NUCLEAR INNOVATION
AND RESEARCH OFFICE

Advanced Modular Reactors Technical Assessment

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Acknowledgements

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Executive Summary

The Department for Business, Energy and Industrial Strategy (BEIS) are seeking to make decisions on the direction of the Advanced Modular Reactor (AMR) R&D Demonstration programme, building on commitments made in the Energy White Paper: Powering our Net Zero Future [1] and the Ten Point Plan for a Green Industrial Revolution [2] for an AMR demonstration by the early 2030s, at the latest, to prove the potential of the technology. Higher temperature outputs of AMRs have potentially broad applications in terms of high-grade heat, hydrogen production, industrial decarbonisation, and the production of synthetic fuels. This research paper from the Nuclear Innovation and Research Office (NIRO) presents an assessment of the most promising AMR technologies and uses Multi-Criteria Decision Analysis (MCDA) to identify the preferred choice of AMR technology that could support UK objectives of meeting Net Zero climate change targets by 2050.

This analysis indicates that High Temperature Gas Reactors (HTGRs) are the preferred technology of choice because:

- HTGRs have a high Technology Readiness Level (TRL) of 7, and with further development and demonstration could potentially make a significant contribution to achieving Net Zero by 2050.
- With output temperatures of 700°C – 950°C, HTGRs provide for greater versatility in the applications that they could potentially support to supply to a heat and hydrogen economy, and thus provide the greatest opportunity for achieving Net Zero by 2050.
- HTGRs can be considered as evolutions of Advanced Gas Reactor (AGRs), a technology which the UK has significant experience in and many of the safety characteristics of the HTGR design concepts, including passive safety are broadly proven, however these will need to be substantiated for a particular design.
- HTGRs operate with an open fuel cycle, as with existing nuclear plants in the UK, therefore present no significant issues for security and safeguards, or additional costs associated with closed fuel cycle infrastructure.
- The UK's historical experience with Magnox reactors and AGRs could provide an advantage for the development and fleet roll-out for HTGRs in terms of transferable skills and supply chain capability, the potential for the development of UK intellectual property, and the potential for international partnership which could further reduce cost and risk to an AMR R&D Demonstration Programme.

It should be noted that for HTGRs graphite waste streams are anticipated both in the form of moderator bricks and as part of the spent fuel. The open fuel cycle nature of the proposed HTGR operation is anticipated to result in higher volumes of waste compared to other AMR systems, and similar or the same in nature to those previously managed in the UK. The supply of helium coolant (a non-renewable resource) in the quantities required is also a factor for consideration throughout the life of reactor operation. Indications are that a fleet of HTGRs will require a very small percentage of current known helium reserves [16].

This assessment should not preclude future Government and/or private sector support for the development of other AMR technologies, and technical expertise and knowledge of these systems in the UK should be maintained. This will enable the UK to adapt to market changes, have future options on the nuclear fuel cycle and maintain strategic capabilities required to support longer term deployment of alternative reactor technologies.

Introduction

To support the development of the UK Advanced Modular Reactor (AMR) Research and Development Demonstration (R&D) Programme an assessment of the six main AMR technologies[1], as outlined in Table 1, was made with respect to the objectives of the programme. Multi-Criteria Decision Analysis (MCDA) was used to determine the AMR technology that can best support the overarching UK objective of supporting Net Zero climate change targets by 2050. This document provides a summary of the assessment process and outcomes. It should be noted that:

- MCDA is a tool that can be used to support decision making in a structured way, however other non-technical factors may influence the outcome.
- The assessment is made by NIRO's expert judgement on available evidence and therefore involves an element of subjectivity.
- The assessment is dynamic and should be periodically reviewed as technologies mature and more data is made available, and where objectives may change. This assessment represents a snapshot analysis of the current information available.
- The analysis is on reactor technology types and further assessment will be required to select a specific reactor model to take forwards to demonstration.

This analysis, which draws on several techno-economic studies of AMRs [3-13], indicates that High Temperature Gas Reactors (HTGRs) are the preferred technology, particularly when considering key objectives of deployment on timescales sufficient to make a significant contribution to Net Zero by 2050 via multiple energy vectors (such as electricity, heat, and hydrogen). The other AMR technologies are typically at lower Technology Readiness Levels (TRLs) and/or have significantly more development needs.

AMRs and the Net Zero Challenge

In 2019 the UK became the first major global economy to pass legislation requiring the UK to bring all greenhouse gas emissions to Net Zero by 2050. This was followed by the Prime Minister's 10 Point Plan for a Green Industrial Revolution [2] and the Energy White Paper: Powering Our Net Zero Future [1] which showed Government support for all three strands of nuclear reactor technologies (large gigawatt (GW) scale systems, Small Modular Reactors (SMRs) and AMRs) in supporting the Net Zero target. Of these three, AMRs are the least developed towards commercialisation and require research and innovation activities to develop the technology. AMRs are the next generation of nuclear reactors, sometimes referred to as

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[1] In this paper the term AMR technology refers to a generic AMR design concept as opposed to a specific licensed reactor design. Fusion reactors are not considered as data is not currently available to assess these systems and they are of a low TRL.

Generation IV, that aim to advance nuclear energy with potentially significant benefits in terms of sustainability, safety and reliability, economic competitiveness, proliferation resistance and physical protection. They use novel coolants and/or fuels and as a result are not as technologically mature as GW scale reactors or SMRs. However, AMR technologies are developing quickly around the world and some countries already operate demonstrator reactors and have concept designs for commercial plants. Alongside this, innovation activities are underway to develop the technologies that enable AMRs to support widespread decarbonisation through the direct use of heat and hydrogen production.

The six main AMR technologies being developed internationally are shown in Table 1.

Table 1: Summary Characteristics of AMR Reactor Technologies [13-15]

System	Neutron Spectrum	Coolant	Outlet Temp (°C)	Fuel Cycle	Technology Readiness Level[2]
HTGR / VHTR High / Very High Temperature Gas Reactors	Thermal	Helium	700 – 950 900 – 1000+	Open	7 / 5
SFR Sodium-Cooled Fast Reactors	Fast	Sodium	500 – 550	Closed	7
SCWR Supercritical Water-Cooled Reactors	Thermal / Fast	Water	510 – 625	Open / Closed	2
GFR Gas-cooled Fast Reactors	Fast	Helium	850	Closed	2
LFR Lead-cooled Fast Reactors	Fast	Lead	480 – 570	Closed	4
MSR Molten Salt Reactors	Thermal / Fast	Fluoride Salts	700 – 800	Closed	4 Thermal 3 Fast

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[2] Technology Readiness Levels (TRLs) are an assessment of how mature a technology is and therefore is indicative of the timescale for commercial readiness, the investment needs and the risk of technological failure. There are nine TRL levels, with 1 representing the lowest maturity and 9 representing a system that has achieved commercial deployment.

AMR Technology Assessment

Multi-criteria decision analysis (MCDA) can be utilised to support the development of the BEIS AMR R&D demonstration programme by structuring the assessment of AMR technologies with respect to key objectives. The primary objective is to produce high temperature heat to decarbonise via multiple energy vectors in time to contribute to Net Zero by 2050. The steps in the MCDA process, which we go on to describe for this assessment, are:

- Identify key criteria and sub-criteria for the decision-making process – factors relevant for the UK AMR demonstration programme.
- Assess reactor technologies – qualitative assessment of the AMR technologies, using NIRO’s expert judgement and based on available evidence. Scores for each sub-criteria are then assigned and a score formulated for each high-level criteria.
- Apply weightings to high-level criteria to reflect importance of criteria to the decision – criteria that are viewed as more important to the programme are given higher weightings than those of a lower importance.
- Rank AMRs – combining formulated scores from the technical assessment of the reactor technologies, and weighting factors applied to reflect objectives.
- Conduct sensitivity analysis – varying weighting to establish which factors could impact on rankings.

Identify Key Criteria and Sub-Criteria

The high-level criteria outlined in Table 2 were developed to best reflect objectives for the UK AMR R&D Programme, and are categorised as those of primary importance, high importance, and other criteria of importance. The full list of high-level criteria and sub-criteria for the assessment are outlined in Figure 1.

Table 2: High-Level Criteria for Assessment

Criteria of primary importance: These criteria are viewed as the key objectives for a UK AMR R&D demonstration Programme.

- **Timescales for delivery** – The technology needs to have the potential to be commercially deployable on timescales with sufficient confidence to make a significant contribution to Net Zero by 2050.
- **Heat** – The technology must be able to contribute beyond electricity through multiple energy vectors, including the ability to generate high temperature heat that could offer efficient routes to low-carbon hydrogen production, industrial process heat & low-carbon fuels.

Criteria of high importance: These criteria are viewed as important requirements for a UK R&D Demonstration programme, however they are not necessarily the primary drivers.

- **Safety** – Safety and compliance with regulation is a fundamental principle of the Generic Design Assessment and subsequent licensing processes and no reactor could be built without regulatory permission. Within those parameters different reactor designs have different enhanced safety features and these can be compared. Co-generation will be an important factor and the system must have a level of safety whereby the regulator can be satisfied with co-location.
- **Security** – The technology needs to present low proliferation and security issues and risks.
- **UK value** – The technology needs to have the potential to draw on UK supply chain capability, existing UK knowledge skills and supply chain base and potential for UK jobs.
- **Economic costs** – The technology needs to be cost competitive for costs associated with construction, operation, decommissioning and waste disposal.
- **Deployability**[3] – Factors for consideration with respect to fleet roll-out, including load-follow capability (responsiveness to changes in grid demand), flexibility of location, reactor size, scalability, fuel cycle and fuel utilisation.

Other criteria of importance: These factors are additional features or considerations that should be evaluated and are important to overall delivery.

- **Adaptability** – Flexibility of the system to adapt to address potential future requirements, e.g. the ability for multi-purpose functions in future, such as plutonium and minor actinide management, or medical radioisotope production.
- **Waste & Environment** – Impacts on the environment through the nuclear lifecycle, from extraction of uranium ore to waste disposal.
- **International** – The prospects for international collaboration and UK export potential.

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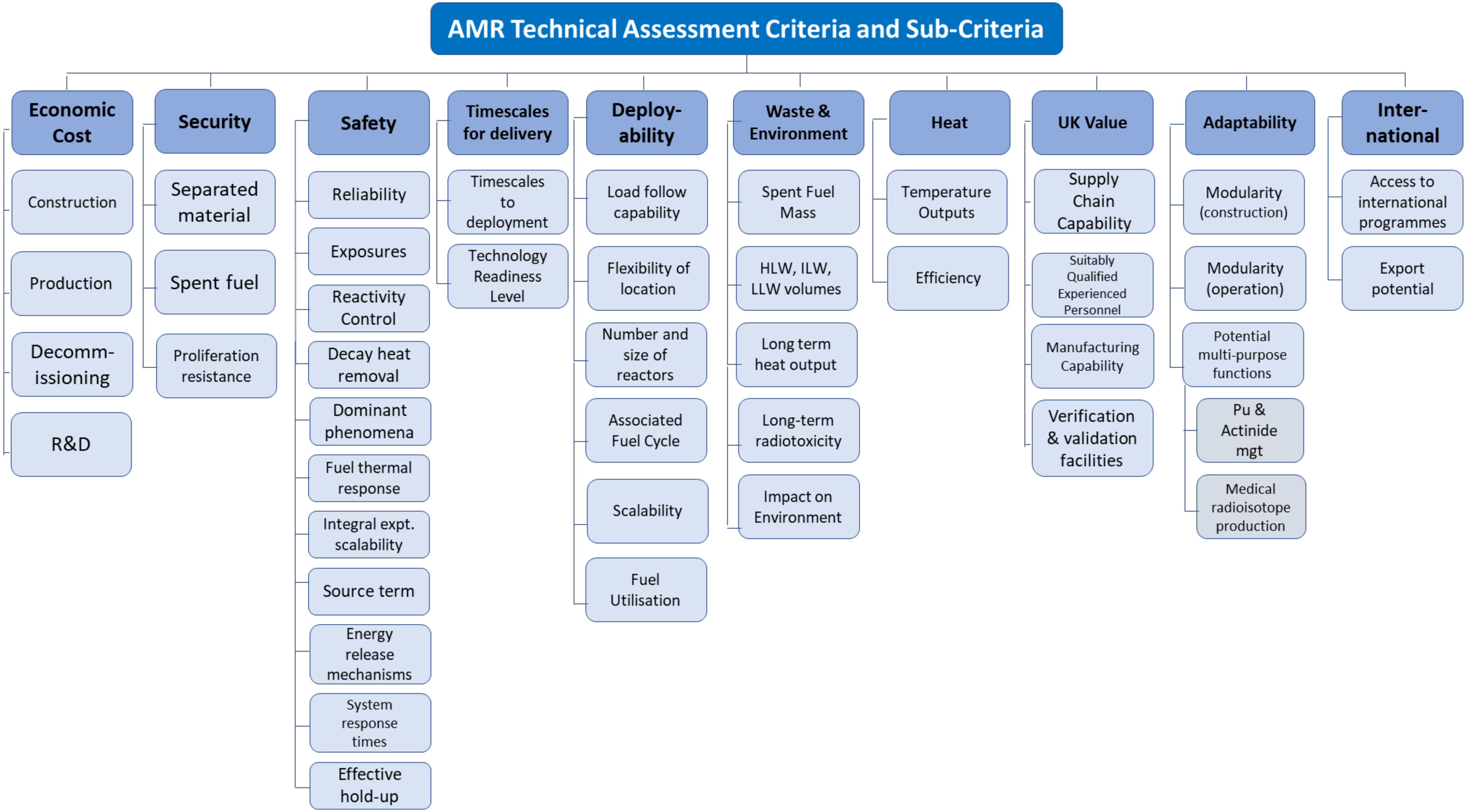
[3] Given the potential complexities in performing load following in some advanced systems, particularly where there may be limited data to support rapid power changes as part of a safety case, designers are considering options that enable the plant to operate the reactor at full power even when grid demand for electricity is low. This could be achieved via coupling energy storage to the plant and/or using the energy for providing other services such as steam for industrial use.

Figure 1: Criteria and Sub-Criteria for Assessment of AMR Technologies



Assessment of AMRs with Respect to Criteria

The AMR reactor technologies listed in Table 1 were assessed with respect to the sub-criteria outlined in Figure 1 and assigned a score on a four point scale according to whether the performance of a system is assessed as Very High (4), High (3), Medium (2) or Low (1) respectively[4]. Scores were assigned by NIRO expert judgement following a qualitative assessment of the available evidence from several techno-economic studies [3-13], with additional sources as referenced. Scores assigned for the sub-criteria were then formulated (with weights) to give scores for the high-level criteria for each technology. Table 3 gives the assessment for the high-level criteria, with more detailed explanation in Appendix 1 and 2.

It should be noted that the scoring and weighting system, as outlined in more detail in Appendix 3, is a simple way of comparing the AMR technologies. It is underpinned by NIRO's qualitative assessment of the available evidence, as summarised in Appendix 2. Some gaps in knowledge exist and there are uncertainties associated with some of the data. The assessment should be viewed in this context, it is dynamic and should be periodically reviewed as technologies mature and more data is made available, and where objectives may change.

Table 3: Assessment of AMR Technologies with Respect to High-Level Criteria

	HTGR	**SFR**	**LFR**	**MSR**	**SCWR**	**GFR**
Timescales for delivery	Very High	Very High	Medium	Medium	Low	Low
Heat	Very High	Medium	Medium	High	Medium	High
Safety	Very High	Medium	Medium	Medium	Low	Low
Security	Very High	Medium	Medium	Medium	Medium	Medium
UK Value	High	High	Medium	Low	Low	Low
Economic Cost	High	Medium	Medium	Medium	Medium	Medium
Deployability	High	High	High	High	Medium	High
Adaptability	High	High	High	Very High	Medium	High
Waste & Environment	Medium	High	High	High	High	Very High
International	Very High	High	Medium	Medium	Low	Low

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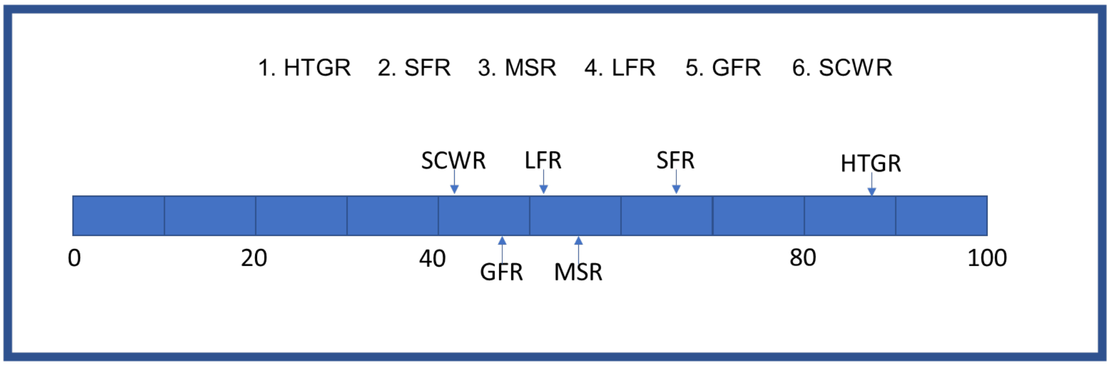
[4] A higher performing system scores a higher number. For example, with economic cost a low-cost system would score 'very high' and a high-cost system would score 'low'

The assessment described ranks the AMR technologies in order out of a score of 100, as outlined in Figure 2:

Figure 2: Scores and Rankings of AMRs



Sensitivity analysis varies the weightings applied to the criteria to assess how changing objectives could impact the rankings. Sensitivity analysis indicates that HTGRs are consistently ranked 1, including when Timescales for Delivery is assigned a weighting of 0. This is because HTGRs perform strongly with respect to Heat, Safety, Security, and UK Value, all of which are important factors in the decision-making process. Only eliminating these factors, alters the rankings of the different reactor technologies considered.

HTGRs are the preferred reactor of choice because:

- HTGRs have a high TRL of 7, and with further development and demonstration could potentially make a significant contribution to achieving Net Zero by 2050.
- With output temperatures of 700°C – 950°C, HTGRs provide for greater versatility in the applications that they could potentially support to supply to a heat and hydrogen economy, and thus provide the greatest opportunity for achieving Net Zero by 2050.
- HTGRs can be considered as evolutions of Advanced Gas Reactor (AGRs), a technology which the UK has significant experience in and many of the safety characteristics of the HTGR design concepts, including passive safety are broadly proven, however these will need to be substantiated for a particular design.
- HTGRs operate with an open fuel cycle, as with existing nuclear plants in the UK, therefore present no significant issues for security and safeguards, or additional costs associated with closed fuel cycle infrastructure.
- The UK's historical experience with Magnox reactors and AGRs could provide an advantage for the development and fleet roll-out for HTGRs in terms of transferable skills and supply chain capability, the potential for the development of UK intellectual property, and the potential for international partnership which could further reduce cost and risk to an AMR R&D Demonstration Programme.

It should be noted that for HTGRs graphite waste streams are anticipated both in the form of moderator bricks and as part of the spent fuel. The open fuel cycle nature of the proposed

HTGR operation is anticipated to result in higher volumes of waste compared to other AMR systems and similar or the same in nature to those previously managed in the UK. The supply of helium coolant (a non-renewable resource) in the quantities required is also a factor for consideration throughout the life of reactor operation. Indications are that a fleet of HTGRs will require a very small percentage of current known helium reserves [16].

Conclusion

This assessment points to High Temperature Gas Reactors (HTGRs) as the preferred AMR for the UK Government's AMR R&D demonstration programme. HTGRs are assessed to have the greatest potential to meet the UK's primary objectives of making a significant contribution to Net Zero by 2050 via multiple energy vectors. Further development and demonstration of HTGRs is needed to establish the viability to deliver on heat and hydrogen energy vectors and enable demonstration in the early 2030s. This assessment does not preclude future Government and/or private sector support for the development of other AMR technologies, and technical expertise and knowledge of these systems in the UK should be maintained. This will enable the UK to adapt to market changes, have future options on the nuclear fuel cycle and maintain strategic capabilities required to support longer term deployment of alternative reactor technologies.

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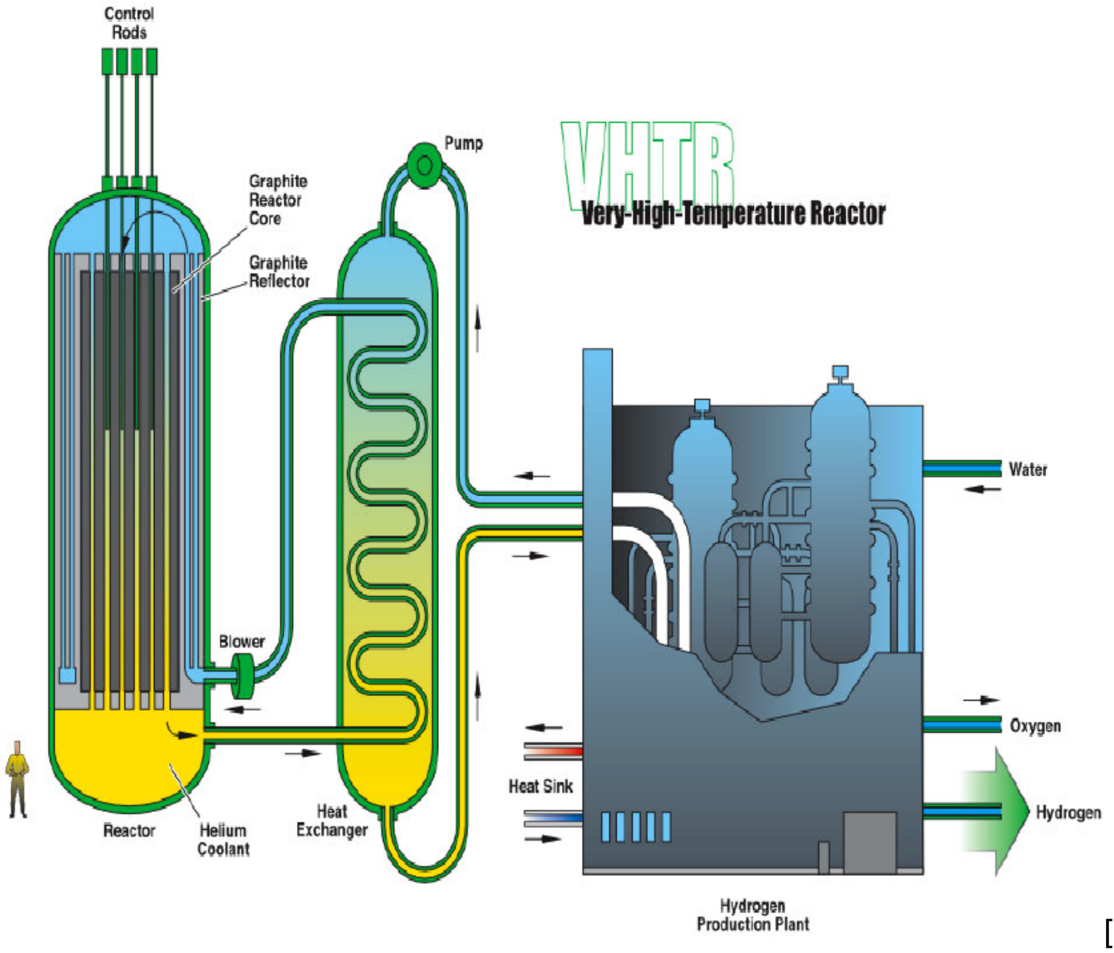
Appendix 1: Overview and Qualitative Assessment of AMR Technologies

Appendix 1 provides context for the assessment of AMR technologies as summarised in Table 3. Descriptions of the AMRs have been extracted from [3]. The AMR technologies have been assessed with data from several techno-economic studies [3-13] with additional sources as referenced. It should be noted that the assessment has been done on available evidence, gaps in knowledge exist and there are uncertainties associated with some of the data.

High / Very High Gas Temperature Reactors (HTGR / VHTR)

The High / Very High Temperature Reactor (HTGR / VHTR) is primarily dedicated to the generation of electricity and/or high temperature heat - with hydrogen, being extracted from water by using thermo-chemical, electro-chemical or hybrid processes. Its high outlet temperature makes it attractive also for the chemical, oil and iron industries. Original target of outlet temperatures of HTGR / VHTR can support the efficient production of hydrogen by thermo-chemical processes. The technical basis for VHTR is the TRi-structural ISOtropic (TRISO) coated particle fuel, the graphite as the core structure, helium coolant, as well as the dedicated core layout and lower power density for removal of decay heat via passive mechanisms (such as natural convection). The VHTR has potential for inherent safety, high thermal efficiency, process heat application capability, and modular construction.

HTGR systems can supply nuclear heat and electricity over a range of core outlet temperatures between 700 and 950°C [14], or more than 1000°C as a future target for VHTR. The reactor core type of the VHTR can be a prismatic block core, such as the Japanese HTTR, or a pebble-bed core such as the Chinese HTR-10. Although the shape of the fuel element for the two configurations are different, the technical basis for both configurations are similar, such as the TRISO coated particle fuel in a graphite matrix, full ceramic (graphite) core structure, helium coolant, and low power density.



[3]

HTGRs are able to accommodate a wide variety of fuel types (uranium, thorium and plutonium) without major modifications to the core design [19]. Furthermore, a variety of fuel forms have been investigated based on these fuel types, including UO_2, UCO and thorium fuels. However, in the realm of accident testing of fuels most experience is with oxide fuel [20]. Whilst a number of theoretical studies have been performed on destruction/re-use of legacy plutonium, there appears less experimental work on their behaviour in the public domain than for uranium and thorium fuels [20-22].

For electricity generation, a helium gas turbine system can be directly set in the primary coolant loop, which is called a direct cycle or at the lower end of the outlet temperature range, a steam generator can be used with a conventional rankine cycle. For nuclear heat applications such as process heat for refineries, petrochemistry, metallurgy, and hydrogen production, the heat application process is generally coupled with the reactor through an intermediate heat exchanger (IHX), the so-called indirect cycle. The VHTR can produce hydrogen from only heat and water by using thermochemical processes (such as the sulfur-iodine (S-I) process or the hybrid sulfur process), high temperature steam electrolysis (HTSE), or from heat, water, and natural gas by applying the steam reformer technology.

While the original approach for VHTR at the start of the Generation IV program focused on very high outlet temperatures and hydrogen production, current market assessments have indicated that electricity production and industrial processes based on high temperature steam that require modest outlet temperatures (700-850°C) have the greatest potential for application in the next decade and also reduce technical risk associated with higher outlet temperatures.

For hydrogen produced from a nuclear reactor such as a HTGR, a key safety concern is the ability of tritium to pass through metallic walls, penetrating the water/steam and/or product gas cycle. Tritium's extreme mobility requires effective retention mechanisms in a process heat plant [20]. For hydrogen produced via nuclear process heat to be usable as a commodity, it must have a tritium contamination below the tolerated limits specified by national legislation [22]. Therefore, one important safety requirement is to minimise tritium contamination in the downstream products. To minimise tritium contamination, it is essential to keep the fraction of defective/failed TRISO coated fuel particles and the level of He-3 and Li impurities as low as possible, in addition to designing an effective helium purification system. Nevertheless, there will always be some level of tritium that can be transported to the process side by permeation through the heat exchanger tubes into the downstream products [22].

HTGR / VHTR Assessment Criteria	**Score**
Timescales for Delivery	**VH**
• TRL: 7 for HTGR, 5 for VHTR • R&D requirements [10]: • Modelling and Simulation: support for licensing and experimental programme validation. • Fuel Cycle and Waste Management: Coated Particle Fuels (CPFs) have been made across globally with significant irradiation testing built up. 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. For VHTRs, significant additional R&D required if Zirconium Carbide (ZrC) is used. • Instrumentation and Control (I&C): the high temperatures of HTGRs raise challenges for reactor monitoring, requiring the development and demonstration of suitable sensors and equipment. I&C challenges are dependent on technology (pebble bed vs prismatic) and size of system. • Provision of heat: while not required for initial reactor deployment, enabling work to support the siting of HTGRs close to industrial areas or a hydrogen production facility is required. • Materials: Existing nuclear qualified materials are not licensed to the temperatures required for HTGRs/VHTRs, requiring their development, and nuclear qualification. [AGRs tested and operated extensively at 650°C]. • Reactor Equipment: will require demonstrating at the enhanced temperatures required in VHTRs. • 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. For HTGR systems employing the Rankine cycle technology there is more experience, which reduces technology risks.

- Other: consideration needs to be given to the supply of Helium, and the treatment and disposal of significant volumetric quantities of graphite.

Heat **VH**

- HTGRs typically operate at 700 - 950°C.
- VHTRs aim to operate at temperatures greater than 950°C, and potentially more than 1000°C in the future [12].
- Therefore HTGR / VHTR systems have the potential to support hydrogen production via all several production methods, and support industrial decarbonisation and synthetic fuel production.
- Development required to understand the performance of materials at these higher temperatures. Current AGR systems tested up to 650°C, HTTR in Japan has operated for 50 days at 950°C.
- Thermal efficiency: ~45% [37].

Safety [23-25] **VH**

- A high degree of safety has already been demonstrated for HTGRs although there is a significant amount of effort needed to support safety claims [12].
- The reactor is designed to achieve passive safety to avoid release of fission products under all conditions of normal operation and fault conditions. The robust nature of fuel and reliance on passive safety features, means the likelihood of radionuclide release is significantly reduced over existing reactor technologies.
- More work is needed to justify higher temperature operation and to understand some of the material ageing effects.
- The thermal mass of the graphite moderator and negative temperature coefficient in these designs results in a long grace time, natural tendency towards a safe / stable state and strong claims on passive safety. Graphite dust management is needed to protect worker exposure and likely increased radioactive arisings and decommissioning radioactive inventory. Graphite waste stream and spent fuel streams will need to be managed throughout operation as well as during decommissioning.
- Helium coolant is corrosive under certain conditions, work is needed to understand this. This is less of an issue if impurities are kept to very low levels [24].

Security [17-18] **VH**

- In terms of proliferation resistance and physical protection, HTGRs score Very High for separated materials and spent fuel characteristics, and High for sabotage resistance [4-7].
- Fuel with high thermal stability and a high degree of inherent safety.

- HTGR/VHTRs operate with a once-through cycle, using Low Enriched Uranium (LEU) TRISO fuel, avoiding the production of weapons usable materials. HTGRs further improve Proliferation Resistance and Physical Protection (PRPP) due to the highly robust nature of HTGR fuel and very low uranium concentrations in individual fuel elements, for example in a pebble bed reactor, each pebble contains only ~6 g of uranium [9].
- It is noted that, as with other AMR systems, High Assay LEU (HALEU), a subset of LEU[5] is required for the fuel. HALEU is uranium that has been enriched to between 5 and 20 wt.% 235U[6] which is a higher level of enrichment than for existing LWR fuels (enriched up to 5%).

UK Value

H

- UK has relevant plant operational and fuel cycle experience from demonstrators through to commercial Magnox and AGR plants, including: expertise in Reactor design, construction, operation, decommissioning, fuel and core design and fuel manufacture, disposal, recycling, and uranium enrichment. In these areas the UK has knowledge and experience of codes and standards, regulation, asset management (including aging), modelling, safeguards and security.
- Expertise waning on HTGRs due to time since AGR was built in UK.
- Lack of UK facilities to do testing and manufacturing.

Economic Costs [35-36]

H

- R&D costs relatively low given high TRL.
- Infrastructure costs relatively low as there is no requirement for reprocessing facilities.
- HTGRs / VHTRs, have relatively low power density cores. This may raise the cost per MW as a result [36].
- Costs associated with waste disposal are mixed, on decay heat front (due to low power density/diluted fissile material) there are benefits, however significant volumes of graphite and other waste products expected. However, the additional geological disposal costs will be a negligible proportion of the energy cost at any non-negligible discount rate.

Deployability

H

- Load follow capability: Potentially very responsive core.
- Flexibility of location: High safety and security features, therefore high potential for co-generation / co-location.

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[5] IAEA definitions: High enriched uranium (HEU) is Uranium enriched to at least 20% ^{235}U by weight. Low enriched uranium (LEU) is Uranium enriched in the ^{235}U isotope from 0.711% by weight in natural uranium up to 19.999%. IAEA-TECDOC-1452

[6] What is High-Assay Low-Enriched Uranium (HALEU)? | Department of Energy. HALEU is required for most U.S. advanced reactors to achieve smaller designs that get more power per unit of volume. HALEU will also allow developers to optimise their systems for longer life cores, increased efficiencies and better fuel utilisation.

- Reactor size: typically 10 MWth to 600 MWth.
- Fuel utilisation: once-through cycle, therefore relatively low sustainability, and relatively higher volumes of Uranium needed.
- The supply of helium coolant (a non-renewable resource) in the quantities required is a factor for consideration throughout the life of reactor operation. Indications are that a fleet of HTGRs will require a very small percentage of current known helium reserves.

Adaptability **H**

- HTGRs are able to accommodate a wide variety of fuel types (uranium, thorium and plutonium.
- Potential burner of plutonium and minor actinides.
- Reactor demo depending on its specification, may have the potential to support development of materials and codes and standards for use at very high temperatures. Would also have potential to test out novel advanced techniques such as electron beam welding.

Waste & Environment **M**

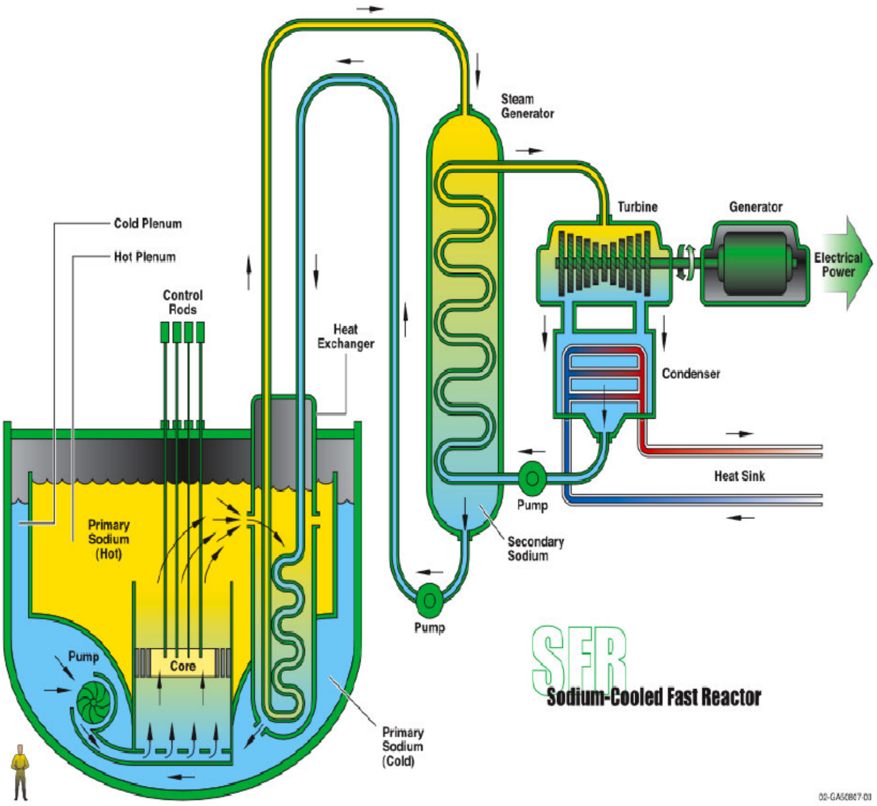
- HTGRs graphite waste streams are anticipated both in the form of moderator bricks and as part of the spent fuel.
- The open fuel cycle nature of the proposed HTGR operation is anticipated to result in higher volumes of waste compared to other AMR systems and similar or the same in nature to those previously managed in the UK.
- In terms of disposability, the ability of TRISO particles to effectively retain fission products is a favourable characteristic for direct disposal. However, there are significant uncertainties surrounding the necessary preconditioning processes for irradiated graphite and limited experience with disposing of TRISO fuel. The low power density of high temperature reactor cores results in larger volumes of waste that require storage and eventual disposal.

International **VH**

- As noted above, the UK has significant knowledge and expertise in graphite moderated, gas-cooled reactors systems of relevance to HTGRs through the historic Magnox and AGR capability. Partnership with the US, Canada, or Japan could be advantageous to both sides.
- US/Canadian are progressing towards demonstration through several competing Government backed programmes.
- US is at the forefront in fuel cycle development with strategic drivers to produce HALEU fuel.
- Japan has the latest developed design and is in the process of restarting its demonstrator.

Sodium-Cooled Fast Reactors (SFR)

The SFR uses liquid sodium as the reactor coolant, allowing high power density and operation at low pressure. While the oxygen-free environment prevents corrosion, sodium reacts chemically with air and water and requires a sealed coolant system, with additional engineering barriers and systems to reduce the likelihood of sodium reactions with air/water.



[3]

Plant size options under consideration range from small, 50 to 300 MWe, modular reactors to larger plants up to 1500 MWe [44]. The outlet temperature is 500-550°C for the options, which allows the use of the materials developed and proven in prior fast reactor programmes.

The SFR closed fuel cycle enables regeneration of fissile material and facilitates management of minor actinides. However, this requires that recycle fuels be developed and qualified for use. Important safety features of the Generation IV system includes: 1) a high level of thermal inertia, thereby enabling longer grace times in certain transients. 2) a reasonable margin to coolant boiling. and 3) a primary system that operates near atmospheric pressure. Water/steam, supercritical carbon-dioxide or nitrogen can be considered as working fluids for the power conversion system to achieve high performance in terms of thermal efficiency, safety and reliability. In addition, the fast neutron spectrum greatly extends the uranium resources compared to thermal reactors. The SFR is considered to be the nearest-term deployable system for actinide management.

Much of the basic technology for the SFR has been established in former fast reactor programmes, and is being confirmed by the Phenix end-of-life tests in France, and the BN-600, BN-800, and BN-1200 in Russia [45]. New programs involving SFR technology include the

Chinese experimental fast reactor (CEFR) which was connected to the grid in July 2011, and India's prototype fast breeder reactor (PFBR).

The SFR is an attractive energy source for nations that desire to make the best use of limited nuclear fuel resources and manage nuclear waste by closing the fuel cycle.

Fast reactors have been demonstrated to achieve efficient fuel utilisation due to their use of fast neutrons which can more effectively fission actinide material and covert fertile material (such as U-238) into new fissile material (Pu-239). The main characteristics of the SFR for actinide management are:

- Consumption of transuranics in a closed fuel cycle, thus reducing the radiotoxicity and heat load which facilitates waste disposal and geologic isolation.
- Enhanced utilisation of uranium resources through efficient management of fissile materials and multi-recycle.

High level of safety achieved through inherent and passive means also allows accommodation for certain classes of transients and bounding events with significant safety margins. The reactor unit can be arranged in a pool layout or a compact loop layout.

The need to develop similarly effective Inservice Inspection and Repair (ISI&R) methods for SFRs is currently the subject of large R&D programmes and is considered a major challenge [23]. A considerable complication with ISI&R in liquid metal-cooled fast reactors is the opaqueness of the coolant medium prohibiting visual inspection. There are a number of ways to try and compensate for this property, which focus on design simplifications and development of new instrumentation system [23]. Whilst there is some significant experience from previous and current SFR programmes in the areas of ISI&R for SFRs, technical challenges still remain and is an active area of international research [9].

SFR Assessment Criteria	**Score**
Timescales for Delivery	**VH**
• TRL: 7 [10] • R&D requirements [10]: • Modelling and Simulation: support for licensing and experimental programme validation. • Instrumentation and Control: the high temperatures as well as the optically 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 particular the irradiation field and temperatures) 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 for those systems, that aim to employ Minor Actinide (MA)-bearing fuels (which can reduce heat load in a geological disposal facility and therefore overall repository footprint).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, and associated leak detection systems are required to minimise the potential for water-sodium interactions.
- Other: Development of codes and standards are also needed.

Heat	**M**

- ~550°C, limiting versatility and contributions to multiple energy vectors, noting however that a significant proportion of current industrial heat demand (around 60%) is below 550°C and there is research interest into developing hydrogen production routes utilising lower temperature heat.
- Thermal efficiency: ~38% [38].

Safety [23, 24, 26, 27, 34]	**M**

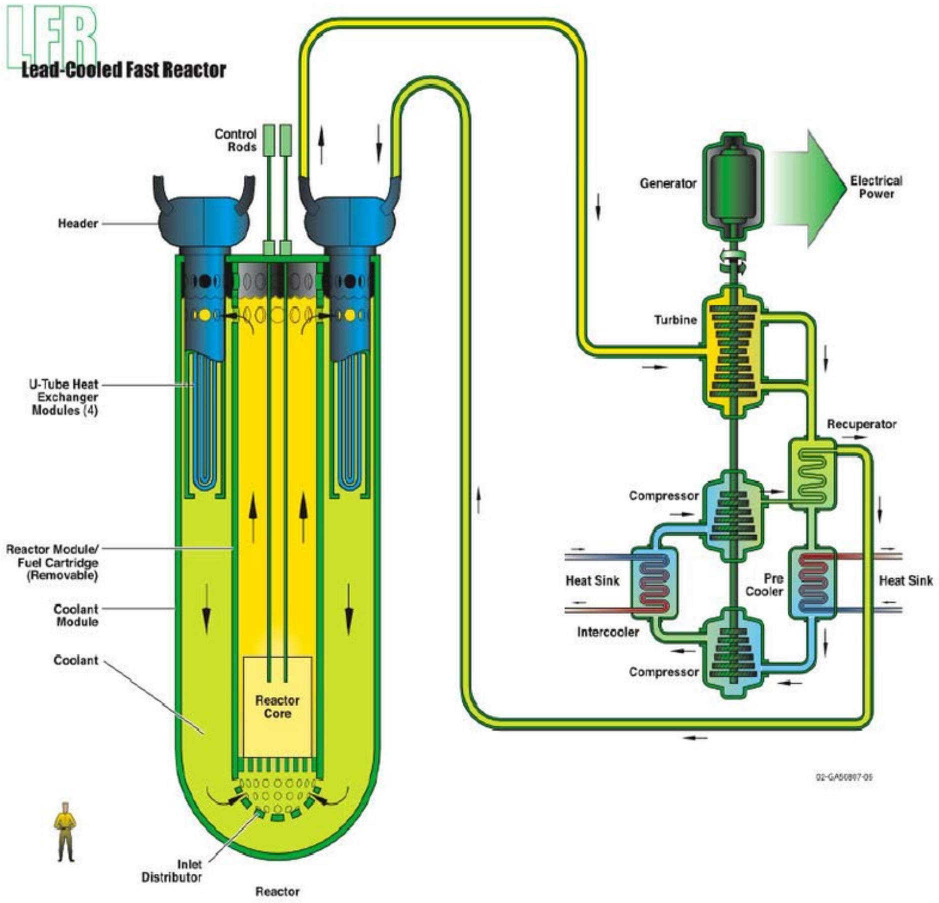
- There is a significant amount of experience with this type of reactor that, depending on the design, may be transferrable to modern designs.
- Operates at near atmospheric pressure which reduces the safety challenges with pressurised failure hazards. Sodium reacts exothermically with air and water (e.g. leading to sodium jet fires).
- High irradiation of materials is expected due to the high energy fast neutrons.
- Voids in the coolant can result in a rapid growth in the rate of energy release.
- Implementing diverse shutdown systems is a challenge because the injection of boron is not available as an alternative means of inserting negative reactivity. Demonstrating diversity of shutdown systems is a challenge if based on rod systems only.
- The properties of sodium make In-Service Inspection, repair, and failed-fuel management challenging and hazardous.
- Worker exposure in pool-type sodium reactors is lower by a factor of 10 when compared to pressurised water reactors.
- There are challenges in reprocessing, waste treatment and decommissioning and some used fuel (i.e. metallic sodium bonded fuel) is not passively safe without treatment.
- New front and back end infrastructure will be required.

Security [17-19]	**M**
• Closed fuel cycles have greater proliferation risks than reactor systems employing an open fuel cycle. Where spent fuel is reprocessed, there is the potential for the inherent PRPP performance to be less favourable. • SFR systems can (with a suitably designed core using a fertile blanket) lead to a production route for very high quality Pu that could be used for non-peaceful purposes. However most designs avoid such blanket configurations. • Security and safeguards will be designed to offer adequate protection and inherent PRPP.	
UK Value	**H**
• For SFRs, the UK nuclear supply chain is viewed as having the current capacity and capability to produce approx. 17% of the components assessed and deemed necessary for a future SFR-AMR, including 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 [10]. • UK capability limited to Dounreay research fast reactor, ceased operation in 1994. • Existing codes and standards are not suitable for SFRs. • 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.	
Economic Costs	**M**
• Higher cost of capital due to need for secondary sodium circuit [8]. • Additional Infrastructure costs required for reprocessing facilities.	
Deployability	**H**
• Load Follow Capability: Limited information in public domain. • Flexibility of location: relatively low. • Reactor size: variable, 50-150, 300-1500, and 600-1500MWe envisaged. • Fuel utilisation: Closed cycle, therefore high sustainability.	
Adaptability	**H**
• SFR is considered to be the nearest-term deployable system for actinide management.	

Waste & Environment	**H**
• SFRs are assessed as High for spent fuel mass, VHLW, ILW, and LLW volumes, long term heat output, and long-term radiotoxicity, and very high for environmental impact [4-7]. • There are challenges in reprocessing, waste treatment and decommissioning and some used fuel (i.e. metallic sodium bonded fuel) is not passively safe without treatment. New front and back end infrastructure will be required. • Reprocessing of fuel at short cooling times presents challenges. • Fuel reprocessing and waste management is more challenging for fast reactor spent fuel than it is for LWRs.	
International	**H**
• Commercial scale prototypes have been built and operated in France, Japan, Russian Federation, UK and USA. • Russia have significant capability and are operating prototypes. • UK, US and France have demonstration experience and are currently dismantling fast reactor prototypes (reactor, fuel and recycle). • UK contributing to R&D collaboration through the Generation IV international Forum. Opportunities for collaboration / partnership.	

Lead-Cooled Fast Reactors (LFR)

The Lead-cooled Fast Reactors (LFRs) feature a fast neutron spectrum, high temperature operation, and cooling by either molten lead or lead-bismuth eutectic (LBE), both of which support low-pressure operation, have very good thermodynamic properties, and exhibit fewer challenges with respect to water-air interactions in comparison to sodium coolants. They could have multiple applications including production of electricity, hydrogen and process heat.



[3]

The LFR has good spent fuel management capabilities since it operates in the fast-neutron spectrum and uses a closed fuel cycle for efficient conversion of fertile uranium. An important feature of the LFR is the optimised safety that results from the choice of molten lead (which has fewer challenges with water/air interactions than sodium) and low-pressure coolant. In terms of sustainability, lead is abundant and hence available, even in case of deployment of a large number of reactors. however, for lead coolants employing a lead-bismuth eutectic, bismuth has much more limited availability. More importantly, as with other fast systems, fuel sustainability is greatly enhanced by the conversion capabilities of the LFR fuel cycle. Because they incorporate a liquid coolant with a very high margin to boiling and relatively benign interaction with air or water, LFR concepts offer substantial potential in terms of safety, design simplification, and the resulting economic performance.

The LFR has development needs in the areas of fuels, materials performance, and corrosion control. The LFR utilises molten lead (Pb) or Lead Bismuth Eutectic (LBE) as a coolant resulting in a fast neutron spectrum. The utilisation of lead-based coolants offers some advantages over other coolants such as sodium, namely: 1) A very high boiling point (~1600°C), thereby allowing for much higher safety margins than associated with other coolants. However, it should be noted that failure of structural materials will occur at a significantly lower temperature than 1600°C. 2) it does not exhibit a strongly exothermic chemical reaction with water or air (unlike sodium) resulting in improved safety characteristics. 3) and low neutron absorption and moderation which permits higher coolant to fuel ratios. (The large coolant to fuel ratios is necessary in LFR designs to reduce pumps speeds and limit temperature gradients.) However, there are technical challenges associated with the use of Pb and LBE, these include: their corrosiveness at temperatures above approximately 500°C. and protective iron oxide films are eroded by coolant flows greater than 2 m/s [9]. For LBE coolants there are also concerns around the production of hazardous polonium aerosols.

As in the case with SFRs, the optical opaqueness of lead-based coolants significantly complicates Inservice Inspection and Repair (ISI&R). However, the characteristics of lead-based coolants (high density and high melting point) are likely to further complicate ISI&R relative to SFRs for the following reasons [24]:

- The higher melting point of lead-based coolants, in particular molten lead, implies that ISI&R would have to be performed at high temperatures. Therefore ISI&R systems must be capable of surviving such an aggressive environment.
- The high density of lead-based coolants may make it difficult to insert inspection systems due to buoyancy forces.
- There will be a reliance on ultrasound measurement systems to image core components due to the optical opaqueness of lead-based coolants. However, unlike liquid sodium, the limited density difference between lead-based coolants and steel implies a reduction in the sensitivity of ultrasound inspection methods.

LFR Assessment Criteria	**Score**
Timescales for Delivery	**M**
• TRL: 4 • R&D requirements [10]: • Modelling and Simulation: support for licensing and experimental programme validation. • 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.
- Other: Existing codes and standards are not suitable for LFRs.

Heat	**M**

- LFRs have an outlet temperature of ~550°C, therefore limiting versatility. Note however that a significant proportion of current industrial heat demand (around 60%) is below 550°C and there is research interest into developing hydrogen production routes utilising lower temperature heat.
- Thermal Efficiency: ~41% [39].

Safety [23, 24, 26, 29]	**M**

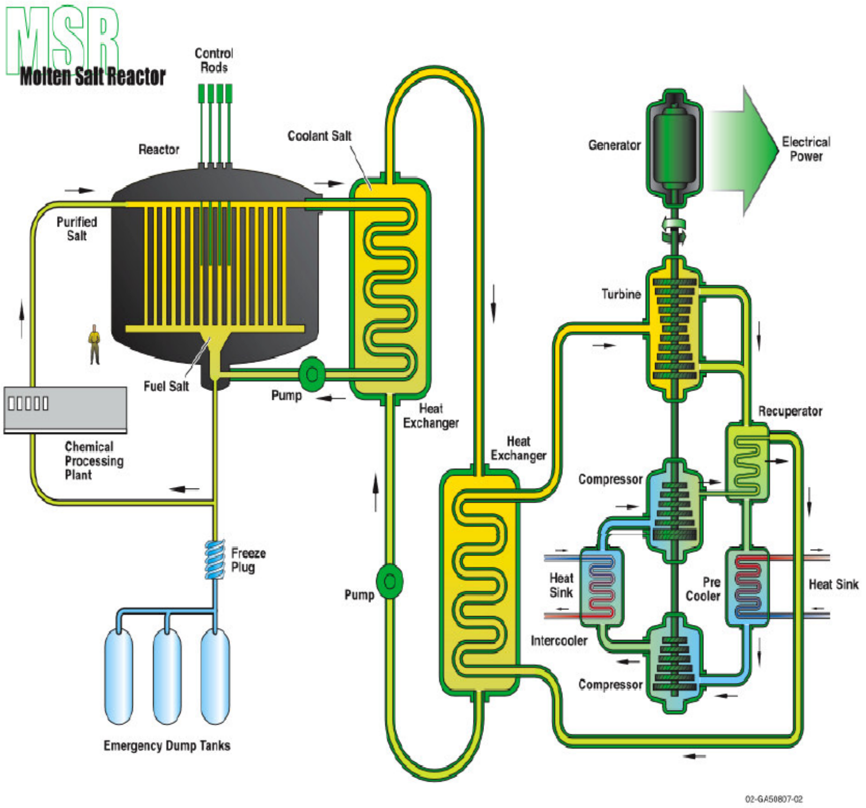
- Operational experience of lead cooled reactors is limited, with most experience associated with Russia's early submarine programme, however there is limited information in the public domain regarding performance.
- Operates at near atmospheric pressure which reduces the safety challenges with pressurised failure hazards. Lead has a high thermal inertia and natural convection creates long grace times following loss of coolant flow. Also, successive safety barriers and the properties of lead produce a low source term associated with fission products. However, for LBE coolants there may be significant hazards associated with irradiated bismuth.
- High irradiation of materials is expected due to the high energy fast neutrons. Molten lead is corrosive, so coolant chemistry and flow rates need to be finely controlled. Also, performance of materials needs careful consideration due to the high energy fast neutrons associated with the system.
- Voids in the coolant can result in a rapid growth in the rate of energy release. This and other changes (e.g. lead – water interaction, seismic events) in the primary coolant can result in a shock wave and sloshing loads which could challenge civil structures.
- Implementing diverse shutdown systems is a challenge because the injection of boron is not available like in other reactor systems such as LWR systems. Also, control rod movement could be impaired by corrosion, erosion, buoyancy effects and/or solidification associated with the coolant.

• The properties of lead make In-Service Inspection, repair, failed-fuel management and waste management very challenging and potentially hazardous.	
Security [17-19]	**M**
• Closed fuel cycles have greater proliferation risks than reactor systems employing an open fuel cycle. Where spent fuel is reprocessed, there is the potential for the inherent PRPP performance to be less favourable. Simple compact core, low pressure operation, integral power conversion equipment, no intermediate cooling system, and lead coolant that is less reactive chemically (e.g. than sodium with water/air) and has a high margin to boiling. If lead leaks, it will solidify and will be the outer protective layer. • Security and safeguards will be designed to offer adequate protection and inherent PRPP.	
UK Value	**M**
• UK experience of LFRs is limited. However there may be some relevance with SFR knowledge to LFR systems and supply chain could potentially supply some components [10]. • 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.	
Economic Costs	**M**
• Considerable R&D investment required to increase TRL. • Infrastructure costs associated with recycling facilities and management of Pu. • Complex and technically demanding systems potentially increase costs. • High power density, potential for high degrees of enhanced passive safety and fewer issues with water-air interactions than sodium are attractive economic factors but need to be carefully balanced against R&D investment required to increase overall TRL.	
Deployability	**H**
• Load Follow Capability: Limited information in public domain. • Flexibility of location: Medium. • Reactor size: variable, 20-180, 300-1200, and 600-1000 MWe envisaged. • Fuel utilisation: closed fuel cycle, therefore high sustainability.	
Adaptability	**H**
• Can be used as a burner to consume actinides, and as a burner/breeder with thorium matrices.	
Waste & Environment	**H**
• As with SFRs, LFRs are assessed as High for spent fuel mass, VHLW, ILW, and LLW volumes, long term heat output, and long term radiotoxicity, and very high for environmental impact [4-7].	

• The properties of lead make waste management challenging and hazardous. No disposal routes currently foreseen due to hazardous properties of lead.	
International	**M**
• System concepts represented in plans of the Generation IV International Forum (GIF) System Research Plan (SRP) are based on Europe’s ELFR lead-cooled system, Russia’s BREST-OD-300 and the SSTAR system concept designed in the US. Numerous additional LFR concepts are also under various stages of development in different countries including China, Russia, the USA, Sweden, Korea and Japan.	

Molten Salt Reactors (MSR)

The MSR is distinguished by its core in which the fuel is dissolved in molten fluoride or chloride salt. The technology was first studied more than 50 years ago. Modern interest is on fast reactor concepts as a long-term alternative to solid-fuelled fast neutrons reactors. The onsite fuel reprocessing unit using pyro-chemistry allows breeding plutonium from uranium-238 or uranium-233 from thorium. R&D progresses toward resolving feasibility issues and assessing safety and performance of the design concepts. Key feasibility issues focus on a dedicated safety approach and the development of salt redox potential measurement and control tools in order to limit corrosion rate of structural materials. Further work on the batch-wise online salt processing is required. Much work is needed on molten salt technology and related equipment.



[3]

MSR technology was partly developed, including a demonstration reactor, in the 1950s and 1960s in the USA (Oak Ridge National Laboratory). The earlier work on MSRs focused on thermal-neutron-spectrum graphite-moderated concepts. Since 2005, R&D has focused on the development of fast-spectrum MSR concepts (MSFR) combining the generic assets of fast neutron reactors (extended resource utilisation, waste minimisation) with those relating to molten salt fluorides as fluid fuel and coolant (low pressure and high boiling temperature, optical transparency). MSFR concepts also avoid issues associated with lower power density and irradiation/handling of moderator/graphite.

In contrast to most other molten salt reactors previously studied, the MSFR does not include any solid moderator (usually graphite) in the core. This design choice is motivated by the study of parameters such as feedback coefficient, breeding ratio, graphite lifespan and 233U initial inventory. MSFR exhibit large negative temperature and void reactivity coefficients, a unique safety characteristic not found in solid-fuel fast reactors.

Compared with solid-fuel reactors, MSFR systems have lower fissile inventories, no radiation damage constraint on attainable fuel burn-up, no requirement to fabricate and handle solid fuel, and a homogeneous isotopic composition of fuel in the reactor. These and other characteristics give MSFRs potentially unique capabilities for actinide burning and extending fuel resources.

MSR developments in Russia on the Molten Salt Actinide Recycler and Transmuter (MOSART) aim to be used as efficient burners of transuranic (TRU) waste from spent UOX and MOX light water reactor (LWR) fuel without any uranium and thorium support and also with it. Other advanced reactor concepts are being studied, which use the liquid salt technology, as a primary coolant such as the Fluoride salt-cooled High-temperature Reactors (FHRs), which uses coated particle fuels similar to high temperature gas-cooled reactors (these are not assessed in this analysis).

More generally, there has been a significant renewal of interest in the use of liquid salt as a coolant for nuclear and non-nuclear applications. These salts could facilitate heat transfer for nuclear hydrogen production concepts, concentrated solar electricity generation, oil refineries, and shale oil processing facilities amongst other applications.

MSR Assessment Criteria	**Score**
Timescales for Delivery	**M**
• TRL: 3 (fast) / 4 (thermal). • Notable change in technology - no solid nuclear fuel. The fissile core is made up of a mixture of molten fluoride and other salts that circulates through the core and then to heat exchangers. • Pre-conceptual design stage. • R&D requirements [10]: • Modelling and Simulation: for licensing and experimental programme validation. 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: suitability 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.

Heat

H

- ~700°C, therefore have the ability to deliver on several energy vectors.
- Thermal efficiency@ ~45% [40, 41].

Safety [25, 26, 28, 35]

M

- There are a wide variety of molten salt designs available but operational experience is limited. Molten fuel form will demand a new approach to safety.
- Operates at near atmospheric pressure which reduces the safety challenges with pressurised failure hazards.
- Some designs are claimed to not require control rods due to the strong negative reactivity coefficient (thermal neutron designs only). However, the need to demonstrate independence of systems may result in the need to provide them. For fast spectrum designs, high irradiation of materials is expected due to the high energy fast neutrons.
- In many designs the fuel is in solution form with the primary coolant or have dispersed or pseudo fuel assembly structures.
- The need for salt purification in proximity to the reactor (e.g. to prevent material corrosion) can lead to the introduction of hazards, faults and complexity.
- Molten salts generally have a high freezing point so there is a risk of coolant solidification and blocking during cooldown faults. This may limit passive safety through natural circulation claims.
- Designs where the fuel is in solution form are likely to result in the on-line reprocessing facilities being within the first layer of containment. Therefore, operator radiological exposure during maintenance activities has the potential to be significant.

Security [17-19] **M**

- Closed fuel cycles have greater proliferation risks than reactor systems employing an open fuel cycle.
- MSRs utilise a liquid fuel and nominally operates with extensive on-line reprocessing, the barriers to accessing fissile material and other radioactive materials are potentially reduced relative to spent fuel from solid fuel reactors. Hence, there is the potential for the inherent PRPP performance to be less favourable [9].
- Onsite reprocessing increases number of target facilities where safeguards would be required.
- The weakest point of the MSR is that for thorium-uranium fuel cycles pure U233 can be obtained through protactinium (Pa) separation which is a vulnerability. This also broadly applies to MSR systems operating with a uranium-plutonium fuel cycle.
- For fast spectrum MSR systems, they have some interesting characteristics from the viewpoint of proliferation resistance. Its fissile inventory is low due to a high power density and the absence of excess fuel reactivity for operations. The fissile material is disseminated in small quantity in the fuel salt. To obtain the critical mass of fissile material would require a reprocessing system designed for a large amount of salt. For systems operating with a U-Th fuel cycle, the unavoidable production of uranium-232 accompanying uranium-233 production, even in small fractions, would generate very strong constraints on the handling of uranium, preventing undesirable use. This would produce a visible signature for the detection of fissile material transport. However this is unlikely to deter determined individuals or nation states.
- Security and safeguards will be designed to offer adequate protection and inherent PRPP.

UK Value **L**

- UK experience and capability is limited.
- The UK nuclear supply chain is viewed as having the current capability and capacity to produce approx. 5% of the components assessed. Existing capability is predominantly limited to the manufacture of electrical panels, cabling, insulation, and emergency generators. Targeted development with significant support could enable UK manufacture of ~58% of the components assessed in this study [10].

Economic Costs **M**

- Although MSRs have an unpressurised primary circuit vessel, the vessel will need to meet a very high standard of containment, which may require a second vessel. There will need to be robust barriers in place anywhere fuel/coolant could escape throughout the reactor system. Incorporating an on-line reprocessing system will almost inevitably increase plant capital costs relative to systems that utilise a centralised reprocessing system. Fuel costs are expected to be low, however these are likely to be offset by higher operational and maintenance costs associated with working with a corrosive, highly active coolant. MSRs are of low technical maturity and therefore very high R&D costs associated.

Deployability	**H**

- Load Follow Capability: Potential for improved load-following over LWR systems (low to medium confidence).
- Flexibility of location: low, onsite reprocessing limits siting.
- Reactor size: Range of 3.6-250. 32.5-291, & 1000 MWe.
- Fuel utilisation: closed fuel cycle, therefore high sustainability.

Adaptability	**VH**

- Flexibility to use virtually any fissile material.

Waste & Environment	**H**

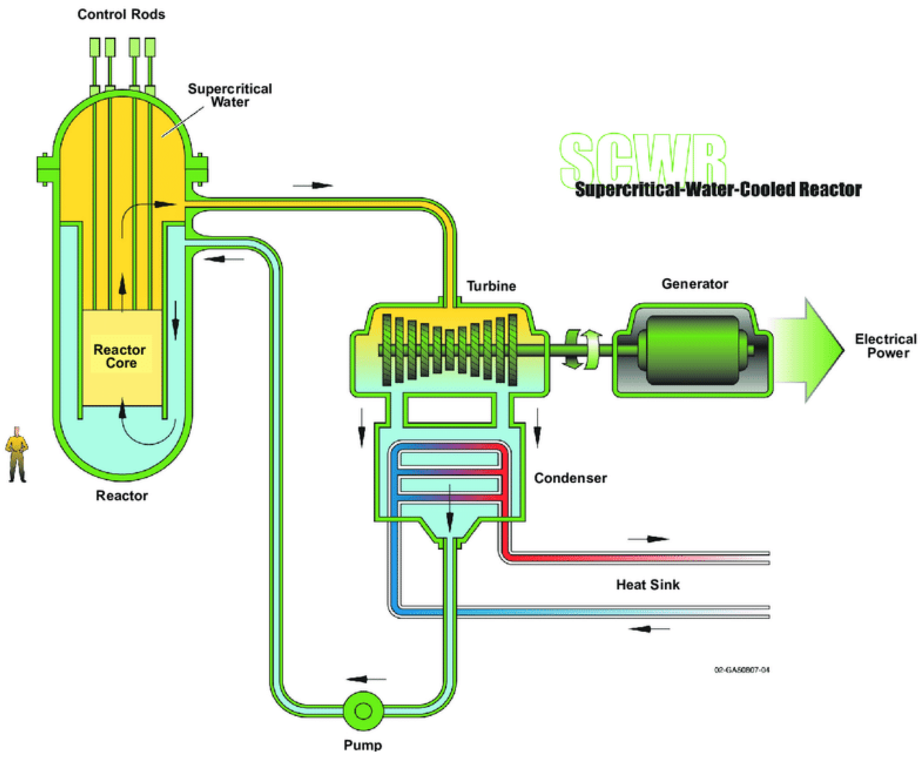
- MSRs are assessed as Medium for spent fuel mass, High for VHLW, ILW, and LLW volumes, long term heat output, and long term radiotoxicity, and very high for environmental impact [23, 24].
- The spent fuel characteristics of MSRs require a new fuel cycle infrastructure based on pyro processing. The waste forms will also be different and will need to be assessed for compatibility with disposal in the GDF.
- The coolant and fuel pose challenges to reprocessing, waste treatment and decommissioning. Waste disposal routes for contaminated molten salt do not currently exist in the UK.
- Salt purification in proximity to the reactor can lead to the introduction of potential waste issues.
- New front and back end infrastructure will be required.

International	**L**

- US, Canada, Russia and China funding new R&D programmes.
- US has historic demonstration experience. However the relevance to current designs may be limited. Furthermore historic US operation did highlight technical challenges that were not fully resolved such as the behaviour of materials under the intense irradiation, temperature and chemical conditions.
- UK start-up design organisations engaging with Canadian funded Programmes.
- UK recycle capability is relevant.

Supercritical Water-Cooled Reactors (SCWR)

SCWRs are high temperature, high-pressure, light-water-cooled reactors that operate above the thermodynamic critical point of water (374°C, 22.1 MPa). SCWRs are in the early stages of development with many unproven concepts and design features. Significant research is needed before these reactors could be considered for demonstration purposes.



[3]

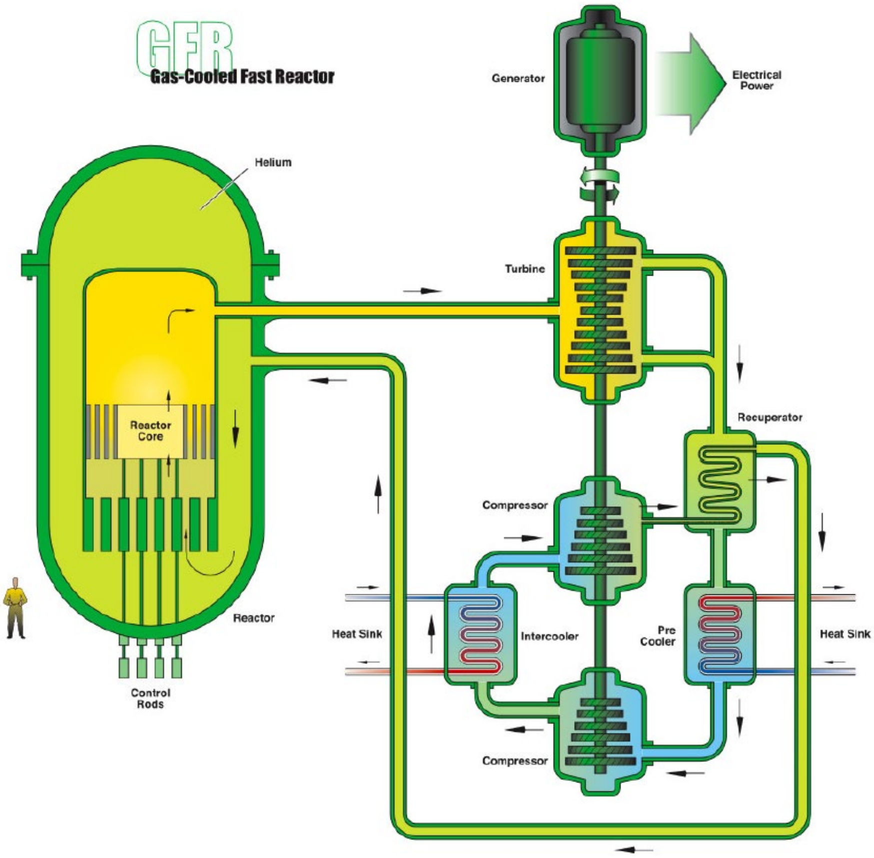
The reactor core may have a thermal or a fast-neutron spectrum, depending on the core design. The concept may be based on current pressure vessel or on pressure tube reactors, and thus use light water or heavy water as moderator. Unlike current water-cooled reactors, the coolant will experience a significantly higher enthalpy rise in the core, which reduces the core mass flow for a given thermal power and increases the core outlet enthalpy to superheated conditions. For both pressure vessel and pressure-tube designs, a once through steam cycle has been envisaged, omitting any coolant recirculation inside the reactor. As in a boiling water reactor, the superheated steam will be supplied directly to the high pressure steam turbine and the feed water from the steam cycle will be supplied back to the core. Thus, the SCWR concepts combine the design and operation experiences gained from hundreds of water-cooled reactors with those experiences from hundreds of fossil-fired power plants operated with supercritical water (SCW). SCWRs can potentially be developed incrementally step-by-step from current water-cooled reactors.

SCWR Assessment Criteria (for closed fuel cycle)	**Score**
Timescales for Delivery	**L**
• TRL: estimated to be ~2 • R&D activities [31]: • Pressure vessel and pressure tube designs: • Safety analysis • Testing of materials and selection and qualification of candidate alloys • Out-of-pile fuel assembly testing • Qualification of computational tools • Integral component tests • In-pile tests of small-scale fuel assembly • Start design studies of prototype • Some of these challenges can be mitigated through lowering the operating temperature of the coolant in SCWRs in order to reduce the peak cladding and fuel temperature. • Other: Reactor type is at a very early stage of development.	
Heat	**M**
• 510-625°C – limited versatility with relative to other designs. Note however that a significant proportion of current industrial heat demand (around 60%) is below 550°C and there is research interest into developing hydrogen production routes utilising lower temperature heat. • Thermal Efficiency: ~44% [42].	
Safety [30]	**L**
• Supercritical Water-Cooled Reactors are in their early stages of development with many unproven concepts and design features. Significant research is needed before these reactors could be considered for demonstration purposes. No GIF safety assessment is available for this AMR family.	
Security [17-19]	**M**
• In theory thermal SCWRs are low security risk, using LEU fuel, operating on an open cycle and comparable to current LWR systems. • For fast SCWRs, operating on a closed fuel cycle, they have greater proliferation risks than reactor systems employing an open fuel cycle. Where spent fuel is reprocessed, there is the potential for the inherent PRPP performance to be less favourable. • Security and safeguards will be designed to offer adequate protection and inherent PRPP.	
UK Value	**L**
• No known UK expertise.	
Economic Costs	**M**
• Potential of lower capital costs for the given electric power of the plant and of better fuel utilisation, offering a clear economic advantage compared with current water-cooled reactors. However high development costs.	

Deployability	**M**
• Load Follow Capability: Limited information in public domain • Flexibility of location: low • Reactor size: variable, 300-700 and 1000-1500MWe envisaged • Fuel utilisation: for closed fuel cycle, high sustainability. Open, once through have higher fuel utilisation.	
Adaptability	**M**
• SCWRs assessed as medium for Pu and actinide management [5-7]	
Waste & Environment	**H**
• The goal of SCWR conceptual design is to reduce waste mass, volume, thermal load on the repository, and the level of radiotoxicity. The reuse of plutonium can result in significant reductions (between 25% and 50%) in decay heat and radiotoxicity for long term storage (i.e., from 1,000s to 10,000s of years). • The high-level waste per unit electricity produced is also reduced by approximately 25% when Heavy Water Reactor (HWR) Pu is recycled.	
International	**L**
• Low level of international research and development focused through the Generation IV international Forum. • R&D work continues in the US and Russia. Some activity in Japan, Canada and Europe on preconceptual designs of pressure vessel types. No known demonstrators.	

Gas-cooled Fast Reactors (GFR)

The GFR system is a high-temperature helium-cooled fast-spectrum reactor with a closed fuel cycle. It combines the advantages of fast-spectrum systems for long-term sustainability of uranium resources and waste minimisation (through fuel multiple reprocessing and fission of long-lived actinides), with those of high-temperature systems (high thermal cycle efficiency and industrial use of the generated heat, for hydrogen production for example).



[3]

GFRs are in their early stages of development with many unproven concepts and design features. Significant research is needed before these reactors could be considered for demonstration purposes.

The GFR uses the same fuel recycling processes as the SFR and the some of the same reactor technologies associated with VHTR systems. Therefore, its development approach is to rely, in so far as feasible, on technologies developed for the VHTR for structures, materials, components and power conversion system. Nevertheless, it calls for specific R&D beyond the current and foreseen work on the VHTR system, mainly on core design and safety approach.

The reference design for GFR is based around a 2,400 MWth reactor core contained within a steel pressure vessel. The core consists of an assembly of hexagonal fuel elements, each consisting of ceramic-clad, mixed-carbide-fuelled pins contained within a ceramic hex-tube. The favoured material currently for the pin clad and hex-tubes is silicon carbide fibre reinforced silicon carbide.

The coolant is helium and the core outlet temperature will target 850°C. A heat exchanger transfers the heat from the primary helium coolant to a secondary gas cycle containing a helium-nitrogen mixture which, in turn drives a closed cycle gas turbine. The waste heat from the gas turbine exhaust is used to raise steam in a steam generator which is then used to drive a steam turbine. Such a combined cycle is common practice in natural gas-fired power plant so represents an established technology, with the only difference in the GFR case being the use of a closed cycle gas-turbine. Safety is a major challenge for the development of GFR systems [24].

GFR Assessment Criteria	**Score**
Timescales for Delivery	**L**
• TRL: 2 • R&D requirements: Extensive. • For Gas-cooled fast reactor (GFR) 2 400 MWth reference design R&D priorities are: • Finalising design and initiating licensing process of a GFR experimental reactor (ALLEGRO) • Qualification of the mixed oxide fuel adapted to the specific operating conditions of the ALLEGRO start-up core • Development of dense fuel elements capable of withstanding very high temperature transients • Validation studies (experiments addressing innovative ceramic materials, unique GFR specific abnormal operating conditions such as depressurisation and steam ingress) • Air and helium tests on subassembly (mock-ups under representative temperature and pressure conditions) • Large-scale air and helium tests to demonstrate passive decay heat removal functions • GFR-specific components development and qualification [33]. • Other: At early stage of development.	
Heat	**H**
• ~850°C, providing versatility • Thermal efficiency: ~45% [43].	
Safety	**L**
• No GIF safety assessment or views from the regulators are available for this AMR family. Safety is a major challenge for the development of GFR systems [44]. • High pressure gas coolant with limited thermal inertia that won’t pool like sodium or lead.	

Security	**M**
• Closed fuel cycles have greater proliferation risks than reactor systems employing an open fuel cycle. Where spent fuel is reprocessed, there is the potential for the inherent PRPP performance to be less favourable. GFRs share similar safeguards and non-proliferation characteristics with other fast neutron reactor systems (either sodium or lead-cooled). However, there are uncertainties associated with GFR systems that are not well defined [31].	
UK Value	**L**
• No known UK expertise	
Economic Costs	**M**
• Unknown. Development costs likely to be very high given material and safety challenges	
Deployability	**H**
• Load Follow Capability: Limited information in public domain • Flexibility of location: low – large scale plant • Reactor size: variable, 1200MWe • Fuel utilisation: closed fuel cycle, therefore high sustainability. GFR is capable of achieving a high breeding ratio, which allows a self-sustained fuel cycle not dependent on uranium supply [4-7]	
Adaptability	**H**
• An integral fuel cycle is envisaged, with full actinide recycle and on-site processing to eliminate off-site transport of nuclear materials [5].	
Waste & Environment	**VH**
• Combines the advantages of fast-spectrum systems for long-term sustainability of uranium resources and waste minimisation (through fuel multiple reprocessing and fission of long-lived actinides). • GFRs are assessed as Medium for spent fuel mass, High for VHLW, ILW, and LLW volumes, long term heat output, and long term radiotoxicity, and very high for environmental impact [4-7]	
International	**L**
• Low level of international research and development focused through the Generation IV international Forum. • No known demonstrators	

Appendix 2: Further Analysis for Technology Assessment of AMRs

This report draws on previous evaluations that have been made of the AMR technologies that are outlined in Table 1:

- Assessment 1 draws on the 2012 NNL assessment of advanced reactor systems [4-7].
- Assessment 2 draws on NNL's 2016 SMR Techno-Economic Assessment and Generic Feasibility Assessment [8-9]. and
- Assessment 3 puts forward a new analysis, drawing evidence from several techno-economic studies [3-13] with additional sources as referenced, developed to better reflect BEIS priorities and to support the development of the UK AMR R&D Programme. This assessment is outlined in the main body of the report and in Appendix 1.

Data from these studies have been used and scores and weightings have been applied to evaluate the AMR technologies with respect to the high-level criteria outlined in Table 2. The sections in Appendix 2 provide further detail on the analysis.

Assessment 1

In 2012 National Nuclear Laboratory (NNL) developed a comprehensive list of criteria for assessing reactor types [4][7], with key high-level criteria for Costs, Inherent Proliferation Resistance and Physical Protection (IPRPP), Safety, Strategic factors, Deployability, Sustainability, and Waste. These criteria and sub-criteria were reviewed to ensure that there was no duplication and to avoid double counting [6]. The revised set of criteria with descriptors are listed in Table A1. In [5, 7] the AMR technologies were assessed with respect to these criteria and assigned a score on a four point scale against each metric according to whether the performance of a system is assessed as Very High (4), High (3), Medium (2) and Low (1) respectively, with Light Water Reactors (LWR) used as a reference case (i.e. the scoring for AMR technologies was relative to LWRs).

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[7] This report assesses very high temperature gas cooled reactors (VHTRs). For the purposes of Assessment 1 these will be assumed to be applicable to HTGRs since HTGRs can offer similar temperatures and capability to VHTRs but offer higher technical maturity than VHTRs. The score of 4 for the potential to drive thermal processes is applicable to HTGRs as the temperature outputs allow capability for hydrogen production by all currently available methods (S-I, CuCl, Steam Electrolysis).

Table A1: Assessment Criteria for NNL Study [4-7]

Criteria
1. Generating costs
a. Construction Overnight construction cost is the cost that would be incurred if construction could be completed instantaneously i.e. without finance charges. The overnight construction cost is the substantive cost, meaning the actual cost of construction materials, components and labour.
b. Production Operation and maintenance costs
c. Decommissioning
d. R&D
2. Inherent Proliferation Resistance and Physical Protection
a. Separated material Production of nuclear materials such as high enriched uranium (HEU), Weapons-Grade plutonium (WG-Pu) or reactor grade plutonium (RG-Pu)
b. Spent fuel characteristics Proliferation resistance characteristics of spent fuel determined by the combination of the isotopic composition of the fissile material and the physical and radiological characterisation of the fuel material that would constitute inherent barriers to accessing the fissile material.
c. Proliferation resistance Demonstration of increased proliferation resistance by design
3. Safety
a. Reliability The forced outage rate, which should preferably be very low
b. Radiological exposures Radiological exposures to workers and the public from normal operations and from accidents.
c. Reactivity control Demonstration that the reactor system can be shutdown safely from any operating condition with a specified margin and accounting for uncertainties. There is also a requirement for an independent shutdown mechanism
d. Decay heat removal Demonstration that a reactor system is able to dissipate decay heat following any normal or abnormal operating condition.
e. Low uncertainties on dominant phenomena Uncertainties affecting the engineering parameters controlling safety.

f.	**Fuel thermal response** Timescale on which the temperature of the fuel responds to off-nominal operation. If the response time is long, then this provides more time to sense the abnormal condition and take mitigating actions.
g.	**Integral experiment scalability** Important consideration during the R&D phase of a new reactor or fuel cycle plant.
h.	**Source term** The part of the radiological inventory of a reactor core that can potentially be released in an accident condition. It is important because it determines whether there is a need for emergency response arrangements to be made outside the site boundary.
i.	**Energy release mechanisms** There should be no mechanisms that release energy during accident conditions.
j.	**System response times** Time constants associated with the balance of the nuclear system design. Slow response times associated with large heat capacities and low specific ratings are desirable, but must be balanced against the economic penalties of low ratings and large masses.
k.	**Effective hold-up** Mechanisms in the design of a plant for containing radioactive material following an accident condition.
4.	**Strategic**
a.	**Scalability** Scalability effects relating to the construction and decommissioning of modular reactor systems.
b.	**Timescales to deployment** Timescales at which new reactor systems could realistically be deployed
c.	**Technology readiness level** Systematic method of assessing how mature the technology is and therefore is indicative of the timescale for commercial readiness, the investment needs and the risk of technological failure.
5.	**Deployability**
a.	**Load follow capability** Ability to operate in responsive mode to changes in grid demand. There are two basic requirements: 1) Frequency control - small changes in power output (a few percent) in response to changes in grid frequency, which contributes to stability of the grid. 2) Pre-programmed load-follow - cycle output from 100% down to as low as 30% and back again overnight as demand falls.
b.	**Flexibility of location** Relevance for siting

c.	**Number and size of reactors needed**
d.	**Associated fuel cycle** Fuel cycle plants needed
e.	**Potential to drive thermal processes** The ability of nuclear reactors to provide heat sources for processes such as hydrogen production or petrochemical conversion
6.	**Sustainability**
a.	**Fuel utilisation** The mass of uranium ore needed to meet the fuelling requirements of the reactor.
7.	**Waste**
a.	**Spent fuel mass** The spent fuel arising is most meaningfully expressed as the heavy metal (HM) mass of fuel per GWye (tHM/GWye).
b.	**HLW, ILW, and LLW volumes**
c.	**Long term heat output** A measure of the hazard potential of radioactive material.
d.	**Long term radiotoxicity** A measure of the hazard potential of radioactive material.
e.	**Environmental impact** e.g. visual. gaseous and aqueous emissions. carbon footprint. impact of uranium mining.
f.	**Plutonium and minor actinide management** Capability of recycling plutonium destroying minor actinides

For this report, Assessment 1 used the scores that were assigned to these criteria for the AMR technologies listed in Table 1, and then applied % weightings to reflect current BEIS priorities with respect to the high-level criteria. The outputs were then used to generate an overall score to rank the AMR technologies in order. Sensitivity analysis was then conducted to establish how changing the weightings of the criteria would affect the ranking. To illustrate this, four sets of weightings and rankings are shown in Tables A2 and A3. Further sensitivity analyses with different weights can be conducted if needed to further explore which factors have an impact on outcomes.

Analysis A applies weights the criteria to reflect the current BEIS prioritisation of criteria, with an emphasis on the ability to deliver multiple energy vectors and to make a significant contribution to meeting net zero climate targets by 2050. In this scenario HTGRs are ranked highest. Sensitivity analyses applied different sets of % weightings to illustrate how changing the priority of the criteria affects the ranking of the different AMR technologies. Analysis B weights the Strategic criteria (time/readiness) at zero, removing time and technological readiness as a factor in the assessment to establish the impact of this criteria on the ranking. This analysis indicates that if time were not a key factor in the decision process, HTGRs would still be ranked at 1. This can be attributed to the strong performance of HTGRs with respect to Safety, Inherent PRPP, Economic Costs, and Deployability. Analysis C weights all of the criteria equally, with these weighting the AMR technologies are much closer together with HTGRs ranked top, followed closely by SFRs and MSRs. For Analysis D Safety and Strategic were eliminated from the assessment (with a weighting of zero) and weightings for Sustainability and Waste at 20%. In this scenario HTGRs ranked 5 with MSRs ranked 1. However, it should be noted this is an unrealistic scenario given the importance of technology readiness and safety to overall deliverability.

Weightings and Rankings for Assessment 1

Weightings were applied and sensitivity analysis conducted, varying the weightings applied to the criteria to assess how changing priorities could impact the rankings. Table A2 gives the weightings applied and Table A3 gives the overall scores and rankings for Assessment 1. Analyses A-D describes how the different weightings applied affect the scores and rankings.

Table A2: Weightings for Assessment 1

Top level criteria	A	B	C	D
Generating Cost	15%	20%	14.4%	20%
Inherent Proliferation Resistance and Physical Protection (PRPP)	15%	20%	14.4%	20%
Safety	15%	20%	14.4%	0%
Strategic	22.5%	0%	14.4%	0%
Deployability	22.5%	20%	14.4%	20%
Sustainability	5%	10%	14.4%	20%
Waste	5%	10%	14.4%	20%
Total	100%	100%	100%	100%

Table A3: Overall Scores (S) and Rankings (R) for Assessment 1

	S A	R A	S B	R B	S C	R C	S D	R D
SFR	57	2	56	4	63	=2	64	= 2
GFR	47	=5	55	5	56	5	64	= 2
LFR	53	4	57	3	61	4	64	= 2
HTGR / VHTR	69	1	69	1	64	1	58	5
SCWR	47	=5	51	6	46	6	50	6
MSR	55	3	63	2	63	=2	70	1

Analysis A

Weightings have been applied to reflect current BEIS priorities. A weight of 22.25% has been applied to the Strategic and Deployability (which includes heat) criteria, as the primary importance is the ability to deliver to timescales that will make a significant contribution to meeting net zero climate targets by 2050 via multiple energy vectors. Safety, Inherent PRPP, and Cost are deemed to be of high importance, therefore these criteria have been weighted at 15%. Waste and Sustainability (fuel utilisation) have been weighted 5% as these are criteria of other importance. With these weights the clear choice is HTGRs with a 12% margin over the next ranked SFR.

Analysis B

This set of weights takes the key criteria of Strategy (time) out of the equation in order to assess the impact of this on the ranking. Weights on Deployability, Safety, IPRPP, Costs other criteria are set at 20% to give them an equal ranking, and waste and sustainability are weighted at 10%. HTGRs remain the highest ranked reactor type with a 6% margin over the next highest ranked MSR.

Analysis C

This analysis attempts to determine what high-level criteria will affect the overall ranking and sets all of the weights equally as 14.4% of the overall score. This is not meant to be a robust assessment as it gives a disproportionate weighting to Sustainability. With this approach the numbers are much closer together but HTGRs still remain ranked the most favourable but only by a margin of 1%, followed closely by SFRs and MSRs.

Analysis D

This set of weightings is set to draw out what criteria would need to be prioritised in order to remove HTGRs as highest ranked option, and which would need to be deprioritised. Reducing the weightings on Strategic and Safety to 0% and distributing weightings on the other criteria where HTGRs score lower, including sustainability, ranks MSRs at 1 and HTGRs at 5. This is an unrealistic scenario given the importance of technology readiness and safety to overall deliverability.

Assessment 2

In March 2016 NNL conducted a Techno-Economic Assessment of SMR Technologies for the Department of Energy and Climate Change [8-9]. Part of this work involved the development of the Generic Feasibility Assessment (GFA) methodology to provide a high-level method of assessing the different nuclear reactor and fuel cycle systems which the UK might want to consider in the future.

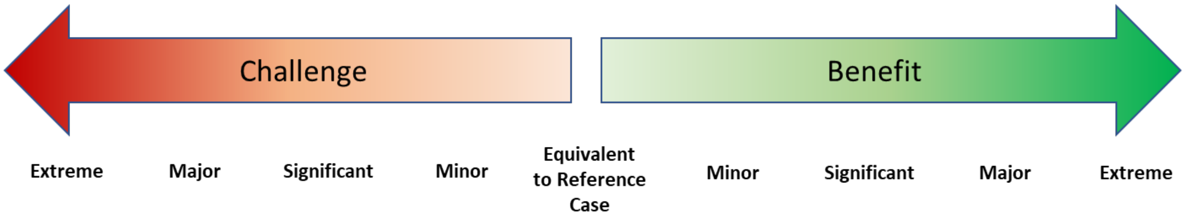
For this analysis, the GFA concept starts from the recognition that, in the UK context, safety, environmental and proliferation/security attributes are all covered by well-developed regulatory regimes – so that reactor system deployment is not about how safe, secure, and environmentally benign a system is but rather how much time and effort must be expended to allow the system to conform with these tried and tested regulatory frameworks.

The GFA methodology defines a number of attributes to provide an assessment of reactor types, as outlined in Table A4. To provide a baseline, a generic Small Modular Pressurised Water Reactor (SM-PWR) was compared with a Gigawatt-sized PWR. The AMR technologies were then assessed by expert judgement against this agreed generic SM-PWR as the reference case to obtain a review of their relative benefits and challenges in relation to the attributes, as outlined in Table A4. Note that this assessment does not assess SCWRs or GFRs.

Many of the attributes in this assessment are interlinked, therefore it is not appropriate to weight them in the same way as with the data in Assessment 1. However, this assessment also points to HTGRs as being the best positioned to support decarbonisation, with some minor challenges to be overcome.

Table A4: Generic Feasibility Assessment of AMRs

	HTGR	SFR	LFR	MSRF	MSRTh
Time and effort to license	Minor Challenge	Significant Challenge	Major Challenge	Extreme Challenge	Major Challenge
Environmental Authorisation	Equivalent to Reference Case	Equivalent to Reference Case	Significant Challenge	Major Challenge	Major Challenge
PRPP Acceptability	Significant Benefit	Minor Challenge	Minor Challenge	Significant Challenge	Significant Challenge
Economic Competitiveness	Minor Challenge	Significant Challenge	Major / Significant Challenge	Major Challenge	Significant Challenge
Fuel Security	Equivalent to Reference Case	Major Benefit	Major Benefit	Major Benefit	Minor Benefit
Disposability	Significant Challenge	Significant Challenge	Significant Challenge	Major Challenge	Major Challenge
Siting (reactor and fuel cycle)	Minor Benefit	Equivalent to Reference Case	Equivalent to Reference Case	Significant Challenge	Equivalent to Reference Case
Access to International Programmes	Minor Benefit	Significant Benefit	Significant Benefit	Significant Benefit	Significant Benefit
Time and Cost to Deployment	Minor Challenge	Significant Challenge	Major Challenge	Extreme Challenge	Major Challenge
Enable UK Supply Chain	Minor Benefit	Significant Benefit	Significant Benefit	Significant Benefit	Significant Benefit
Flexibility (load follow capability)	Minor Benefit	Minor Benefit	Minor Benefit	Minor Benefit	Minor Benefit
Process Heat	Major Benefit	Significant Benefit	Significant Benefit	Significant Benefit	Significant Benefit



Assessment 3

This assessment is detailed in the main body of this report. It draws on data from several techno-economic studies [3-13], with additional sources as referenced. It should be noted that the assessment was done with the available evidence, gaps in knowledge exist and there are uncertainties associated with some of the data. This assessment includes additional high-level criteria of Heat[8], UK Value, Adaptability, and International that are important to the UK AMR R&D demonstration programme:

Heat

The technology must be able to contribute beyond electricity through multiple energy vectors, including the ability to generate high temperature heat that could offer efficient routes to low-carbon hydrogen production, industrial process heat & low-carbon fuels.

Heat Sub-Criteria

- Temperature outputs
- Efficiency

Decarbonisation to net zero by 2050 will require diversification. A key function of the chosen technology must be its ability to contribute beyond electricity through other energy vectors of heat and hydrogen production, and other functions such as the generation of synthetic fuels. The measure of how the AMR technologies could deliver on Heat are through temperature outputs and efficiency of the resulting processes. The temperature outputs of the AMR technologies are known and a score can be attributed to this criteria. The ability of the AMR technologies to contribute to heat and hydrogen networks is at an early stage of development and could be verified through the building of a demonstrator. An overall assessment for Heat, based on temperature output and thermal efficiency is given in Table A5. Extracting to a higher-level criteria will enable more weight to be put on this criteria to reflect the importance to the programme.

Table A5: Assessment for the High-Level Criteria of Heat

	SFR	GFR	LFR	HTGR	SCWR	MSR
Heat	Medium	High	Medium	Very High	Medium	High

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[8] Potential to drive thermal processes was included in Assessment 1 as a sub-criteria, in this assessment it is elevated to a high-level criteria to reflect the importance to the UK AMR R&D programme.

UK Value

The technology needs to have the potential to draw on UK supply chain capability, existing UK knowledge skills and supply chain base and potential for UK jobs.

UK Value Sub-Criteria

- Verification and validation facilities - availability of facilities such as environmental test loops, zero-power research or materials test reactors.
- Suitably Qualified & Experienced Personnel (SQEP)
- Manufacturing Capability

[10] provides an assessment of the current capability of the UK supply chain to deliver the AMR technologies. An assessment for UK Value is outlined in Table A6.

Table A6: Assessment for the High-Level Criteria of UK Value

	SFR	GFR	LFR	HTGR	SCWR	MSR
UK Value	High	Low	Low	High	Low	Low

Note that [10] does not provide assessment of SCWRs or GFRs. NIRO have given an indicative score for these, based on knowledge of UK supply chain.

Adaptability

Flexibility of the system to adapt to address potential future requirements, e.g. the ability for multi-purpose functions in future, such as plutonium and minor actinide management, or medical radioisotope production.

Adaptability Sub-Criteria

- Modularity (Construction) – A significant proportion of the nuclear plant must be capable of being manufactured, constructed, replaced and decommissioned in a modular manner.
- Modularity (Operation) – Technology should be able to be deployed in multiples dependent upon need in any one location.
- Ability for multi-purpose functions in future
  - Plutonium (Pu) and Minor Actinide Management
  - Medical radioisotope production

It is possible to assign a score for Pu and actinide management as in [5, 7], and it is expected that all AMR technologies (particularly for demonstrators) have the potential to produce medical radioisotopes, therefore would score similarly and would have no impact on rankings. However, the AMR technology designs are not at a stage where it is possible to assess modularity. Table A7 gives the scores for Adaptability.

Table A7: Assessment for the High-Level Criteria of Adaptability

	SFR	GFR	LFR	HTGR	SCWR	MSR
Adaptability	High	High	High	High	Medium	Very High

International

The prospects for international collaboration and UK export opportunities of AMRs.

International Sub-Criteria

- Access to international programmes
- Export potential

The UK may wish to collaborate with international partners in order to accelerate the development of an AMR system by 2030. Table A8 gives an assessment for International.

Table A8: Assessment for the High-Level Criteria of International

	SFR	GFR	LFR	HTGR	SCWR	MSR
International	High	Low	Medium	Very High	Low	Medium

Weightings and Rankings for Assessment 3

Weightings were applied and sensitivity analysis conducted, varying the weightings applied to the criteria to assess how changing priorities could impact the rankings. Table A9 gives the weightings applied and Table A10 gives the overall scores and rankings for Assessment 3.

Table A9: Assessment 3 Weightings

	A	B	C
Economic Costs	9%	10%	10%
Security	9%	15%	10%
Safety	9%	15%	10%
Timescales for Delivery	24.5%	0	10%
Deployability	9%	10%	10%
Waste & Environment	2%	10%	10%
Heat	24.5%	15%	10%
UK Value	9%	10%	10%
Adaptability	2%	10%	10%
International	2%	5%	10%

Table A10: Assessment 3 Scores and Rankings

	Score A	Rank A	Score B	Rank B	Score C	Rank C
SFR	66	2	57	=2	64	2
LFR	51	4	54	=4	54	4
HTGR	88	1	80	1	80	1
MSR	54	3	57	=2	56	3
GFR	48	5	54	=4	49	5
SCWR	42	6	45	6	43	6

Analysis A reflects BEIS objectives, weighting Time and Heat (energy vectors) as primary criteria, Safety, Security, Economic Costs, UK Value, and Deployability as high criteria, and International, Adaptability, and Waste & Environment as criteria of other importance, HTGRs again are ranked highest, with and without weighting on time. Analysis B takes time out of the analysis by weighting 0%, and Analysis C weights all of the criteria the same. In both Analysis B & Analysis C HTGRs remain ranked at 1 but with smaller margins.