Aircraft Reactor Experiment (ARE) and Molten Salt Reactor Experiments (MSRE) did not generate power, being exclusively research reactors. The Concentrated Solar Power (CSP) sector has demonstrated power generation from molten solar salts. This precedent provides a proof of concept and CSP systems are like the secondary/tertiary loop of an MSR. However, solar salts (typically mixed nitrates) operate up to a maximum temperature of 565°C – due to onset of thermal decomposition above 600°C. Heat transfer R&D is required to transfer the precedent from the CSP sector to MSRs – enabling them to operate at the temperatures of approx. 700°C. The key R&D need is the heat exchanger (steam generator, superheater or reheater) as the remaining components in a power generation system (pipework, turbines, pumps etc.) are assumed to be standard across the energy sector. Heat exchanger development would initially focus on need definition and be reliant on the development of suitable MSR materials. Experimental testing would be required to support qualification. The UK lacks the necessary thermal hydraulic facilities necessary for equipment testing. Partnering with a likeminded nation, may enable access to suitable facilities that exist globally. Domestic supply of heat exchangers outside of the nuclear sector means the UK supply chain is well positioned once clarity as to material needs and design has been received from vendors.

Brayton Cycle

Brayton power conversion cycles, using nitrogen (N_2) or supercritical carbon dioxide (s-CO_2), have been proposed in the Concentrated Solar Power (CSP) sector and are actively being researched. Internationally, Brayton cycles are at the experimental stage, but nations such as France and Japan are conducting R&D for their use in SFRs and VHTRs respectively. Leveraging this research is beneficial for MSRs, with the potential synergies in R&D needs. A key need unique to MSRs is the demonstration of heat transfer from the molten salt to the gas/supercritical fluid. Additional challenges that require overcoming prior to Brayton Cycle deployment are applicable to all AMRs, large reactors and non-nuclear sectors and are discussed for VHTRs on page 23 and SFRs on page 34.

A capability gap is present for domestic manufacture of Brayton Cycle heat exchangers (both molten salt to N_2 and s-CO_2), engagement of the supply chain to discuss expected material and design needs could reduce this and would identify if existing infrastructure is suitable. Domestic supply chains that support the aerospace industry are viewed as being well placed to compete globally for the manufacture of produce turbines and compressors - once clarity as to the operating requirements (e.g. pressure, temperature and design) has been received.

H_2 Production/ Process Heat

The high outlet temperatures of MSRs (~700°C) offer the potential for thermochemical water splitting to produce H_2. This includes the Copper Chloride process that is under development in Canada and requires temperatures of circa 550°C – accessible with MSRs. Significant R&D is still required to develop the H_2 production process, test its resilience on scale and design a plant, prior to commercial deployment. Initial R&D to identify potential process and understand their benefits could be undertaken at domestic universities or research centres. Following this, large scale trials would require the construction of facilities to investigate the robustness and scalability of the process, that do not exist in the UK and are globally limited.

The supply of process heat from MSRs requires R&D to support. The supply of steam has similar needs to those identified for the **Rankine Cycle**. If a secondary gas, such as N_2 was to be used, the R&D requirements would align with those discussed in **Brayton Cycle**. Supply of process heat through the transfer of molten salt, in a tertiary loop, would face similar challenges to those identified and discussed on page 55.

Common to both H_2 production and process heat applications are the additional licensing and safety challenges associated with siting such a facility close to a reactor (Figure 25).

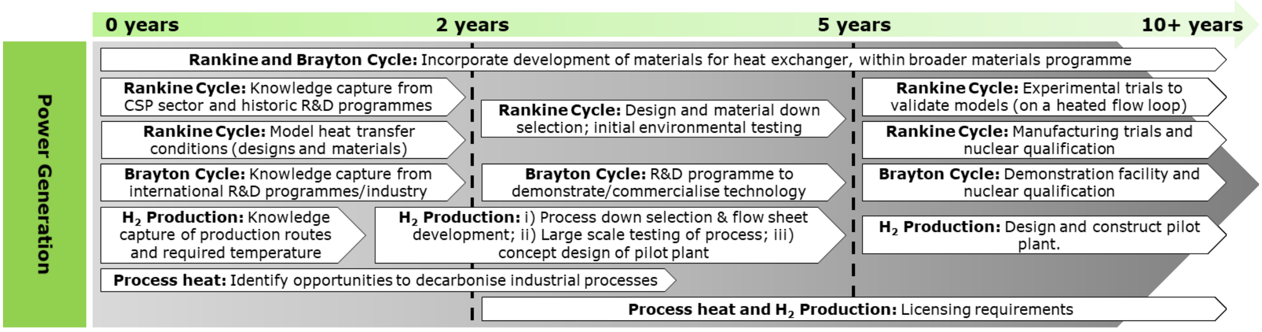

Figure 25: Roadmap of MSR Power Generation needs

5.5. MSR Fuel Cycle Discussion

Nuclear Fuel

Molten salt reactors (MSRs) unlike the other AMR concepts discussed in this study are expected to use liquid fuel salts. This is typically a halide salt, containing fissile material (U-233, U-235 or Pu-239) dissolved in the primary coolant. As such, the reactor vessel is effectively the fuel cladding. MSR designs where the fuel is immobilised from the primary coolant have also been proposed but are not considered in this study.

Two MSRs operated in the 1960s and both used fluoride salts (due to the single stable F-19 isotope) for the coolant. The first, the Aircraft Reactor Experiment (ARE) used NaF-ZrF_4 as the salt. While the Molten Salt Reactor Experiment (MSRE) built on this initial learning and utilised LiF-BeF_2 with 5% ZrF_4 (oxygen scavenger); isotopic enrichment of lithium to remove the Li-6 isotope is required for efficient reactor operation due to the high neutron capture cross-section. The ARE and MSRE demonstrated that in principle a Th-U and U-Pu fuel cycle were both possible. In the 1970s, the UK developed a design for a liquid chloride fuelled fast reactor, but it was never constructed. Recent theoretical studies indicate that thorium breeding, (production of more fuel than is used by the reactor) is possible in the thermal neutron spectrum and could minimise the volume of minor actinide (MA) production due to the greater number of neutron captures required to transmute Th-232, compared to U-238. Spent Light Water Reactor (LWR) fuel has also been proposed as fuel for MSRs.

Active facilities able to manufacture and understand the fundamental fuel salt chemistry, including the interaction between fuel salt and materials are required. These do not exist in the UK and are also viewed as an international facilities gap. The experimental data from such a facility could validate models and act as a test bed to refine fuel salt manufacture and reprocessing techniques. In addition, given limited global active fuel salt facilities it could acting as a UK contribution to R&D programmes with likeminded nations, international bodies (IAEA or GIF) and vendors. Once UK infrastructure is complete, an initial experimental programme could be undertaken. Currently the UK has limited suitably qualified experienced personal (SQEP) to support investment of MSR fuel. To support UK upskilling, knowledge capture of domestic and international R&D programmes could be carried out. An experimental programme would as a priority look to down select a fuel salt, due to the impact on reactor materials, equipment and reprocessing (Figure 26). Over the longer term, this would lead to the development of candidate fuel, which would then need to be qualified in a suitable Test Reactor (TR). An irradiation programme is a multi-year commitment and would need to be undertaken for all MSR fuel options across both thermal and fast spectrum reactors prior to MSR-AMR deployment. The UK lacks the infrastructure to undertake an irradiation programme. However, international facilities, such as those hosted by the Netherlands (Petten), Belgium (BR1 and BR2), France (Jules Horowitz Reactor) or US National Labs could be used to undertake the thermal spectrum testing. A global facility gap exists for a fast neutron source with a molten salt loop. Prior to a fuel irradiation programme, it would be important to engage the supply chain to understand the challenges of producing MSR fuel for commercial deployment and undertaken the necessary actions to overcome this.

Reprocessing

Molten Salt Reactors (MSRs) assessed as part of this study, are expected to require online reprocessing of the primary fuel salt to remove fission products and enable efficient reactor operations. This was not a feature of the MSRs that operated and has yet to be demonstrated and is required prior to initial MSR-AMR deployment. A two-step process is proposed: i) gas bubbling to remove insoluble fission products; and ii) pyrochemical processing to remove soluble fission products leaving fertile and fissile material in the salt. Additional challenges associated with MSR reprocessing include the lack of spent fuel/fission product cooling, which will have dose implications that will have to be considered during facility design and operation. Russia are proposing a pyrochemical reprocessing strategy for LFRs, and thus have experience in this area. While the US has historic knowledge gained from the thermal Molten Salt Breeder Reactor (MSBR) programme, the never constructed follow-on to the MSRE.

UK facilities and SQEP gaps identified for nuclear fuels are the same for reprocessing. A suitably designed facility could in principle support research into both fuel manufacture and reprocessing. Edinburgh University are investigating MSR reprocessing; however, additional domestic capability is necessary to support an ambitious MSR-AMR R&D programme. Domestic upskilling could be achieved through knowledge capture of domestic programmes, both historic (chloride fuelled fast reactor from the 1970s) and current (off-gas capture and treatment from commercial reprocessing at Sellafield) and international R&D. Development of a reprocessing flowsheet first requires clarity as to the fuel salt and fuel cycle. Existing facilities at the University of Edinburgh (Pyro-Reprocessing Laboratory) could support non-active flowsheet development. The MIDAS Laboratory at the University of Sheffield could support research into the immobilisation of waste arising from reprocessing using simulants. However, flowsheet validation through an experimental programme would require a suitable facility able to handle active substrates.

Licensing of a combined MSR and reprocessing facility is not without its own challenges. The unique nature of MSR fuel (liquid) is in stark contrast to the solid fuelled gas-, water- or metal-cooled reactors of the past. Existing regulations, such as those relating to core meltdowns are no longer valid (as the core is already molten). Requiring new regulations to be developed. Regulators will also need to be upskilled, and vendors clear as to the claims and justification of passive features. MSRs with online reprocessing will need to address potential challenges associated with fissile material accountancy (i.e. Nuclear Safeguarding and Proliferation). Existing methods employed for solid fuelled reactors and aqueous reprocessing, where fissile material is separated from spent fuel, are not applicable for MSRs. As such, online reprocessing provides a potential nuclear proliferation risk. This is unlikely to be an insurmountable challenge prior to domestic deployment, as the UK is a nuclear power, signature of the UN Non-Proliferation Treaty, abides by the IAEA Safeguarding regulations and has the largest civil stockpile of separated plutonium. However, potential markets for export of such technology could be limited.

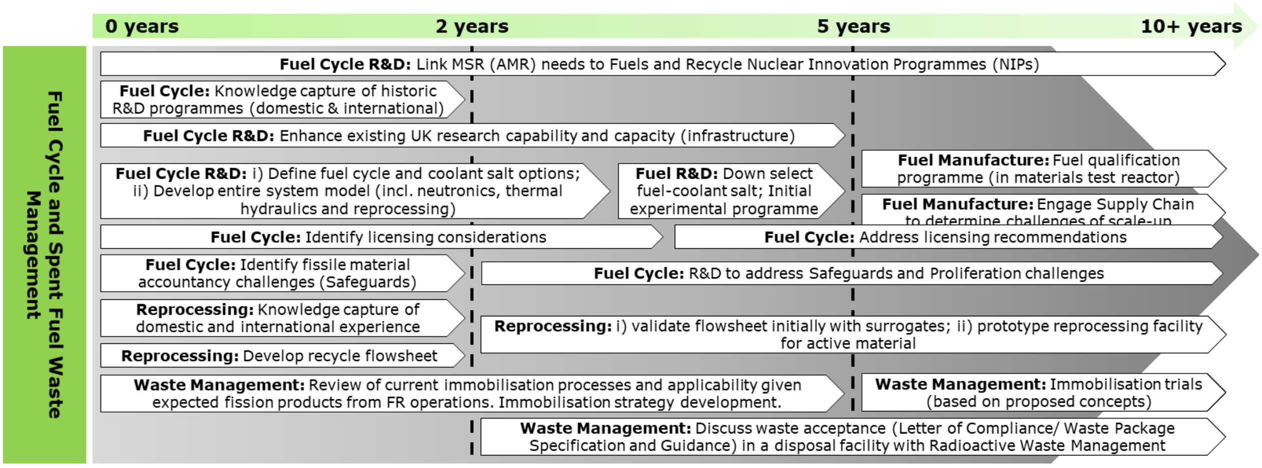

Figure 26: Roadmap of MSR Fuel Cycle and Spent Fuel Waste Management needs

5.6. Molten Salt-fuelled Reactor Technology and Supply Chain Summary

Two Molten-Salt fuelled Reactors (MSRs) previously operated in the US, the most recent, the Molten Salt Reactor Experiment (MSRE), shut down in the 1960s. Renewed interest in MSRs has resulted in R&D being carried out worldwide, with multiple test loops building on the experience from the solar sector. The TRL assessment of (Figure 27) MSRs concluded that thermal spectrum molten salt reactors (MSThRs) had a TRL of 4 and fast spectrum molten salt reactors (MSFRs) had a TRL of 3. Multiple R&D challenges still exist that could potentially inhibit or cause a long delay to commercial deployment of an MSR-AMR and include:

- **Modelling and Simulation:** all AMRs require support for licensing and experimental programme validation. Exact requirements are vendor specific. MSRs will also require an entire reactor system model that incorporates core physics, thermal hydraulics and the fuel cycle information.
- **Coolant:** an understanding of fundamental coolant chemistry is necessary to support other R&D activities.
- **Materials:** suitable for 60-year operating lives in MSRs need to be developed, tested and qualified. Especially given the corrosive coolant, radiation dose and temperatures.
- **Instrumentation and Control:** the high temperatures, liquid nature of fuel in the coolant and potential materials corrosion are challenges for reactor monitoring. Requiring the development and demonstration of suitable equipment.

- **Reactor equipment:** such as pumps and heat exchangers require developing and qualifying, due to the coolant, temperature and lack of operational precedent.
- **Fuel Cycle and Waste Management:** limited precedent exists for the manufacture of liquid fuels. R&D into fuel manufacture and qualification are required for all MSRs. The development and demonstration of an advanced pyrochemical reprocessing flowsheet to remove fission products/waste from fuel salt is required prior to MSR deployment. Unique material accountancy challenges also exist.
- **Waste Management:** containers for the disposal of reactor coolant and vessel materials will be unique to MSRs and require developing and qualifying.

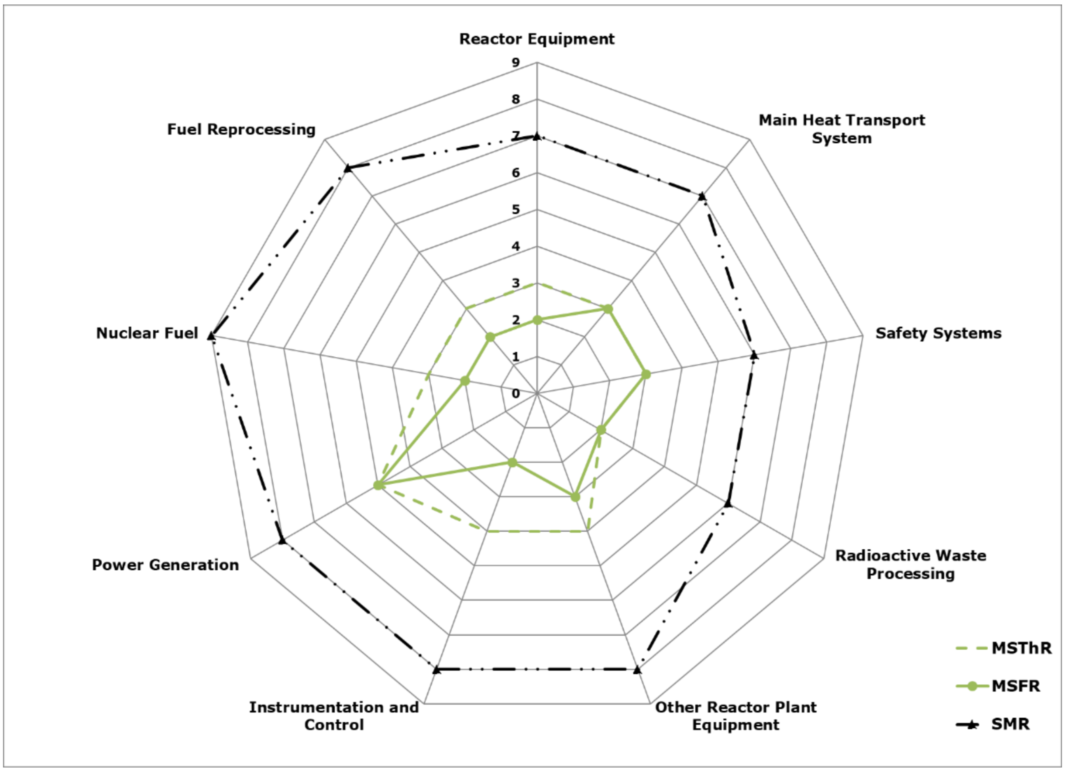

Figure 27: Comparison of MSR and SMR TRLs

The materials required for MSRs are not covered by existing Nuclear Design Codes and Standards. Requiring the development and implementation of new codes and standards prior to commercial deployment. Liquid fuelled reactors are unique in terms of the technical and licensing requirements. This includes the expected need for higher fissile material enrichments than allowed on existing commercial reactors and above those covered by regulations for both fuel manufacture and transportation in many countries. The licensing of a suitable spent fuel reprocessing facility, as part of a reactor is required to close the MSR fuel cycle, to realise the potential waste minimisation benefits of MSRs and support economic MSR operations. The licensing of such a facility would be unique internationally and would also require identification of a suitable materials accountancy process. For MSRs to support the decarbonisation of industry, they must be sited close to industrial areas. In the UK, nuclear facilities are typically located away from such environments. Such a significant licensing gap would need to be overcome to enable this that is necessary for all AMRs.

The UK nuclear supply chain was historically able to support advanced reactor development and deployment. This is no longer viewed as being the case, following the end of the UK Fast Reactor Programme and the time since construction of the last new nuclear power station was completed. Supply chain readiness is also hindered by the relative immaturity of many AMR concepts, with many vendors yet to demonstrate feasibility at the concept design stage resulting in a lack of clear requirements. To address the gaps, support and development of targeted areas of the UK supply chain are required. This is not unique to MSRs, as all AMRs would benefit from support of the domestic supply chain.

Based on this study, the UK nuclear supply chain is viewed as having the current capability and capacity (Blue) to produce approx. 5% of the components assessed and deemed necessary for a future MSR-AMR (Figure 28). Existing capability is predominantly limited to the manufacture of **electrical panels**, **cabling**, **insulation**, and **emergency generators**. Targeted development, through minor (Green) or significant support (Amber) of the nuclear supply chain capability or infrastructure could enable UK manufacture of ~58% of the components assessed in this study. A domestic supply chain capability or capacity gap (Red) has been identified for the manufacture of circa 37% of the components assessed in this study. This is partly due to the existence of international supply chains for **control** and **shutdown rods**, and their relevant **drive mechanisms** that impact all AMRs. The limited experience of the UK nuclear supply chain with the materials (nickel-based alloys), that are expected to be required by Molten Salt Reactors (MSRs) is a key issue. Impacting on domestic ability to manufacture **reactor vessels**, **reactor internals**, **manifolds**, **piping**, **pumps**, **valves**, **waste containers**, **heat exchangers**, **sensors**, **reactor control systems** and **inspection equipment** due to the needs of MSRs.

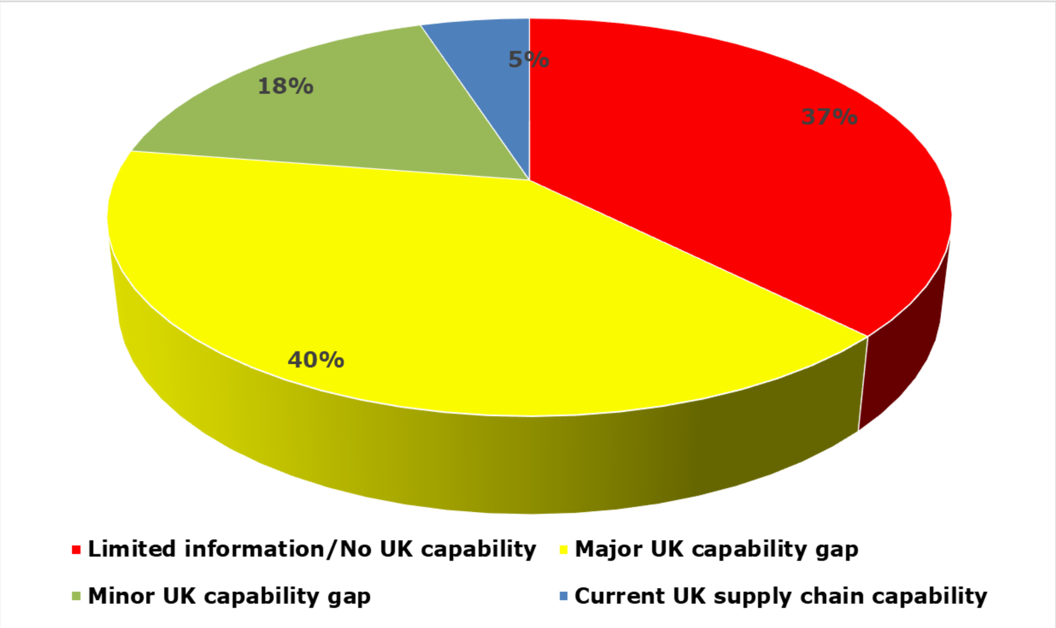

Figure 28: Summary of UK supply chain capability for MSRs

6. Conclusions

The outputs from this report, inform Government on the current state of Advanced Modular Reactor (AMR) technologies, and the key R&D and manufacturing challenges that remain. It is important that Government and the energy sector recognise the potential of these technologies to support net zero legislation, and the level of support and development that is needed before AMRs can be deployed in the UK.

This work showed that research and development needs exist for all AMRs, yet, these vary in number and complexity depending on system maturity. It is important to note that until these needs are addressed, the technologies will remain at the assessed Technology Readiness Levels (TRLs). To aid the direction of future R&D for AMRs, the multidisciplinary roadmaps developed in this study identify fundamental development needs over a 2-, 5- and more than 10-year timeframe. The roadmaps show that the majority of AMRs 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 would also align with government's current position which is to understand the feasibility of AMR technologies.

The key R&D needs required to progress AMRs beyond the assessed TRLs include: **modelling and simulation** activities; the demonstration and licensing of **materials**, reactor **equipment**, **instrumentation and control** systems; AMR **fuel** development**;** and **waste management** R&D. UK capability to support these R&D needs is highly variable. A lack of domestic facilities was a key barrier for the development of the TRL these AMR technologies; in addition to the availability of enough suitably qualified and experienced personal (SQEP). International facilities gaps, such as coolant flow loops, thermal hydraulics capability, zero-power and demonstration AMRs are thus UK opportunities. The domestic hosting of such facilities could support UK skills, enable UK access to international R&D programmes, enable global investment and accelerate AMR deployment.

An important finding of this report highlighted that multiple regulatory gaps exist for all AMRs. This includes nuclear codes and design standards which are not currently suitable for most AMRs (HTGRs are the exception); this is fundamental for the deployment of AMR technologies and requires concerted domestic UK and international action.

This study found that many components required for AMRs cannot currently be manufactured by the UK nuclear supply chain. It is important to note that until these needs are addressed, the technologies will remain at the assessed Supply Chain Readiness Level (SCRLs). The key manufacturing needs required to progress SCRLs are dependent on facilities. These include: **modular assembly and testing**; **advanced fuel manufacture**; and **reactor vessel** and **component manufacture** due to the physical size of and/or need for the use of advanced materials. The capability of the UK Supply Chain to address these needs is limited. As mentioned above this is centred around the lack of domestic facilities. However, a lack of awareness of the opportunities of AMRs was also found – particularly for less mature systems due to a lack of experience with the technology.

If the UK supply chain is to be a world leader in the manufacture of Advanced Nuclear Technologies (ANTs) then a highly productive and capable supply chain employing cutting-edge technology and processes that supports significant off-site manufacture, testing and assembly of nuclear components is essential. In addition, this work found that employing learning from historical UK nuclear programmes across reactor technologies (PWR, HTGR and SFR) and implementing technology transfer from non-nuclear sectors (e.g. aerospace, oil and gas or rail) could support the development of the UK supply chain. As an example, the UK could be well placed to manufacture Brayton power conversion cycles due to knowledge and expertise gained from the aerospace sector, where the UK currently leads a strategic supply chain.

As a result of the findings, the report makes the following recommendations:

- 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.

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Appendix 1. US Department of Energy Technology Readiness Level (TRL) Criteria

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.

Appendix 2. AMR 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 Inspection & Maintenance	7	5	6	4	4	2	8
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

Appendix 3. 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

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