National Nuclear Laboratory

Assessment of advanced reactor systems against UK performance metrics

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EXECUTIVE SUMMARY

The UK National Nuclear Laboratory has been contracted by the Department of Energy and Climate Change (DECC) to review and assess the relevance to the UK of several of the advanced reactor systems currently being developed internationally. The scope of work calls for the review to consider the six advanced reactor systems being developed by the Generation IV (Gen IV) International Forum (GIF), as well as other systems being developed outside Gen IV. In total, nine systems are considered, the first six of which come under Gen IV: Sodium fast Reactor (SFR); Gas Fast Reactor (GFR); Lead Fast Reactor (LFR); Very High Temperature Reactor (VHTR); Super Critical Water Reactor (SCWR) Molten Salt Reactor (MSR); Accelerator Driven Sub-critical Reactor (ADSR); Hyperion Power Module (HPM) and Small modular Light Water Reactor (LWR).

It should be noted that the assessment completed in this paper should only be classed as preliminary; the paper and the associated assessments are <u>not</u> intended to act as an exhaustive review and assessment of potential advanced reactor technologies in order for DECC or other UK interested parties to immediately down select reactor options. The study and the approach developed was deliberately limited in its assessment of reactor options primarily due to time and in particular budget constraints. As such, only a limited cross section of reactor technologies were assessed and no design variants were assessed either e.g. prismatic or pebble VHTR options. The paper is intended to provide an early insight into the technologies that could have a potential role in the UK, but moreover, the assessment is intended to highlight the barriers to be overcome by a given reactor technology if it is to prove to be successful in the UK context. This information can then be used to assist the UK stakeholders in determining not just which technologies have greater barriers to overcome, but the types of R&D needed to be undertaken, either by the UK (which can be used to determine potential commercial or strategic benefit to the UK) or by those involved internationally in the programmes. This assessment therefore also assists in informing regulators, researchers etc as to the likely risk areas in the future.

The NNL has undertaken this study from an independent and authoritative position. In addition to the open literature papers and studies available, the assessments have been based on NNL's decades of industrial, international experience in the fields of reactor and fuel cycle development, assessment and deployment. This experience, combined with the expertise in the relevant scientific and engineering fields has enabled the NNL to apply a realistic assessment of the technologies, including the timescales and amount of man effort required to develop and deploy a commercial system.

In an earlier report produced as part of this same study [2], a set of 42 metrics were identified as being relevant to the assessment of advanced reactor designs in the UK. The first 26 of these metrics are actually those used by the Generation IV International Forum (GIF) and the remaining ones have been developed and included by NNL as part of this study as additional metrics for completeness. This report assesses each of the nine advanced reactor systems of interest and evaluates them against the metrics, using a simple scoring method. Three slightly different scoring systems were used: (1) the 42 metrics were all treated with equal weightings; (2) those metrics related to technological readiness were removed from the overall scoring (effectively they were given zero weightings); (3) only those metrics that are relevant for non base-load electricity production such as high temperature process heat production, hydrogen production, load balancing and plutonium/minor actinide management. The second approach highlights

the benefits a particular reactor option would deliver if all the technological feasibility issues associated with it were removed. This highlights whether a particular option holds any promise of improved performance over current technology, which is judged to be a necessary condition for R&D spend – if a system fails to deliver significant benefits even if proved feasible, then R&D spend on it is not justified. It is believed that the combination of these three approaches provides a fair overall assessment.

In summary, when including consideration of technical maturity (scoring system 1), VHTR has the highest aggregate score, on account of its inherent safety characteristics, despite the fact that its performance in terms of long term sustainability is only comparable with that of current LWRs. SFR, LFR, MSR, ADSR and HPM all rank about equally and close to the reference once-through LWR. All these systems offer the possibility of a closed fuel cycle that would be independent of uranium ore availability. However there are technical feasibility issues with all these systems and they would also require substantial investment in the fuel cycle infrastructure. Small modular LWRs again are ranked about the same, showing a marginal improvement over current LWRs. Small modular LWRs might have a role in the UK in plutonium disposition or in scenarios with high nuclear deployment limited by the availability of suitable sites. Technology feasibility is not a major consideration and the key issue would be to address the operating and maintenance cost basis. The remaining systems (GFR and MSR) fail to match the overall scoring of the LWR reference, primarily because of technology feasibility.

When the metrics related to technological readiness are excluded (scoring system 2), VHTR remains the highest ranked, but now MSR and ADSR have the next highest scores. Indeed, all nine advanced reactor systems considered here now rank ahead of the PWR reference, this scoring system disregards metrics related to technological maturity and therefore measures the potential of the advanced systems assuming the technological issues will all be resolved satisfactorily.

Under scoring system 3, the rankings are again similar, with VHTR in the leading position on account of its suitability for high temperature process heat applications.

It should be noted that depending on the priorities for the deployment and/or development of the role of nuclear in the UK, then clearly the relative weightings of the metrics and thus scores provided in this analysis will change. Nevertheless, it is believed that this approach and report provides a strong and independent basis from which further thinking can be based depending on future priorities. The UK Nuclear Fission Technology Roadmap, currently being developed, should identify the priorities and could be used to determine the appropriate weightings that will reflect them.

Finally, recommendations are made as what should be the guiding principles for UK participation in international advanced reactor programmes and in deciding on the direction of any future engagement by the UK in international advanced reactor R&D. It is highlighted that the UK needs to be very clear on the reasons for participating.

The UK NNL would like to also recognise and thank all of the external reviewers for their time taken to review the study and for their comments on the paper. As with any such review process, not all of the comments were able to be included in the final version of the report either due to opposing views not simply between the authors and the reviewers, but also between the reviewers themselves. Nevertheless, every comment was considered and included where appropriate.

VERIFICATION STATEMENT

This document has been verified and is fit for purpose. An auditable record has been made of the verification process. The scope of the verification was to confirm that : -

- The document meets the requirements as defined in the task specification/scope statement
- The constraints are valid
- The assumptions are reasonable
- The document demonstrates that the project is using the latest company approved data
- The document is internally self-consistent

HISTORY SHEET

Issue Number	Date	Comments
Issue 1	28 April 2011	Issued for comment.
Issue 2	3 June 2011	Revised to address customer comments.
Issue 3	5 Jan 2012	Re-issue taking account of comments received from reviewers.
Issue 4	27 Jan 2012	Correction of minor typographical errors.
Issue 5	5 Mar 2012	Security clearance removed to allow publication.

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1. Introduction

The UK National Nuclear Laboratory has been contracted by the Department of Energy and Climate Change (DECC) to review and assess the relevance to the UK of the advanced reactor systems currently being developed internationally. The scope of work calls for the review to consider the six advanced reactor systems being developed by the Generation IV (Gen IV) International Forum (GIF) [1], as well as other systems being developed outside Gen IV. In total, nine systems are considered, the first six of which come under Gen IV:

1. Sodium Fast Reactor (SFR).
2. Gas Fast Reactor (GFR)
3. Lead Fast Reactor (LFR)
4. Very High Temperature Reactor (VHTR)
5. Super Critical Water Reactor (SCWR)
6. Molten Salt Reactor (MSR)
7. Accelerator Driven Sub-critical Reactor (ADSR)
8. Hyperion Power Module (HPM)
9. Small modular Light Water Reactor (LWR)

These nine systems span a very wide range of technological maturity, from systems for which the technology is already very highly developed, to ones where the technology is still at the early conceptual stage. They are all claimed to improve on current reactor technology, which is taken here to mean large Light Water Reactors (LWRs), with outputs in the region of 1 GWe or more, with either a once-through fuel cycle or a reprocessing cycle based on the conventional PUREX separation process. In the first instance, new build in the UK will be based on large Pressurised Water Reactor (PWR) designs, either the Westinghouse AP-1000 or AREVA EPR. It is recognised that the main priority for the UK at present is to ensure that new build proceeds in a timely way to ensure energy security and achieve CO_2 targets. However, with a 60 year design life, the timescale over which the new build PWRs will be operational will extend well towards the end of the century where the world energy situation may well be very much changed and where more advanced systems might have a legitimate role.

In an earlier report carried out as part of this same study for DECC [2], a total of 42 metrics were defined which are considered relevant to the UK. The report made an initial indication of the UK relevance of each metric and also what level of discrimination each metric will likely give between the different systems. This could at a later date form the basis for defining weighting factors for combining the metrics, though at this stage this has not been attempted.

Of the 42 metrics defined in [2], the first 26 coincide with those used by GIF and the remaining metrics are additional ones that were considered applicable in the UK. This report applies the 42 metrics to each of the nine advanced reactor systems and combines the results in a very simple multi-attribute utility analysis (MAUA), with no attempt being made to assigns importance weighting factors to the different metrics. It is acknowledged that at this stage there is duplication amongst the metrics and it would be beneficial at some time to rationalise the metrics to eliminate the duplications, but that is not included in the current scope

Despite the simplicity of the approach, it is thought the resulting analysis provides a useful assessment of the relative merits of the nine systems. The analysis compares the performance of each of the nine systems against a baseline defined by current Light Water Reactor (LWR) technology, assuming a once-through fuel cycle. For completeness, a comparison is also made with an LWR recycle case, which is assumed to be single plutonium recycle in the form of PuO_2-UO_2 mixed oxide (MOX) fuel. Single recycle means that the MOX assemblies are irradiated then assigned to direct disposal rather than continued recycle, which represents current LWR recycle practice. A more sophisticated MAUA approach, including weighting factors that could perhaps be agreed by a consensus of interested parties, could be carried out at some future date.

The UK Nuclear Fission Technology Roadmap, currently being developed, will identify the UK's strategic priorities and could be used to determine the appropriate weightings that will reflect them. The Roadmap will be framed around a number of reference scenarios ranging from replacement new nuclear build to a very ambitious nuclear expansion. The weightings which would apply to the metrics would be different in each scenario, reflecting the different strategic drivers and in consequence the relative ranking of the different systems might be expected to change.

Section 2 summarises the salient features of each of the nine reactor systems considered. Section 3 describes the MAUA approach adopted and the Section 4 presents the results for each of the 42 metrics. Section 5 discusses what the level of international activity/R&D is for each of the systems. Finally, Section 6 summarises the main conclusions and discusses the way forward.

2. Systems descriptions

2.1. SFR

The sodium-cooled fast reactor (SFR) [8] uses liquid sodium as the coolant, in either a loop or pool-type configuration. Three SFR concept cores are considered: a 1500 MWe loop design; a 600 MWe pool design and a 50 MWe small modular design. The coolant operates at close to ambient pressure and has a high thermal inertia. The neutron spectrum is fast, although there is some moderation in the sodium and SFR is capable of operating a breeding cycle. The fuel can be either metal or oxide. SFR technology is already demonstrated to a large extent, with commercial scale prototypes having been built and operated in France, Japan, Russian Federation, UK and USA, though further development work will be needed to meet the Gen IV requirements.

A major limitation of SFR is the energetic reaction of sodium with water. This has necessitated the provision of a secondary heat transfer loop in all historic SFR designs. The first heat exchange is between the active sodium that has passed through the core and the inactive secondary loop. The secondary loop then exchanges heat with the water in the steam generating circuit, which ensures that any sodium/water interaction will be with non-radioactive sodium. The need for a secondary circuit significantly penalises the capital cost.

There is an issue with voiding the sodium coolant, which in SFR cores increases reactivity. However, it is known [3] that for SFR breeder cores the positive void coefficient is counteracted by fuel temperature feedback and the overall reactivity feedback is acceptable. However, the addition of minor actinides is known to cause a deleterious trend in the void coefficient that might restrict the permissible minor actinide load.

Within the Generation IV Project, SFR was selected partly because it is known to be capable of being operated as a breeder, which would allow a fleet of SFRs to operate a long term sustainable fuel cycle, independent of uranium supplies. It is also capable of operating with zero or positive breeding gain, giving the flexibility to operate as a burner of plutonium and minor actinides. The aim within GIF is to replace PUREX reprocessing with alternative processes designed to avoid the production of separated plutonium at any point in the fuel cycle. Another benefit, shared with all closed fuel cycle fast reactors, is that the radiotoxicity generated per GWy(e) is smaller than that from thermal reactors.

The EFR (European Fast Reactor) was a sodium-cooled fast reactor designed by a consortium called the European Fast Reactor Associates [5]. Although the design was sufficiently advanced the project did not reach the prototype construction phase.

Table 1: EFR (A SFR type reactor) Parameters

Parameter	EFR
Thermal/electric power output (MW)	3600/1458
Pressure (MPa)	Un-pressurised
Thermal efficiency (%)	40.5
Effective core height/diameter (m)	1.0/4.5
Average power density (MW/m^3)	225
Core inlet/outlet temperature (°C)	395/545

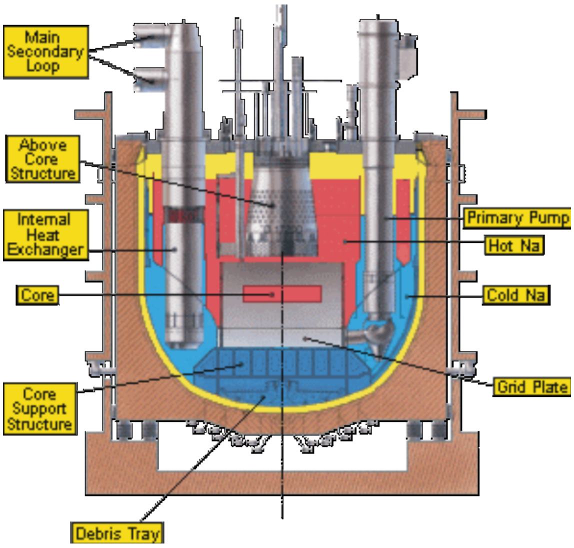

Figure 1: Sectional View of EFR core and EFR core components.

2.2. GFR

The gas-cooled fast reactor (GFR) uses pressurised helium gas as the coolant which is chemically inert and has only a slight neutron moderating effect. The reference concept for GFR in Gen IV [8] assumes all-ceramic fuel plate or fuel rod designs capable of withstanding high operating temperatures, though a plate fuel element with vanadium alloy cladding is being considered as well. Helium coolant is used with a direct Brayton cycle that gives a very high thermal efficiency. An alternative energy conversion option is the use of a supercritical CO_2 indirect cycle. An integral fuel cycle is envisaged, with full actinide recycle and on-site processing to eliminate off-site transport of nuclear materials. GFR is capable of achieving a high breeding ratio, which allows a self-sustained fuel cycle not dependent on uranium supply.

The high operating temperature of GFR is a very attractive feature, as is the inert coolant, which eliminates the need for heat exchangers in the direct cycle. However, GFR technology is presently very immature, with some major areas still requiring fundamental R&D. One such area is fuel technology, the all-ceramic fuel still being at the concept development stage. Another is the management of decay heat following loss of pressure in the reactor circuit.

The ‘GCPU01’ reactor was a gas-cooled fast reactor design concept intended to remain with the engineering limits of the AGR design, the design was an extension of that of the ET-GBR (Existing Technology Gas Breeder Reactor) developed by the UK in collaboration with European partners [6].

Table 2: Optimised GFR design ‘GCPU01’ parameters

Parameter	GCPU01
Thermal / electric power output (MW)	3600/1400
Pressure (MPa)	6
Thermal efficiency (%)	40.5
Effective core height / diameter (m)	2.0/5.0
Average power density (MW/m^3)	92
Core inlet / outlet temperature (°C)	300/525

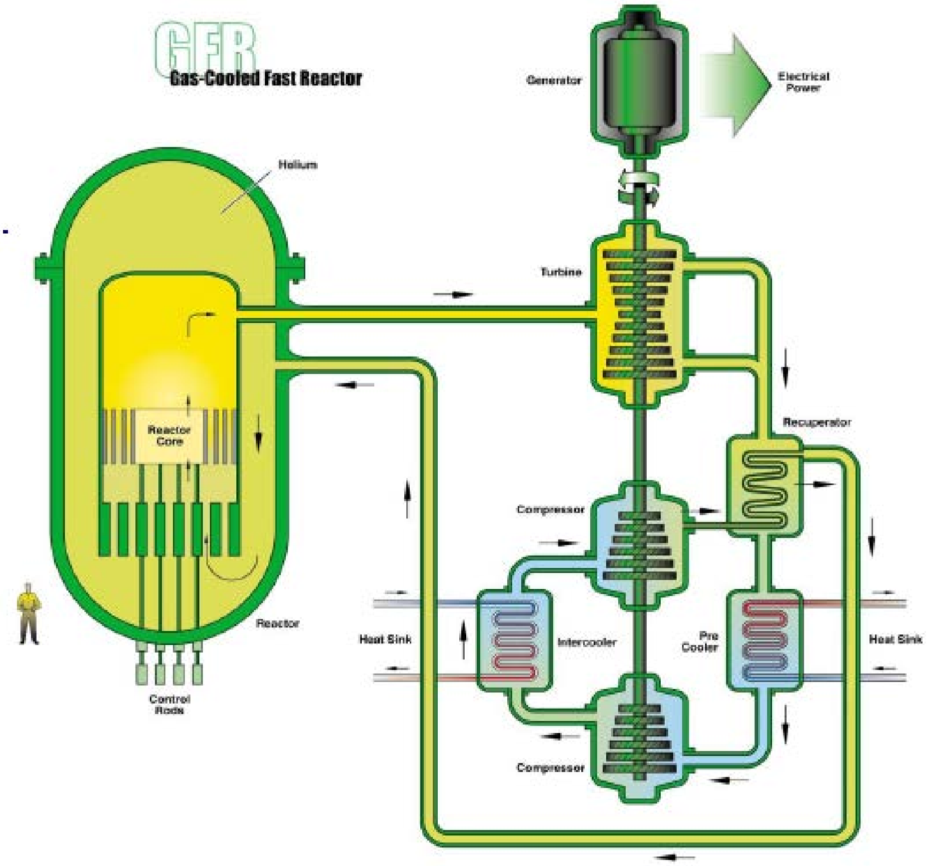

Figure 2: Schematic Gen IV GFR concept

2.3. LFR

LFR was originally developed in Russia for submarine propulsion to power the Alfa class hunter-killer boats. The operational history of the LFR power plant was affected by coolant leakage problems and at least one serious accident occurred that involved damaged fuel. Subsequently, these difficulties were overcome and Russia has developed a conceptual LFR design (BREST-300) for commercial power production. In recent years there have been further conceptual studies carried out by Japan, US and other countries. LFR cores have been proposed for long-life nuclear “batteries” for deployment in remote locations or in developing countries without electricity distribution grids. LFR is flexible enough to fill a wide range of roles, from low power, long core life batteries to high power commercial power reactors.

Two reference designs are proposed in GIF [8], the Small Secure Transportable Autonomous Reactor (SSTAR) and the European Lead-cooled System (ELSY). SSTAR has an output of 20 MWe, while ELSY is a 600 MWe design.

LFR uses molten lead-bismuth (Pb-Bi) eutectic or molten lead (Pb) as the coolant. Pb-Bi has a lower melting point than Pb (125°C cf. 327°C) and is the reference coolant choice for LFR. Although sodium has a lower melting point (98°C), lead and Pb-Bi both offer a significantly higher boiling point (>1670°C cf. 883°C for sodium), reducing the propensity for coolant voiding. Typical core arrangements are based on a pool-type configuration in an unpressurised vessel with a large vertical height. Molten Pb-Bi or Pb has a very high heat transfer capacity, which combined with its large mass gives a very large thermal inertia. Moreover, the high density, combined with the vertical height, provides a large pressure head to drive natural circulation. The large atomic mass of Pb-Bi and Pb is favourable for a hard neutron spectrum and good neutron economy, so that LFR is capable of achieving very high conversion ratios. An unfavourable aspect of Pb-Bi and Pb coolant is the tendency to corrode primary system components and although the Russians have demonstrated that corrosion can be controlled, it nevertheless remains an area where LFR is uncertain. Furthermore, the use of Pb or Pb-Bi coolant yields Po-210, a strong α-emitter, via neutron capture and β-decay processes.

As envisaged in Gen IV, LFR uses a closed fuel cycle with full actinide recycle. ELSY uses a superheated steam cycle, while SSTAR uses a supercritical CO_2 Brayton cycle.

Table 3: ELSY core parameters

Parameter	ELSY
Electric power output (MWe)	600
Thermal efficiency	0.42
Effective core height/diameter (m)	0.9/4.32
Core inlet/outlet temperature (°C)	400/480
Fuel	MOX, Nitrides
Coolant	Lead

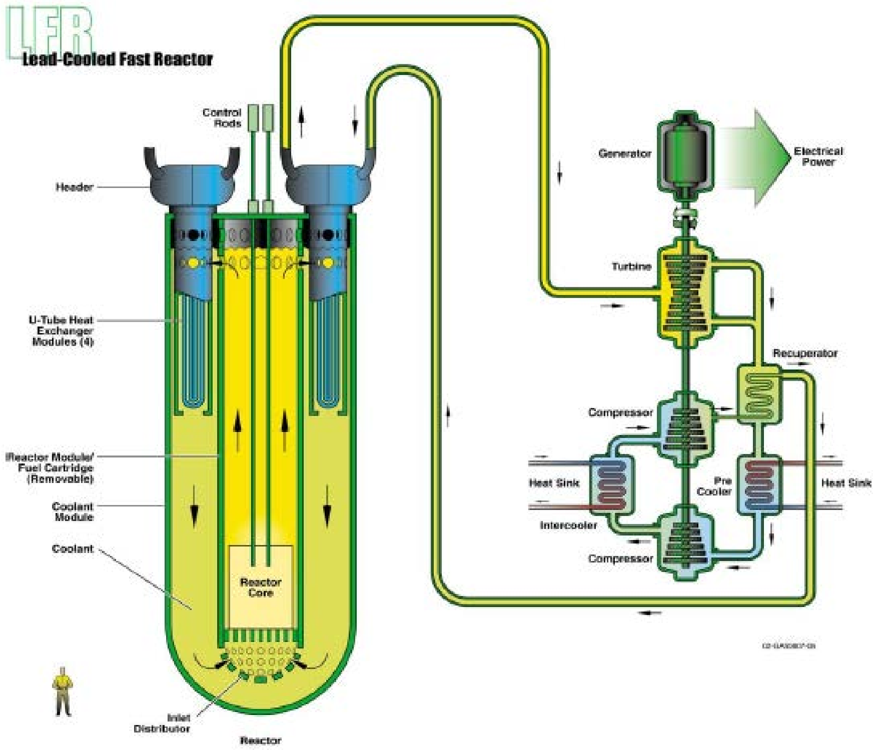

Figure 3: Schematic of a 1200 MWe LFR concept design

2.4. VHTR

The very high temperature reactor (VHTR) [8] is a development of the high temperature reactor (HTR) designs that were built and operated as technology demonstrators in Germany, UK and USA from the 1960s to 1980s. VHTR is a graphite moderated thermal reactor with helium as the coolant. VHTR uses an all-ceramic particle fuel either in the form of a pebble bed or a prismatic core. VHTR's primary application is envisaged to be hydrogen production/high temperature process heat source.

Particle fuel technology is central to VHTRs. Nuclear fuel accumulates fission products and transuranics under irradiation. In conventional reactors, the fission products (some of which are volatile) and transuranics are ultimately retained by a metallic fuel clad. However, it is difficult to envisage any metallic cladding material being able to withstand the very high temperatures (900 to 1000°C coolant temperature) of a VHTR. At these temperatures, only ceramic materials are feasible and this is the main rationale for particle fuels, which comprise very small (<1 mm diameter) microspheres of fuel oxide, oxy-carbide or carbide, surrounded by ceramic multi-layers. There are three multi-layers in the standard arrangement, which is known as the TRISO fuel particle. The multi-layers perform the same containment role as the metal cladding in conventional fuel. The small size of the fuel microsphere also largely eliminates the large centre to edge temperature differential of conventional fuel pellets, thereby reducing the maximum fuel centre temperature.

Figure 4 illustrates a TRISO fuel particle. Working from the centre out, each TRISO fuel particle consists of a fuel or fertile kernel of approximately 0.5 mm (500 μm) diameter. The fuel kernel is encapsulated with a layer of porous pyrolytic carbon, whose function is to absorb damage from fission recoils, accommodate swelling and provide free volume for the fission gas. There then follows a layer of high density pyrolytic carbon. This pyrocarbon layer protects the surrounding silicon carbide layer from reactions with fuel and fission products and also stops chlorine-containing compounds entering the fuel during manufacture. Outside the pyrolytic carbon layers is a layer of silicon carbide or zirconium carbide that forms a pressure vessel around each fuel particle. Finally there is an outer layer of pyrolytic carbon, which protects the silicon carbide from the coolant.

The multi-layered TRISO fuel particles constitute miniature pressure vessels that are strongly resistant to corrosion and very effectively contain the fission products and transuranics. They have a very high thermal stability and are capable of withstanding temperatures as high as 2000°C without failure. Normal operating temperatures are in the region of 1250°C and even in worst case accident scenarios, the core designs are such that the fuel temperature will not exceed 1600°C. This applies even in accident scenarios where there is no forced cooling to remove decay heat and this is the fundamental basis for the inherent safety characteristics of VHTRs.

In the prismatic design, as used in General Atomic's gas-turbine modular helium reactor (GT-MHR), the TRISO fuel particles are encapsulated in a cylindrical fuel compact about 1.3 cm in diameter and 5.1 cm long in a graphite matrix. About 3000 fuel compacts are incorporated in each hexagonal fuel element or fuel block (Figure 5). The individual fuel blocks are stacked in between 19 and 102 columns, depending on core size, to form cores of from 57 to 1020 blocks. The fuel blocks contain coolant channels so that the core region comprises a mix of fuel particles in the graphite matrix of the compact, the graphite matrix of the fuel block and coolant channel voids.

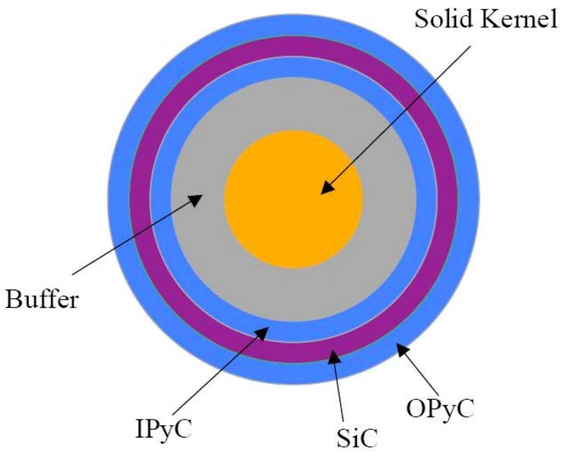

Figure 4: TRISO fuel particle schematic

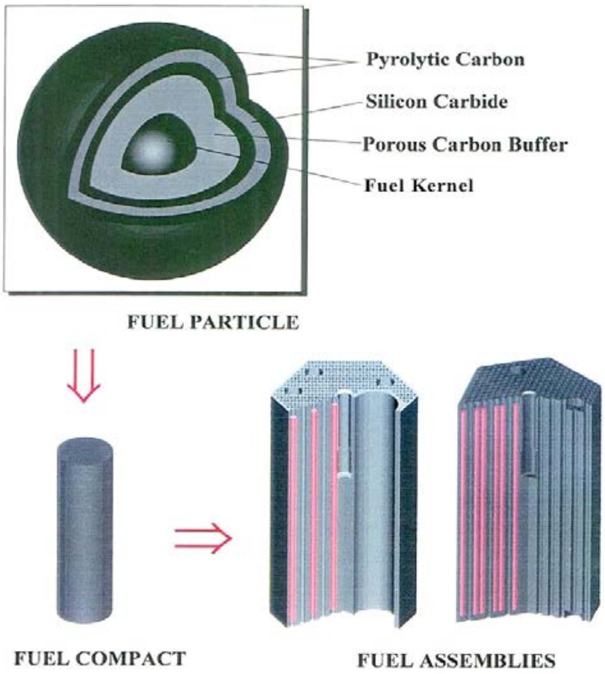

Figure 5: TRISO fuel particle, fuel compact and prismatic fuel blocks for GT-MHR

The pebble bed approach, which is based on the pebble bed modular reactor (PBMR) that was being developed in South Africa, uses fuel in the form of 6 cm diameter graphite pebbles with embedded with TRISO micro-particles. The core comprises a bed of pebbles through which the helium coolant flows. Pebbles are continually removed from the core and either returned to the core or replaced depending on an automated burnup measurement.

Of the six options being pursued by Generation IV, VHTR is the most technologically viable. Given that several HTRs were built and operated almost to the extent of full commercial deployment, VHTR is considered a realistic prospect for mid-term deployment. The technology is well understood and VHTR could use the PBMR or GT-MHR designs at its starting point. However, it should be acknowledged that there were serious operational difficulties encountered and For St Vrain. Also, the PBMR Project in South Africa experienced difficulties with the design of the gas turbine energy conversion unit and later reverted to a conventional steam cycle. This may have been a contributory factor that led to the eventual abandonment of the PBMR Project.

Although the technology is well known, it will require further development to meet the Gen IV goals. The Gen IV Roadmap [1] identifies four important technological areas where VHTR needs to improve on PBMR and GT-MHR: raising the maximum core outlet temperature from 850°C to ~1000°C; increasing maximum permissible fuel temperature on fault conditions from 1600°C to 1800°C; increase fuel burnup to 150-200 GWd/t and improved control of power peaking and thermal streaking. The very high outlet temperature is needed to maximise the efficiency of hydrogen production or other process heat applications, which is VHTR’s main mission. Meeting these higher temperature conditions will require a substantial materials development effort. In addition, significant R&D effort will be required for the thermo-chemical conversion system, power conversion system, fuel cycle and safety.

Table 4: GT-MHR parameters

Parameter	**GT-MHR**
Thermal/electric power output (MW)	600/286
Pressure (MPa)	7
Thermal efficiency	0.48
Effective core height/diameter (m)	8.0/4.84
Average power density (MW/m^3)	6.5
Core inlet/outlet temperature (°C)	491/850
Fuel initial enrichment (w/o)	20

2.5. SCWR

The super-critical water reactor (SCWR) [8] is an extension of current light water reactor technology that uses super-critical water for the coolant and moderator. SCWR development in Gen IV is being led by Canada and Japan, with smaller contributions from EU and USA. Super-critical water is water pressurised beyond the critical point and is characterised by very favourable heat transfer characteristics. Above the critical point, no distinction can be made between the liquid and gaseous phases, so that super-critical water is strictly a single phase medium. Compared with ALWRs, SCWR is theoretically capable of achieving higher thermal efficiencies (up to 44%), being designed with more compact physical size and capable of system simplifications, all of which would be favourable for economics.

Two designs are currently being examined. These are the European High Performance Light Water Reactor (HPLWR) and the CANDU-SCWR[4] pressure tube design proposed by Atomic Energy of Canada Ltd (AECL).

A direct cycle is used, with the super-critical water passing to the turbine, with no requirement for heat exchangers. The lack of a phase change eliminates the steam separators and driers that are needed in the analogous steam cycle in a Boiling Water Reactor (BWR). The very high heat removal capacity of super-critical water means that flow rates through the core are not as high as in ALWRs. Consequently, smaller pump capacities and pipe capacities are needed, reducing the size and complexity of the entire reactor system.

The main technical challenges with SCWR are the development of structural and fuel materials and developing the safety approach.

Table 5: Gen IV SCWR concept parameters

Parameter	SCWR
Thermal/electric power output (MW)	3586/1570
Pressure (MPa)	25
Thermal efficiency	0.44
Effective core height/diameter (m)	4.2/3.28
Average power density (MW/m^3)	101
Core inlet/outlet temperature (°C)	280/508
Feedwater flowrate per MW (kg/s/MW)	1.16

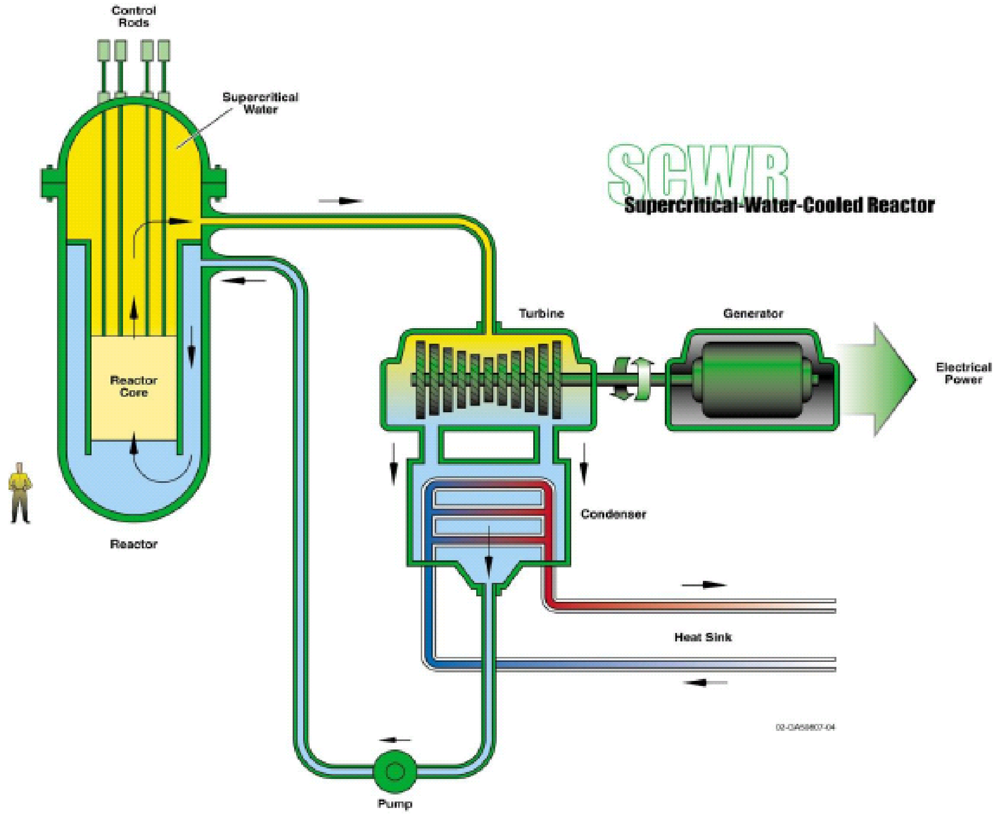

Figure 6: Schematic of the Gen IV SCWR concept

2.6. MSR

Compared with existing reactors and the other Gen IV systems, the molten salt reactor (MSR) is a notable change in technology and approach for reactor systems in that there is 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. A critical configuration is attained by using graphite moderator or using neutron reflectors in the core, depending on whether a thermal or fast neutron spectrum is required. The salt mix contains fluorides of uranium/plutonium or U-233/thorium and minor actinides in a fluoride salt carrier. The mix also contains fission and activation products. By eliminating the mechanical structure of the fuel, MSR avoids the neutron losses associated with mechanical components. It also avoids the materials and engineering and handling issues associated with solid fuel assemblies. The MSR operates a closed fuel cycle in which the molten salt is reprocessed on-line to reduce the equilibrium concentration of fission products. Uranium, plutonium and minor actinides are returned to the reactor for recycle. Within GIF [8], MSR is currently only at the pre-conceptual design stage, with current R&D focused on fast neutron spectrum designs.

MSR was first developed in the early 1950s and 60s for aircraft propulsion and the US operated the 8 MW Molten Salt Reactor Experiment (MRSE) and a 1000 MWe conceptual design was developed. The US research was eventually abandoned until the past decade when it was picked up again by the Russian Federation (led by the Kurchatov Institute) as part of International Science and Technology Centre (ISTC) collaborations with the US.

A unique aspect of MSR is that all the radioactive materials are mobile within the primary circuit, unlike conventional nuclear fuel where the radioactive inventory is largely confined to the nuclear fuel. Caesium and iodine, which are both volatile in conventional reactor fuels are stable within the salt. On-line fuel reprocessing reduces the equilibrium inventory of fission products. Moreover, with a high level of processing intensity the fission product inventory could be made arbitrarily low. However, there will nevertheless be limits as to what intensity is practical and on-line fuel processing will not affect the inventory of heavy nuclides.

MSR is intended to be passively safe, with the molten salt draining into passively cooled tank in the event of the freeze plug melting. There remain significant questions as to whether the safety approach used for MSR would be viewed favourably by licensing authorities. In the 2009 GIF progress report [6], there is a statement that “the safety approach (of MSR) has to be established”. There are also major question marks concerning technical feasibility, particularly materials.

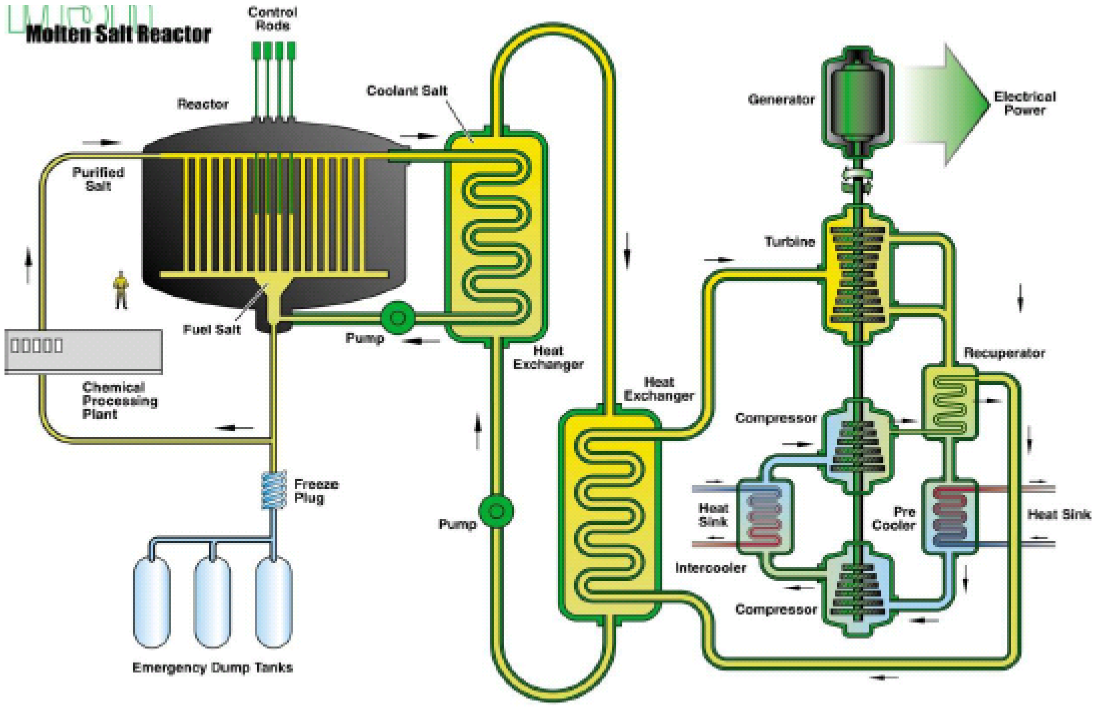

Figure 7: Schematic of the Gen IV MSR concept

Table 6: Gen IV MSR parameters

Parameter	**MSR**
Fuel	Liquid fluorides of U and Pu
Electric power output (MW)	1000
Pressure (MPa)	<0.5
Core outlet temperature (°C)	700-800

2.7. ADSR

The Accelerator Driven Sub-critical Reactor (ADSR) is one implementation of the Accelerator Driven Sub-critical System (ADS). ADSR is similar to the ADS concept being promoted by Thorium Energy Amplifier Associations (thorREA) [5]. ADSR is a sub-critical neutron multiplying system in which the external neutron source needed to support steady state operation is provided by a high power proton beam impinging on a spallation source such as a lead target. Most sub-critical concepts, including ADSR and the Energy Amplifier are designed around the thorium fuel cycle and the Accelerator Driven Thorium Reactor (ADTR) [6] is a particular variant being developed by Jacobs (formerly Aker Solutions) that is specifically based around the thorium fuel cycle.

Each high energy proton produces multiple spallation neutrons which are then used to maintain the sub-critical core at a steady power output. In the absence of the spallation neutrons, the neutron flux and power production in a sub-critical core will quickly decay. The sub-critical system acts to multiply the spallation neutrons according to the system multiplication factor k, the gain being $1/(1-k)$. For a typical sub-critical system, k is in the range 0.95 to 0.98, giving amplification gains between 20 and 50. ADTR is unusual in that it uses a much higher multiplication factor of 0.997, which reduces the accelerator beam power needed.

It is claimed that a sub-critical system is not vulnerable to reactivity insertion accidents in the same way as conventional reactors and that they are therefore safer. Nevertheless reactivity re-distribution events that could threaten the safety of a sub-critical system in much the same way as a critical reactor. Moreover, it could be argued that the main safety issue with all nuclear reactors is decay heat removal and sub-critical systems would be no different. Therefore, the best that can said is that the claimed safety benefits of sub-critical systems will need to be demonstrated and in the meantime it is very unwise just to accept the various claims being made at face value.

In order to understand where the advocates of sub-critical accelerator driven systems are coming from, it should be recognised that the added complexity of accelerator driven systems means they are unlikely to be economically competitive with conventional reactors and therefore the proponents need to find major differentiating factors. Improved safety is one of the cited key differentiators.

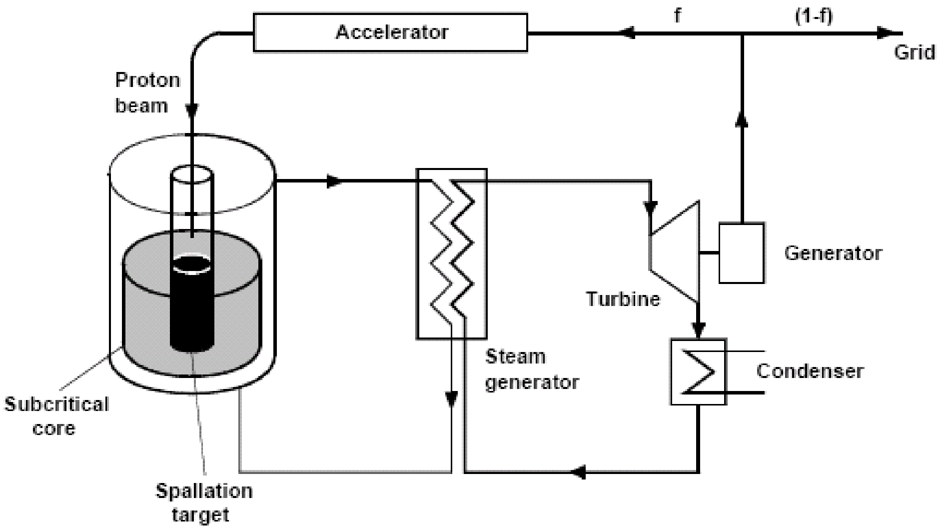

Figure 8: Accelerator Driven Sub-Critical Reactor Concept [8]

2.8. HPM

The Hyperion Power Module (HPM) is an autonomous small power reactor with a capacity of 25 MWe[7]. It is a liquid metal reactor that uses uranium nitride fuel and lead-bismuth coolant. It is designed for passive cooling, passive safety and has a long core life. It was originally developed by engineers and scientists at the Los Alamos National Laboratory (LANL) in the US, and through the commercialisation programme at LANL, Hyperion Power Generation was awarded the exclusive license to develop and deploy to market.

HPM is designed as a sealed unit that is factory assembled. It is sited underground, and eventually returned to the factory for waste and fuel disposition after a useful life of seven to ten years. It uses uranium nitride (UN) fuel, and lead-bismuth eutectic (LBE) as the coolant. The LBE permits ambient pressure operation of core, eliminating pressure vessel requirements. The outer diameter of the entire module fits within a 1.5 m envelope, which facilitates transport to site in a conventional nuclear fuel shipping cask.

Table 7: HPM parameters

Parameter	**HPM**[7]
Fuel	Uranium Nitride
Coolant	Molten Pb-Bi
Thermal/electric power output (MW)	75/25
Fuel Enrichment (weight percent)	<20
Effective core height/diameter (m)	2.5/1.5
Core outlet temperature (°C)	~500

2.9. Small modular water reactors

Small modular reactors (SMRs) are light water reactors (LWRs) which have been scaled down from existing commercial LWRs. Much of the technology is therefore firmly based on existing technology that is well supported by extensive operational experience. This is a particular advantage for fuel design, as it avoids the very long development timescale of 15-20 years that would be required to develop a new type of nuclear fuel. Small LWRs are already in use for marine propulsion and much of the design experience from marine reactors will apply.

It has always been argued that SMRs would be economically disadvantaged compared with large (1 GWe+) conventional plants because of economies of scale. In the UK, this has certainly been taken for granted, though the increased potential for factory build and assembly may be beneficial reducing or reversing the scaling effect. It is possible that in some parts of the world, there may be a new willingness to trade off increased costs with the inherently superior post-accident performance in the event of multiple fault events, as well as the lower upfront capital cost and the quicker return on the investment with SMRs able to come on line more quickly. Many small modular LWR core designs are also claimed not to require an emergency evacuation zone, which would again be very beneficial.

Table 8: Application and power information for selected small modular LWR designs

System	Application	Rating (MWe)	Specific rating (MW/m^3)
IRIS	Modular power unit	Up to ~300	~50
MRX	Barge power unit/marine propulsion	30	42
SMART	Modular power unit	330	-
CAREM	Modular power unit	25	55
SIR	Modular power unit	300	-

Figure 9 shows the schematic for one SMR, the ‘IRIS’ reactor – a medium powered (up to ~300MWe) innovative design that relies on existing LWR technology [9].

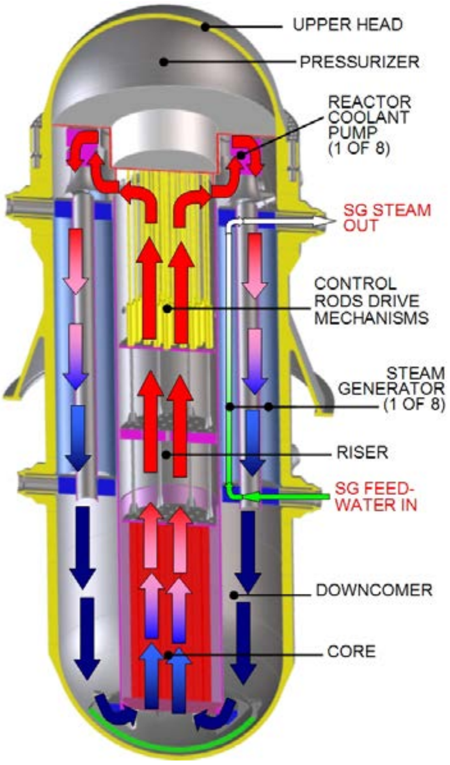

Figure 9: 300 MWe 'IRIS' reactor concept

Component	**Description**
Fuel	UO_2 (or U/PuO_2), ZIRLO^{TM} clad, cylindrical rods
Coolant	H_2O
Moderator	H_2O
Pressure vessel	Stainless steel
Active core size	4.3m/2.3m
Secondary circuit	Yes. Integral water heated steam generators.
Power	Up to 1.0 GW_{th}
Power density	~50 MW/m^3
Fuel mass	~ 48 te HM

3. Analysis Method

Table 9, reproduced from [2], lists the 42 metrics against which the relative performance of the nine advanced reactor systems will be assessed. A very simple approach was used to analyse the advanced reactor systems against each of the metrics:

3.1. Categorisations

For each of the metrics, the performance of each reactor system was assessed against four possible categorisations: LOW, MEDIUM, HIGH and VERY HIGH. Given the sometimes immature technological status of some of the advanced reactor systems, it was considered that four categorisations offered sufficient discriminating power and any further increase would not be very meaningful.

3.2. Baselines

In each case, the baseline was defined by current LWRs operating on a once-through fuel cycle. World-wide, this is the default position, with about 90% of spent LWR fuel being held in long term storage awaiting eventual conditioning and geological disposal. The baseline defined by LWR once-through varies depending on the metric being considered. For example, in respect of fuel utilisation, LWR once-through only manages to fission about 0.5% or so of the heavy metal content of the uranium ore and is therefore assigned to the LOW category. In other areas, such as reliability and environmental exposures, LWR once-through gives very good performance and therefore the baseline is HIGH.

In each case an assessment was also carried out for LWR recycle, which is helpful for those metrics where there is a difference compared with the once-through cycle. The LWR recycle case was also included for completeness, as it might possibly be considered a more suitable choice for the reference, particularly when comparing closed fast reactor cycles.

It is important to understand that the categorisations are intended to measure the performance of each system and that they do not necessarily indicate the correct sense of the metric. Thus in the case of uranium utilisation LWR once-through requires a relatively large amount of uranium ore and therefore its performance is ranked LOW, whereas the fast reactor options with full recycle have virtually zero uranium requirement, so are ranked VERY HIGH. Similarly the environmental impact of LWR once-through is considered to be comparatively very low, so that its performance in this respect is ranked HIGH.

Table 9: List of Metrics

	Attribute		**Attribute**
1	Fuel utilisation	22	Overnight construction costs
2	Spent fuel mass	23	Production costs (O&M?)
3	VHLW volume	24	Construction duration
4	Long term heat output	25	Development costs
5	Long term radiotoxicity	26	R&D costs
6	Environmental impact	27	Plutonium and minor actinide management
7	Separated materials	28	Load follow capability
8	Spent fuel characteristics	29	Scalability
9	Sabotage resistance	30	Timescales to deployment
10	Reliability	31	Technology Readiness Level
11	Worker exposures	32	Flexibility of location
12	Safety	33	Waste arisings (volumes HLW, ILW, LLW)
13	Reactivity control	34	Benefits or risks for security
14	Decay heat removal	35	Number and size of reactors needed
15	Low uncertainties on dominant phenomena	36	Associated fuel cycle
16	Fuel thermal response	37	Proliferation resistance
17	Integral experiment scalability	38	Ease of construction
18	Source term	39	Sustainability
19	Energy release mechanisms	40	Potential to drive thermal processes
20	System response times	41	Decommissioning costs
21	Effective hold-up	42	Primary purpose

3.3. Aggregation and weightings

Scores of 1 for LOW through to 4 for VERY HIGH were assigned to each scoring. The scores for each system were aggregated by addition with no attempt made to apply different weighting factors to the most important metrics. Therefore each metric is treated as being of equal importance and there is no prioritisation made.

Some of the metrics used are very similar or even equivalent to others and so there is some overlap. In this case the overall scoring is affected in the same way as taking the scores for the single attribute and doubling the weighting. At some future date, it may be useful to rationalise the metrics to avoid duplication, though it is thought unlikely the results will change significantly.

If required, the analysis could be refined to include a weighting system, but these would need to be established by consensus.

The absolute values of the aggregated scores have no meaning and all that is important is the relative rankings of the different systems. It might be hoped that the various advanced reactor systems would have an aggregate score which is higher than the LWR once-through baseline, otherwise there is little point in developing an advanced reactor system which provides overall inferior performance; however this could change if selected metrics were given higher weightings (e.g. sustainability). Given the simplistic scoring system, small differences of a few points between different systems should not necessarily be considered very meaningful.

3.4. Limitations

It is acknowledged that there are limitations to the approach adopted here for assessing the different reactor types. Firstly, it is not possible to avoid subjective bias in this sort of approach, especially when the scoring has been done by an individual or a single organisation. The incorporation of reviewers' comments has hopefully helped to reduce the amount of bias, but has not eliminated it. Secondly, no attempt has been made to weight the various metrics in this initial assessment. Assigning different weightings could reverse relative rankings and agreeing a single set of weighting factors agreeable to all stakeholders may be difficult. Finally, some of the metrics in the list in Table 9 are duplicated and their retention effectively doubles their weighting in this initial assessment. Therefore, it is important to use caution when using this assessment and it is intended only as an initial screening tool.

4. Results

Tables 10 to 51 at the end of this document show the analyses for each of the 42 metrics and are intended to be self-explanatory. Where appropriate, a few words of comment or additional explanation have been included in the tables against each system. In each case, current LWR once-through cycle was chosen as the reference and the performance of the other systems assessed relative to the reference. In the analyses, each advanced reactor system was assessed according to the performance that it is expected to deliver, assuming the development programme is successful and meets all its objectives. In practice, the development programme may not be fully successful and the system may fail to fully meet its design goals. Clearly, it will only be worth pursuing an advanced reactor system if it is capable in principle of delivering benefits relative to current reactor technology. If this is the case, then inclusion of an assessment of the technological risk provides an indication of whether it is likely that the system will be able to live up to its design intent. The approach described below attempts to capture these two aspects, the performance that the system promises if its development is successful and its overall performance taking account of technological risks.

Table 52 (TOT1) shows the aggregate scores for each of the nine advanced reactor systems, with each metric assigned equal weighting. Table 52 also shows a second aggregate score (TOT2) which omits all the metrics that relate to technological feasibility (Metrics 15, 17, 25, 26, 29, 30 and 31). This second aggregate score is useful in identifying those systems which show the most promise without being penalised on feasibility. This highlights whether a particular option holds any promise of improved performance over current technology, which is a necessary condition for R&D spend – if a system fails to deliver significant benefits even if technological issues are set aside, then R&D spend on it is not justified. It is hoped that these two approaches combine to give a fair overall assessment.

Note that the difference between the TOT1 and TOT2 scores should not be taken to indicate the level of R&D spend required to bring the various systems to a high technology readiness level.

Table 52 also shows a third overall score (TOT3), which aggregates those metrics which are relevant to assessing the various systems against roles other than baseload electricity generation. Specifically, the objective is to assess the potential of the different systems against roles such as high temperature process heat production, hydrogen production, load balancing and plutonium/minor actinide management. With this in mind, TOT3 aggregates the scores for the following metrics chosen for their relevance to energy services applications:

1. Metric 22: Overnight construction costs.
2. Metric 23: Production costs.
3. Metric 24: Construction duration.
4. Metric 27: Plutonium and minor actinide management.
5. Metric 28: Load follow capability.
6. Metric 29: Scalability.
7. Metric 30: Timescales to deployment.
8. Metric 32: Flexibility of location.
9. Metric 35: Number and size of reactors needed.
10. Metric 38: Ease of construction.
11. Metric 39: Sustainability.
12. Metric 40: Potential to drive thermal processes.
13. Metric 42: Primary purpose.

The LWR once-through system is the reference against which all the other systems are compared. The LWR recycle case was included for completeness and might reasonably have been used instead as the reference, especially since they both rank very closely.

The LWR recycle case is slightly penalised by metrics related to separated materials, proliferation resistance and decay heat output, balanced to some extent by the considerable reduction in the volume of heat producing waste that is obtained through reprocessing.

The results are discussed below for each of the reactor systems in turn. It should be noted that the scoring below, as well as being equally weighted for each of the metrics, are the views of the NNL and as such are open to discussion and challenge by the reader and can readily be adjusted based on either a consensus or by committee.

4.1. SFR

Compared with the LWR once-through reference, SFR performs extremely well on sustainability, since it is capable of a breeding cycle which would be independent of uranium ore availability. However, the overall score is penalised by relatively low scores on: separated materials; source term (fission gas release); energy release mechanisms; overnight construction cost; development cost: R&D cost; timescale to deploy; technological readiness level; fuel cycle; proliferation resistance and ease of construction.

Separated materials and proliferation resistance are duplicated metrics and the penalty arises from the need to recycle plutonium in order to achieve a closed, sustainable fuel cycle. In common with other fast reactors, sodium cooled reactors have a large fissile inventory, several times higher than a thermal reactor. This is necessary to counter the much smaller fission cross-sections which apply in a fast reactor spectrum. Even if the recycle technology avoids the separation of pure PuO_2, it is nevertheless still likely to pose greater risk than a once-through fuel cycle.

Fission gas release is much higher in fast reactor fuels than equivalent thermal reactor fuels, approaching 100% and this feeds into the safety case in accidents involving the release of volatiles in accident scenarios. The risk of sodium/water interactions is a potential energy release mechanism that is a further penalty. However, it should be noted that the large thermal inertia of the sodium pool and natural convection contribute to a degree of intrinsic safety in SFRs such as the EFR design.

Although some SFR designs have the advantage of a very compact, high power density core, this may be negated by the need to accommodate the secondary heat exchange circuit. As such, SFR is penalised on construction costs because of the added complexity of the intermediate sodium loop. For a pool-type design, there is perhaps reduced scope for factory build and modular construction. SFR also suffers a penalty because it requires further R&D spend and will take some years before it is ready for commercial deployment. Furthermore, they may also be more expensive to operate, due to the difficulties of handling fuel in the opaque coolant.

The SFR fuel cycle will require a large and complex infrastructure to support fuel reprocessing and recycle of plutonium. The technological requirements are more demanding than thermal recycle because of the higher burnup and actinide content of fast reactor fuel.

The aggregate TOT1 score for SFR is 99, versus 97 for LWR once-through, the two scores being practically equivalent. This result validates the current position of utilities, who would not be interested in SFR in the current market situation, because even if it meets all its design targets, the overall performance is only equivalent to current LWRs and there is, of course, always the risk of failing to achieve its design intent.

The TOT2 score for SFR is 81 for SFR compared with 72 for LWR once-through. This is an improvement in the relative rankings for the TOT1 score and shows that if the technological maturity issues could be overcome, SFR would appear more attractive than LWR once-through on this equal weighting score.

The TOT3 score for SFR is 29. compared with 25 for the LWR reference. This shows that SFR has some potential merits for non-baseload electricity applications, partly because of the relatively high outlet temperatures which range up to 550°C and partly because of its potential for minor actinide management.

The relative ratings for SFR would be improved by assigning more weight to sustainability issues such as fuel utilisation. In a scenario where world uranium supplies do not meet demand and uranium prices are very high, such a weighting would be justified and there is some merit in retaining an interest in SFR on the understanding that it is intended as a strategic option for a future scenario with uranium in short supply. Although SFR requires considerable further development, it has been demonstrated at prototype scale in France, Japan, Russia, UK and USA and compared with many of the other Generation IV systems, is relatively well understood and its feasibility is high.

The UK has extensive historical experience of SFR technology, which is one reason why this system was one of those which the UK intended to focus on when the UK was proposing to actively participate in the Generation IV International Forum (GIF).

4.2. GFR

GFR shares the same high rating of SFR with respect to sustainability metrics. GFR also scores better on energy release mechanisms, because of the chemical inertness of the coolant. As with SFR, compared with thermal reactors, there would be a lower long term radiotoxicity burden. However, GFR is penalised because there are serious issues concerning technical viability and economics:

Those metrics where GFR is penalised are: separated materials; low uncertainties on dominant phenomena; fuel thermal response; integral experiment scalability; source term; overnight construction cost; development costs; R&D costs; timescale to deployment, technology readiness level; fuel cycle; proliferation resistance and ease of construction. Many of the disadvantages are shared with the SFR e.g. requires a much higher fissile loading than a thermal reactor.

The aggregate TOT1 score for GFR is 88, significantly lower than SFR and also lower than the 97 score for LWR once-through. Although GFR has some attractive features, there are serious technical difficulties to be overcome and therefore significant questions over feasibility. The TOT2 score for GFR is 80, compared with 72 for LWR once-through, confirming that GFR is very heavily penalised by technological feasibility issues.

The TOT3 score for GFR of 28 is close to that of SFR. GFR shows promise against non-baseload electricity applications for the same reasons, notably high working temperature and minor actinide management.

The fact that the TOT1 score for GFR is lower than current LWR is not encouraging and based on this assessment suggests that this system is unlikely to be able to meet the GIF goals except possibly in the very long term. Despite having extensive experience of operating gas reactors, GFR does not appear to hold much relevance to the UK. Nevertheless, research continues with this fast reactor option as an alternative or backup to liquid metal reactors such as SFR and LFR.

4.3. LFR

LFR shares the same high rating of SFR with respect to sustainability metrics. LFR scores much better than SFR on energy release mechanisms, because there is no chemical energy release if the coolant interacts with water. This eliminates the need for an intermediate coolant loop, which is beneficial, though LFR would still suffer from higher overnight costs because of the large physical size of the reactor vessel compared with LWRs (see Figure 3 above for an indication of the potential vessel size). However, this large core does provide a large thermal inertia of the Pb or Pb-Bi pool and natural convection contribute to the level of passive safety. The main areas where LFR is penalised are the development requirements and technical feasibility issues (especially materials issues). LFR cores have been operated only in submarines and there have been technological issues there, especially related to corrosion of reactor components [7]. Scaling up to large power plants will involve considerable R&D work, with no guarantee of success.

LFR scores well on sustainability measures (in the same as SFR), but also loses on many of the same metrics as SFR: separated materials; source term (fission gas release); overnight construction cost; development cost, R&D cost; timescale to deploy; technological readiness level; fuel cycle; proliferation resistance and ease of construction. As is the case for all fast reactors, a large amount of fissile material is required to achieve criticality in a fast neutron spectrum. This means that the nominal core set-up is not the most reactive configuration, e.g. a core compaction accident could lead to the possibility of prompt critical events.

The aggregate TOT1 score for LFR is 97, the same as the current LWR once-through reference and close to SFR. The TOT2 score for LFR is 83, which exceeds both that of LWR once-through (72) and SFR (81), confirming that LFR is penalised by technological feasibility issues. On the TOT2 score, LFR appears marginally more attractive than SFR and this is perhaps to be expected, because the Generation IV systems are all designed to meet the same design goals. The key point to note is that LFR is less technologically mature than SFR and therefore there is more risk that it will fail to attain its goals.

The TOT3 score for LFR of 28 is close to that of SFR and the same as GFR. LFR shows promise against non-baseload electricity applications for the same reasons, notably high working temperature (480°C for ELSY) and minor actinide management.

As for SFR, the ranking for LFR could be improved by assigning increased weight to sustainability metrics. In principle LFR has some attractive features and it offers a breeding capability as an alternative to SFR. However, its technological immaturity implies it is only an option in the very long term. The UK has no previous experience of LFR technology and this, combined with technical immaturity, is why the UK did not previously propose any contributions to LFR within GIF. The absence of energetic coolant/water interactions should possibly merit increased weighting and LFR should perhaps be re-considered.

4.4. VHTR

The aggregate TOT1 score for VHTR is 124, compared with 97 for the LWR once-through reference. The TOT2 score is even more favourable for VHTR, 104 versus 72, because it incurs some penalties on technology maturity. VHTR incurs maximum 4 point scorings on 16 of the metrics (particularly safety related metrics), reflecting the inherent characteristics of the fuel form. VHTR incurs relatively few penalties on the metrics that relate to technological maturity, because the technology has been demonstrated at full scale and is the most technologically mature of the Generation IV systems alongside SFR.

The TOT3 score for VHTR of 34 is the leading score of all the systems. This reflects the fact that VHTR is specifically designed for high temperature heat applications, such as hydrogen production. The high coolant outlet temperature (>900°C) allows its application to high temperature processes not available to the other systems and greatly increases its potential efficiency. VHTR is also potentially capable of minor actinide burning.

VHTR has by far the highest aggregate scores of all nine systems considered. This goes some way towards justifying the UK having identified VHTR as one of the priority systems at the time that the UK was planning to actively participate in GIF. The overall scoring is effectively weighted towards safety and this is the main reason for the high scores. There remain some technological feasibility issues and it is questionable whether VHTR can be economically competitive with LWRs. This is one of the considerations which led South Africa to abandon the Pebble Bed Modular Reactor (PBMR), where in addition to the unfavourable economic climate, the initial aim of economic competitiveness with LWRs was undermined by technology development issues with the direct cycle energy conversion system that led eventually to the adoption of a conventional steam cycle and a consequent loss of thermal efficiency.

4.5. SCWR

The advantage of SCWR over current LWRs is their ability to operate at a much higher specific rating because of the superior heat transfer properties of water in the supercritical thermodynamic state. However, maintaining adequate cooling of the core will be more difficult given the higher rating, in the event of a Loss of Coolant Accident, when the loss of pressure would cause the water to revert out of the supercritical state. SCWR is also penalised heavily on technological maturity, with issues relating to the fuel design and materials for both pressure circuit components and fuel components.

SCWR's status is reflected in its aggregated scorings, with the TOT1 score of 82 failing to match the LWR once-through benchmark of 97, despite a proportion of the technology being based on elements of existing LWRs. The TOT2 score for SCWR is a marginal improvement over the reference (76 versus 72), confirming that it shows promise, but only if the technological feasibility issues are set aside. Even in this case, the advantage is minimal and it is not possible to make a strong case for UK interest.

The TOT3 score for SCWR is 24, marginally lower than the LWR reference. Although SCWR operates with higher outlet temperatures than current LWRs, they are not high enough for high temperature heat applications.

4.6. MSR

MSR has some very attractive features, particularly the molten salt fuel form (which avoids the need for fuel fabrication) and its flexibility to use virtually any fissile material and the on-line fuel reprocessing. However, it suffers from major penalties regarding safety and technological feasibility.

While some aspects of MSR are good from the point of view of safety, it is strongly penalised in this assessment because the molten fuel form will demand a different approach to safety. Conventional fuel can be regarded as providing two barriers to release of radioactive materials – the fuel pellets and the fuel cladding, both of which are credited in plant safety cases. The loss of these two barriers will need a new approach to the safety case and it is not clear how this will be achieved, even if it can be demonstrated that the fission products show a strong preference for the molten salt phase.

MSR uses on-line reprocessing to limit the mass of fission products in circulation and this goes part of the way to mitigating the safety concern over the mobile radioactive inventory. In principle, the intensity of reprocessing could be adjusted to reduce the fission product activity to any required level. In practice, limitations will apply and very intense processing is likely to be impractical and expensive. Even if the equilibrium fission product inventory was driven very low, there will still be high inventories of heavy nuclides and these would constitute a very large mobile radioactive inventory.

The TOT1 score for MSR is 97, the same as the LWR once-through reference. The TOT2 score of 88 shows that MSR has increased attractiveness if the technical feasibility issues are set to one side. The TOT3 score is 32, comparable with, marginally below VHTR, reflecting its potential for high temperature heat applications and minor actinide burning.

4.7. ADSR

Though ADSR offers the potential for plutonium and minor actinide burning, it is heavily penalised in two major areas: The first is economics, where there is a capital cost penalty associated with the accelerator system. The second area is technological feasibility.

The aggregate TOT1 score is 94, compared with 97 for the LWR once-through reference,. However, the TOT2 score is 87 compared with 72, which indicates increased attractiveness once technological feasibility is set aside. The TOT3 score is 30, principally because of its minor actinide burning potential.

This assessment is consistent with intentional perspectives on accelerator driven systems. The view in France, which has very extensively researched the role of accelerator driven systems, is that they cannot compete with current LWR technology on economics. French researchers envisage accelerator driven systems being deployed as “dedicated” minor actinide burners with two tiers of LWRs and conventional fast reactors being used for mainstream power generation. Accelerator driven systems would therefore need a separate mission to be justified and the entire fuel cycle would be optimised to minimise the number of accelerator driven systems needed within the reactor fleet.

4.8. HPM

HPM is a small autonomous power source with an output of just 25 MWe. There are few potential applications in the UK apart from perhaps a secure power source for defence or remote industrial sites. It is unlikely that HPM could ever compete economically with current LWRs. There are also significant reservations regarding technical feasibility.

This is reflected in the TOT1 score of 95, which does not match the LWR once-through reference. The TOT2 score of 84 is higher than the reference and this results from HPM scoring the maximum 4 points against issues related to safety, sabotage resistance and ease of construction and decommissioning. The TOT3 score is 26, only marginally above the LWR reference.

4.9. Small modular LWR

Small modular LWRs involve the scaling down of current LWR designs and this has some attractive features for ease of construction and decommissioning and flexibility of location. The potential use of integral small modular LWRs also means that many of the potential accident scenarios in a conventional LWR (e.g. LOCA, control rod ejection) can be avoided and safety performance is improved still further. However, there would be expected to be a penalty on operating costs relative to large LWRs and this is the main reason why small modular LWRs have not been considered by countries with well developed grid infrastructures. In the UK, small modular LWRs might be suitable for plutonium disposition, perhaps being co-located at Sellafield to avoid having to transport MOX fuel assemblies.

The TOT1 score is 98, which is a marginal improvement over the LWR once-through reference. There are essentially no technology feasibility issues, so this marginal advantage is preserved in the TOT2 score of 74. The TOT3 score is 27, marginally higher than the (large) LWR reference. This is because of extra flexibility of applications offered by the small modular core size e.g. district heating, desalination etc.

4.10. Summary and Discussion

The TOT1 score highlights VHTR as the system with the highest performance ranking against the 42 metrics. Unlike most of the other Generation IV systems, VHTR has been developed extensively in the past and technological feasibility questions are therefore limited. Its inherent safety characteristics are very attractive, driven by the designs original intent to overcome many of the LWR safety issues. This safety performance, combined with the relative technical maturity as well as its role outside of electricity generation alone, ranks this system highly. This view is reflected in the interest in the international community across Europe, North America, Asia and Africa.

SFR, LFR, MSR, ADSR and HPM all rate about equally and close to the reference once-through LWR. All these systems offer the possibility of a closed fuel cycle that would be independent of uranium ore availability. However there are technical feasibility issues with all these systems and they would also require substantial investment in the fuel cycle infrastructure.

Small modular LWRs are ranked about the same, but showing just a marginal improvement over current LWRs. Small modular LWRs might have a role in the UK in plutonium disposition or in scenarios with high nuclear deployment limited by the availability of suitable sites. Technology feasibility is not a major consideration and the key issue would be to address the operating and maintenance cost basis.

The other systems (GFR and SCWR) considered fail to match the overall scoring of the LWR reference, primarily because of technology feasibility. These include GFR that was previously one of the systems that the UK was going to contribute to under GIF (technical feasibility is the main reason for discounting GFR).

VHTR is the highest ranked on the TOT2 score, but now MSR and ADSR have the next highest scores. All three systems and especially MSR and ADSR benefit when the technological feasibility metrics are set aside. Indeed, all nine advanced reactor systems considered here now rank ahead of the PWR reference, because the TOT2 score disregards metrics related to technological maturity and therefore measures the potential of the advanced systems assuming the technological issues will all be resolved satisfactorily.

The TOT3 ranking is again similar, with VHTR having the lead score reflecting its specific design aimed at high temperature heat applications given the high operating temperature and modularity. MSR, ADSR and all three of the Gen IV fast reactors are ranked about equally under TOT3. They all have high working temperatures that makes them potentially better suited for high temperature process heat applications. They can also be used for minor actinide management.

A more rigorous analysis of the performance of the various systems against energy services applications would need to weight the different metrics according to relevance and importance. The UK Nuclear Fission Technology Roadmap will identify the UK’s strategic priorities and could be used to determine the appropriate weightings that will reflect them. The Roadmap will be framed around a number of reference scenarios ranging from replacement new nuclear build to a very ambitious nuclear expansion. The weightings which would apply to the metrics would be different in each scenario, reflecting the different strategic drivers and in consequence the relative ranking of the different systems might be expected to change. A key point that has emerged from developing the Roadmap is the important need to consider reactors systems and their associated fuel cycle as a whole and this point could again be addressed by selecting weightings that reflect the importance of those metrics related to the broader fuel cycle.

5. International programmes

This section looks at which international programmes (e.g. within Generation IV, Global Nuclear Energy Partnership (GNEP), EU Framework Programmes etc) are relevant to the respective reactor systems considered earlier. This will assist in determining the international market and view of the technologies, including the intellectual and financial gearing benefits. This will help the UK identify how it could become involved most effectively in these programmes and how these could best meet future R&D requirements.

Although Generation IV and European Union Framework programmes are not the only large R&D programmes, they do offer the most comprehensive, structured programmes internationally today, with significant financial and intellectual gearing. The partner countries all meet UK requirements for participation in shared civil nuclear technology development programmes. Furthermore, government interest and support in these programmes is appropriate because the time frames associated with such reactor systems are relevant to energy policy, but beyond commercial horizons.

The guiding principles for UK participation in international advanced reactor programmes is likely to include:

1. Avoid spreading modest resources too thinly.
2. Extract maximum benefit from past and current investments.
3. Seek a balanced portfolio capable of addressing a range of future demands, but with a minimum of technology development.
4. Build on available UK expertise and capabilities, especially where these are key to maintaining strategic options.
5. Ensure that at least one “sustainable” system is included (i.e. a fast reactor system)

Where reference is made to participation in GIF projects, the information is taken from reference [8].

5.1. SFR

SFR is one of the best supported projects in GIF with six participating nations and one observer nation. Within GIF there are R&D activities related to advanced fuel; global actinide recycle; component and balance of plant design; safety and operation and systems integration and assessment.

There are active sodium fast reactor R&D programmes in China, France, Russian Federation and Japan, with prototypes operating or planned in all these countries. France is planning to construct a sodium fast reactor demonstrator which will further develop its experience gained previously from Phénix and Super Phénix. The European Union Framework programme has been actively contributing to SFR in GIF. The former US GNEP programme also included R&D into the potential role of SFR in the US nuclear fleet as a means of optimising waste management. GNEP has now evolved into an extensive R&D programme, some relevant elements of which are captured under the themes of Advanced Modeling and Simulation, Fuel Cycle Research & Development and Generation IV Nuclear Energy Systems (Gen-IV).

5.2. GFR

GFR is largely driven largely by France, which views GFR as a possible alternative option to SFR in the long term. There are four signatory nations in GIF, with R&D activities on conceptual design and safety and fuel and core materials.

There is no prior experience of operating GFR systems and the most relevant experience is that of the UK’s MAGNOX and AGR stations. This was the one reason why the UK was intending to contribute to the GFR programme before the UK decided withdraw from active participation GIF.

The EU Framework programme has sponsored research on GFR and the GOFASTR project is currently in progress, with the UK as a contributor.

5.3. LFR

LFR is also one of the mainstream GIF options, though support for it is not as extensive as SFR, with only three provisional participant countries and no major R&D activities identified.

LFR technology is less developed than SFR and the only application to date has been in Russian submarine power plants. The Russian Federation, which is one of the main contributors to the LFR element of GIF, regards LFR technology as capable of being scaled up to large power plants of 1 GWe or more.

The EU Framework programme has supported LFR research, largely because Accelerator Driven Systems (ADS) will rely on lead or lead-bismuth cooling and therefore there is a strong link to LFR. In addition, the LFR, like GFR, is regarded within Europe as an attractive backup fast reactor technology option to SFR.

5.4. VHTR

VHTR is one of the most widely supported systems in GIF, with many countries having very deep interest in the technology. Within GIF there are 8 signatory countries, with R&D activities on hydrogen production; fuel and fuel cycle; materials and computational methods.

HTR prototypes have previously been built and operated in Europe and USA and there are currently HTR prototypes operational in China and Japan, though plans to build a prototype Pebble Bed Reactor in South Africa have now been abandoned.

Several research projects on VHTR research have been sponsored by the EU Framework programme and the UK has been actively involved in some of these. VHTR is one of the systems that have been researched in the USA as part of recent Department of Energy (DOE) research programmes. There are tentative plans to build a demonstrator under the Next Generation Nuclear Plant (NGNP) programme, although, as with PBMR, the project has suffered from the recent economic climate.

5.5. SCWR

SCWR is perhaps the least well supported of the GIF systems, reflecting the very immature status of the technology. Within GIF there are only three signatory countries, with R&D activities in the areas of: materials and chemistry; thermal hydraulics and safety; system integration and assessment and fuel qualification.

SCWR research to date has been limited to theoretical studies only, primarily by Canada as a possible replacement for CANDU reactors. There have been no European Framework research programmes related to SCWR.

5.6. MSR

MSR has only a very narrow support base in GIF, with only three provisional participant countries and no specific R&D programmes identified.

Though small scale research reactors were built in the 1950s in the USA to demonstrate aspects of MSR technology, these were never followed up and there have been no prototypes built. There are currently no concrete plans to develop MSR prototypes.

5.7. ADSR

ADSR is a reactor currently being developed universities with particular interest in accelerator technology. It reflects a widespread interest world-wide in ADS technology, but one which is largely confined to academic research circles only. There is no specific support for ADSR outside the UK, though there have been international R&D collaborations (sponsored by the EU Framework Programme) for ADS such as MYRRHA. However, it should be noted that the MYRRHA programme has been specifically developed by SCK-CEN to also ensure the demonstration concept has a fast reactor capability such that the experience base with lead coolant can be further developed.

5.8. HPM

HPM is being developed by Hyperion Power, which is a spin-off company from Los Alamos National Laboratory (LANL). It is one of many competing small autonomous power systems being developed world-wide with private investment for which there are many different technical approaches. There are no international research programmes based on HPM, though international research on lead cooled systems has some generic relevance.

5.9. Small modular LWR

There are many different small modular LWR designs being developed world-wide, some by established reactor vendors and some by universities. The technology base for small modular LWRs is already mature, based as it is on the same technology as current large LWRs and therefore there has been no requirement for international R&D collaborations in recent years.

6. Summary and Recommendations

This analysis points to VHTR as the system with the highest performance ranking against the 42 metrics. Unlike most of the Generation IV systems, VHTR has been developed extensively in the past and technological feasibility questions are therefore limited. Its inherent safety characteristics are potentially attractive as are its ability to act in an alternative role to simply electricity generation e.g. hydrogen economy, industrial heat etc.

Six of the remaining systems (SFR, LFR, MSR, ADSR and HPM) score between 94 and 99, which is close to the reference score for LWR once-through of 97. SFR, LFR, MSR, ADSR and HPM all score highly on fuel sustainability and metrics related to the back-end of the fuel cycle, but all are penalised by questions over technological feasibility. Of these systems, it could be argued that SFR poses the least technological risk, given that commercial scale prototypes have been built and operated. The other systems all pose varying degrees of technological risk given that there have been no prototypes.

The overall score for SMR of 98 is almost the same as for the reference LWR once-through cycle. Small modular LWRs might have a role in the UK in plutonium disposition or in scenarios with high nuclear deployment limited by the availability of suitable sites.

Technology feasibility is not a major consideration and the key issue would be to address the operating and maintenance cost basis.

GFR and SCWR score poorly because of concerns over their technological feasibility.

In deciding on the direction of any future engagement by the UK in international advanced reactor R&D, the UK needs to be clear on the reasons for participating. These might include:

1. The development of Intellectual Property, products and services for the UK nuclear industry both in the domestic and international setting.
2. To develop the UK as an intelligent customer (assuming other countries will develop the technologies).
3. Skills maintenance and development for industry and regulators.
4. Political/strategic reasons for a conscientious nuclear nation.

Regardless of the reasons, it clearly makes sense to work on those technologies that are likely to be successful, either because:

1. They offer the best prospect of a return on investment.
2. They have the best chance of gaining access to intellectual and financial gearing.
3. They need skills and knowledge relevant to the technologies that will be deployed in the future.

The guiding principles for UK participation in international advanced reactor programmes is likely to include:

1. Avoid spreading modest resources too thinly.
2. Extract maximum benefit from past and current investments.
3. Seek a balanced portfolio capable of addressing a range of future demands, but with a minimum of technology development.
4. Build on available UK expertise and capabilities, especially where these are key to maintaining strategic options.
5. Ensure that at least one “sustainable” system is included (i.e. a fast reactor system).

The UK Nuclear Fission Technology Roadmap will identify the UK’s strategic priorities and could be used as a guide for any future application of the metrics. The Roadmap will be framed around a number of reference scenarios ranging from replacement new nuclear build to a very ambitious nuclear expansion. The weightings which would apply to the metrics would be different in each scenario, reflecting the different strategic drivers and in consequence the relative ranking of the different systems might be expected to change. A key point that has emerged from developing the Roadmap is the important need to consider reactors systems and their associated fuel cycle as a whole and this point could again be addressed by selecting weightings that reflect the importance of those metrics related to the broader fuel cycle.

References

1. “A technology roadmap for Generation IV nuclear energy systems”, GIF-002-00, December 2002
2. “Review of Metrics Relevant to Reactor Systems”, NNL(11) 11491, March 2011
3. K Hesketh & E Whyman “A review of the nuclear physics performance of sodium cooled fast reactor variants”, ARMM/P(02)15, NSTS2995, Dec 2003
4. “SCWR: Overview”, H. Khartabil, GIF Symposium, Paris, France, 9-10 September, 2009
5. “Towards an alternative nuclear energy – Capturing thorium-fuelled ADSR energy technology for Britain”, Thorium Energy Amplifier Association, Oct 2009
6. “Accelerator driven thorium reactor (ADTR) – sustainable technology for 21st century energy requirements”, http://www.akersolutions.com/DE04944/06/48/02
7. C.F. Smith, L. Cinotti, H. Sekimoto, “Lead-Cooled Fast Reactor (LFR) On-Going R&D and Key Issues”, GIF Symposium, Paris, France, 9-10 September, 2009
8. Generation IV International Forum, 2009 Annual Report, OECD-NEA

5\. J Lefevre, C Mitchell & G Hubert, "European Fast Reactor Design", Nuclear Engineering and Design, Vol 162, Issues 2-3, April 1996, Pages 133-143

6\. C Mitchell, P Lo Pinto, M Dominguez, A van Heek, D Every & B Carluec, "Gas-Cooled Fast Reactor Concept Review Studies (GCFR)", Proceedings of ICAPP'03, Cordoba, Spain, May 4-7 2003

7\. “Hyperion Fact Sheet March 2010”, Hyperion Power Generation Inc, March 2010

8\. “Accelerator-driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles”, OECD-NEA, 2002

9\. "IRIS Plant Description Document", BNFL/Westinghouse Proprietary Document, WCAP-16062-P

Table 10: Fuel utilisation assessment

Attribute: Fuel utilisation

UK Relevance	HIGH
Discriminating power	HIGH

System	Performance	Comments
SFR	V HIGH	Capable of fissile material breeding - independent of uranium supply
GFR	V HIGH	Same
LFR	V HIGH	Same
VHTR	LOW	Comparable to current LWR
SCWR	LOW	Equivalent or marginal improvement wrt current LWR
MSR	V HIGH	High conversion ratio thorium core, less dependent on uranium
ADTR	V HIGH	Breeder core, but detailed core design not available
HPM	LOW	Detailed core design not available
Small LWR	LOW	Equivalent to current LWR
LWR once-through	LOW	Uranium requirement approx 200 tU per GWye REFERENCE CASE
LWR recycle	LOW	Uranium requirement approx 160 tU per GWye

Explanatory notes

Comparison is made relative to Gen III & Gen III+ LWR technology, which is dependent on the availability of natural uranium ore
The systems ranked LOW are expected to achieve similar or at best marginally improved performance compared with current LWR

Table 11: Spent fuel mass assessment

Attribute: Spent fuel mass

UK Relevance	LOW
Discriminating power	LOW

System	Performance	Comments
SFR	HIGH	High discharge burnup gives proportional reduction in spent fuel mass
GFR	HIGH	Same
LFR	HIGH	Same
VHTR	LOW	Graphite matrix increases spent fuel volume and mass
SCWR	MED	Equivalent to current LWR
MSR	MED	No conventional spent fuel produced
ADTR	HIGH	Detailed core design not available
HPM	MED	Detailed core design not available
Small LWR	MED	Equivalent to current LWR
LWR once-through	MED	Spent fuel mass approx 23 tHM/GWye REFERENCE CASE
LWR recycle	MED	Same

Explanatory notes

MSR reprocesses the fuel on-line, generating encapsulated fission product waste and recycling uranium and trans-uranics

Table 12: HLW volume assessment

Attribute: HLW volume

UK Relevance	HIGH
Discriminating powe	HIGH

System	Performance	Comments
SFR	HIGH	Comparable to LWR recycle
GFR	HIGH	Same
LFR	HIGH	Same
VHTR	LOW	Graphite matrix increases HLW package volume
SCWR	MED	Equivalent to current LWR once-through
MSR	HIGH	Packaged volume of HLW likely to be lower than LWR recycle
ADTR	HIGH	Detailed core design not available
HPM	MED	Detailed core design not available
Small LWR	MED	Equivalent to current LWR
LWR once-through	MED	Packaged volume of spent fuel approx. 20 m^3/GWye REFERENCE CASE
LWR recycle	HIGH	Packaged volume of HLW approx 2.0 m^3/GWye

Explanatory notes

LWR once-through produces spent fuel that will eventually be packaged as HLW

LWR recycle produces Vitrified High Level Waste Stream (VHLW)

HTR spent fuel volume is adversely affected by the graphite matrix, which if encapsulated without separation greatly increases the HLW volume

SCWR, MSR, ADTR and HPM fuel cycles not well defined at present

VHTR, SCWR, ADTR, HPM & Small LWR fuel cycles assumed to be once-through

Table 13: Long term heat output assessment

Attribute: Long term heat output

UK Relevance	HIGH
Discriminating powe	HIGH

System	Performance	Comments
SFR	HIGH	Assumes full recycle of transuranics
GFR	HIGH	Same
LFR	HIGH	Same
VHTR	MED	Comparable to current LWR once-through
SCWR	MED	Comparable to current LWR once-through
MSR	HIGH	Assumes full recycle of transuranics
ADTR	HIGH	Assumes full recycle of transuranics
HPM	MED	Asssumed comparable to current LWR once-through
Small LWR	MED	Equivalent to current LWR
LWR once-through	MED	REFERENCE CASE
LWR recycle	LOW	LWR Pu recycle increases long term decay heat load

Explanatory notes

LWR recycle assumes since recycle of Pu with direct disposal of MOX fuel assemblies

VHTR, SCWR, ADTR, HPM & Small LWR fuel cycles assumed to be once-through

Table 14: Long term radiotoxicity assessment

Attribute: Long term radiotoxicity

UK Relevance	MED
Discriminating power	MED

System	Performance	Comments
SFR	HIGH	Large decrease possible assuming full recycle of transuranics
GFR	HIGH	Same
LFR	HIGH	Same
VHTR	MED	Comparable to current LWR once-through
SCWR	MED	Comparable to current LWR once-through
MSR	HIGH	Assumes full recycle of transuranics
ADTR	HIGH	Large decrease possible assuming full recycle of transuranics
HPM	MED	Asssumed comparable to current LWR once-through
Small LWR	MED	Equivalent to current LWR
LWR once-through	MED	REFERENCE CASE
LWR recycle	MED	Marginal decrease in long term radiotoxicity

Explanatory notes

LWR recycle assumes since recycle of Pu with direct disposal of MOX fuel assemblies

VHTR, SCWR, ADTR, HPM & Small LWR fuel cycles assumed to be once-through

Table 15: Environmental impact assessment

Attribute: Environmental impact

UK Relevance	MED
Discriminating powe	MED

System	Performance	Comments
SFR	V HIGH	Uranium mining reduced
GFR	V HIGH	Same
LFR	V HIGH	Same
VHTR	HIGH	Comparable to current LWR once-through
SCWR	HIGH	Comparable to current LWR once-through
MSR	V HIGH	Uranium mining reduced
ADTR	V HIGH	Uranium mining reduced
HPM	HIGH	Asssumed comparable to current LWR once-through
Small LWR	HIGH	Equivalent to current LWR
LWR once-through	HIGH	REFERENCE CASE
LWR recycle	HIGH	Closely equivalent

Explanatory notes

Environmental impact includes uranium mining, front-end fuel cycle, reactor operations, back-end fuel cycle & waste disposal

VHTR, SCWR, ADTR, HPM & Small LWR fuel cycles assumed to be once-through

Table 16: Separated materials assessment

Attribute: Separated materials

UK Relevance	HIGH	
Discriminating powe	HIGH	Revised upwards since NNL (11) 11491 following analysis results

System	Performance	Comments
SFR	MED	Depends on recycle process adopted
GFR	MED	Same
LFR	MED	Same
VHTR	V HIGH	Fuel form makes fissile materials relatively inaccessible
SCWR	HIGH	Comparable to current LWR once-through
MSR	HIGH	Assumes full recycle of transuranics and no separated fissile materials
ADTR	MED	Asssumed comparable to current LWR once-through
HPM	HIGH	Asssumed comparable to current LWR once-through
Small LWR	HIGH	Equivalent to current LWR once-through
LWR once-through	HIGH	REFERENCE CASE
LWR recycle	LOW	Produces separated PuO_2

Explanatory notes

MSR fuel cyce does not separate fissile materials

VHTR, SCWR, ADTR, HPM & Small LWR fuel cycles assumed to be once-through

Table 17: Spent fuel characteristics assessment

Attribute: Spent fuel characteristics

UK Relevance	MED	
Discriminating powe	HIGH	Revised upwards since NNL (11) 11491 following analysis results

System	**Performance**	**Comments**
SFR	MED	Spent fuel inventory comparable to current LWR
GFR	MED	Same
LFR	MED	Same
VHTR	V HIGH	Very robust spent fuel form
SCWR	MED	Comparable to current LWR once-through
MSR	V HIGH	No spent fuel arisings - only immobilised fission products
ADTR	MED	Asssumed comparable to current LWR once-through
HPM	MED	Asssumed comparable to current LWR once-through
Small LWR	MED	Equivalent to current LWR
LWR once-through	MED	REFERENCE CASE
LWR recycle	MED	Same

Explanatory notes

This is intended to measure how easily fissile material can be diverted

VHTR fuel is difficult to reprocess because if the in-built barriers of the graphite matrix and the SiC shell

MSR fuel cycle could easily be adapted for diversion

VHTR, SCWR, ADTR, HPM & Small LWR fuel cycles assumed to be once-through

Table 18: Sabotage resistance assessment

Attribute: Sabotage resistance

UK Relevance	HIGH	
Discriminating power	HIGH	Revised upwards since NNL (11) 11491 following analysis results

System	**Performance**	**Comments**
SFR	HIGH	Assumed that protection standard will be at least as robust as current LWR
GFR	HIGH	Same
LFR	HIGH	Same
VHTR	V HIGH	Very high intrinsic performance of ceramic fuel
SCWR	HIGH	Comparable to current LWR once-through
MSR	LOW	Fuel not in solid form
ADTR	HIGH	Asssumed comparable to current LWR once-through
HPM	V HIGH	Underground
Small LWR	HIGH	Equivalent to current LWR
LWR once-through	HIGH	REFERENCE CASE
LWR recycle	HIGH	Same

Explanatory notes

This analysis concentrates on assessing the sabotage resistance of the reactors

Table 19: Reliability assessment

Attribute: Reliability

UK Relevance	HIGH
Discriminating powei	LOW

System	Performance	Comments
SFR	HIGH	
GFR	HIGH	
LFR	HIGH	
VHTR	V HIGH	Gas turbine energy conversion system - increased reliability?
SCWR	HIGH	Comparable to current LWR once-through
MSR	MED	Long term reliability not demonstrated
ADTR	MED	Accelerator reliability is a major concern
HPM	HIGH	Asssumed comparable to current LWR once-through
Small LWR	HIGH	Equivalent to current LWR
LWR once-through	HIGH	REFERENCE CASE
LWR recycle	HIGH	Same

Explanatory notes

Any viable system would need to have demonstrated reliability

Table 20: Radiological exposure assessment

Attribute: Radiological exposures

UK Relevance	HIGH
Discriminating power	HIGH

System	Performance	Comments
SFR	MED	High gas release provides increased volatiles source term in accidents
GFR	MED	Same
LFR	MED	Same
VHTR	V HIGH	Very robust fuel form
SCWR	HIGH	Comparable to current LWR
MSR	MED	No demonstrated
ADTR	MED	Assumed equivalent to fast reactors
HPM	HIGH	Fission gas release fraction assumed low on account of low rating
Small LWR	HIGH	Equivalent to current LWR
LWR once-through	HIGH	Good fission gas retention - REFERENCE CASE
LWR recycle	HIGH	Same

Explanatory notes

This refers to radiological exposure in the front-end fuel cycle, reactor operations and back-end fuel cycle and also in accidents

The main discriminating feature is the behaviour in accidents and possible this metric should be split into two components:

1) Routine radiological exposures

2) Radiological exposures in accident conditions

Alternatively, the latter could be subsumed in Metric 12 (Safety)

Table 21: Safety assessment

Attribute: Safety

UK Relevance	HIGH	
Discriminating powe	HIGH	Revised upwards since NNL (11) 11491 following Fukushima

System	Performance	Comments
SFR	MED	Penalised by high fission gas release
GFR	MED	Same
LFR	MED	Same
VHTR	V HIGH	Very robust fuel form
SCWR	HIGH	Comparable to current LWR once-through
MSR	MED	Safety approach remains to be developed
ADTR	MED	Assumed equivalent to fast reactors
HPM	HIGH	Fission gas release fraction assumed low on account of low rating
Small LWR	HIGH	Equivalent to current LWR
LWR once-through	HIGH	REFERENCE CASE
LWR recycle	HIGH	Same

Explanatory notes

All the systems would need to meet the same very exacting safety and reliability standards to be viable

Table 22: Reactivity control assessment

Attribute: Reactivity control

UK Relevance	LOW
Discriminating power	LOW

System	Performance	Comments
SFR	MED	
GFR	MED	
LFR	MED	
VHTR	HIGH	Passive shutdown capability
SCWR	MED	Comparable to current LWR once-through
MSR	HIGH	Favourable reactivity feedback coefficients. Ability to dump core in criticaility safe geometry.
ADTR	MED	ADTR will need to control reactivity very closely
HPM	MED	
Small LWR	MED	Equivalent to current LWR
LWR once-through	MED	REFERENCE CASE
LWR recycle	MED	Same

Explanatory notes

Table 23: Decay heat removal assessment

Attribute: Decay heat removal

UK Relevance	HIGH	Revised upwards since NNL (11) 11491 following Fukushima
Discriminating powe	HIGH	Revised upwards since NNL (11) 11491 following Fukushima

System	**Performance**	**Comments**
SFR	MED	Assumed that active residual heat removal will be needed
GFR	MED	Same
LFR	MED	Same
VHTR	V HIGH	Passive
SCWR	MED	Comparable to current LWR once-through ?
MSR	HIGH	Passive, but needs to be confirmed with fully engineered design
ADTR	MED	Assumed same as fast reactors
HPM	V HIGH	Assumed passive
Small LWR	MED	Equivalent to current LWR
LWR once-through	MED	REFERENCE CASE
LWR recycle	MED	Same

Explanatory notes

Current LWRs require active decay heat removal, but have high redundancy

AP-1000 has passive decay heat removal capability for 72 hours

Table 24: Low uncertainties on dominant phenomena assessment

Attribute: Low uncertainties on dominant phemonena

UK Relevance	LOW
Discriminating powei	LOW

System	Performance	Comments
SFR	HIGH	Technology mature
GFR	LOW	Technology very immature
LFR	MED	Technology immature
VHTR	HIGH	Technology mature
SCWR	LOW	Technology very immature
MSR	LOW	Technology very immature
ADTR	LOW	Technology very immature
HPM	MED	Technology immature
Small LWR	HIGH	Equivalent to current LWR
LWR once-through	HIGH	Physical phenomena well understood - REFERENCE CASE
LWR recycle	HIGH	Same

Explanatory notes

Table 25: Fuel thermal response assessment

Attribute: Fuel thermal response

UK Relevance	HIGH	Revised upwards since NNL (11) 11491 following Fukushima
Discriminating powe	HIGH	Revised upwards since NNL (11) 11491 following Fukushima

System	Performance	Comments
SFR	HIGH	Large thermal inertia of sodium pool
GFR	LOW	Very low thermal inertia
LFR	HIGH	Large thermal inertia of lead pool
VHTR	V HIGH	Passive
SCWR	LOW	Comparable to current LWR once-through
MSR	HIGH	Large thermal inertia of molten salt
ADTR	HIGH	Large thermal inertia of lead pool
HPM	HIGH	Large thermal inertia of lead coolant and low specific rating
Small LWR	LOW	Equivalent to current LWR
LWR once-through	LOW	Low thermal inertia of primary circuit coolant - REFERENCE CASE
LWR recycle	LOW	Same

Explanatory notes

Table 26: Integral experiment scalability assessment

Attribute: Integral experiment scalability

UK Relevance	LOW
Discriminating powe	LOW

System	Performance	Comments
SFR	HIGH	Largely demonstrated at full scale
GFR	LOW	Very immature technology
LFR	MED	Immature technology
VHTR	HIGH	Largely demonstrated at full scale
SCWR	LOW	Very immature technology
MSR	LOW	Very immature technology
ADTR	MED	Immature technology
HPM	MED	Immature technology
Small LWR	V HIGH	Equivalent to current LWR
LWR once-through	V HIGH	REFERENCE CASE
LWR recycle	V HIGH	Same

Explanatory notes

LWR is rated V HIGH because the technology is already mature and demonstrated at full scale

Table 27: Source term assessment

Attribute: Source term

UK Relevance	HIGH
Discriminating power	HIGH

System	Performance	Comments
SFR	LOW	High fission gas release fraction
GFR	LOW	Same
LFR	LOW	Same
VHTR	V HIGH	Very robust fuel form
SCWR	MED	Equivalent to current LWR
MSR	LOW	Equilibrium inventory controlled
ADTR	LOW	Assumed equivalent to fast reactors
HPM	MED	Fission gas release assumed low on account of low specific rating
Small LWR	MED	Equivalent to current LWR
LWR once-through	MED	Low fission gas release - REFERENCE CASE
LWR recycle	MED	Same

Explanatory notes

The source term considered here is the inventory of volatile fission products available for release in the event of loss of containment

Table 28: Energy release mechanisms assessment

Attribute: Energy release mechanisms

UK Relevance	HIGH	Revised upwards since NNL (11) 11491 following Fukushima
Discriminating power	HIGH	Revised upwards since NNL (11) 11491 following Fukushima

System	Performance	Comments
SFR	LOW	Sodium/water interaction
GFR	HIGH	No energy release mechanisms
LFR	HIGH	No energy release mechanisms
VHTR	V HIGH	No energy release mechanisms
SCWR	LOW	Hydrogen explosion
MSR	HIGH	No energy release mechanisms
ADTR	HIGH	No energy release mechanisms
HPM	HIGH	No energy release mechanisms
Small LWR	LOW	Hydrogen explosion
LWR once-through	LOW	Hydrogen explosion - REFERENCE CASE
LWR recycle	LOW	Same

Explanatory notes

Table 29: System response times assessment

Attribute: System response times

UK Relevance	HIGH	Revised upwards since NNL (11) 11491 following Fukushima
Discriminating powe	HIGH	Revised upwards since NNL (11) 11491 following Fukushima

System	Performance	Comments
SFR	HIGH	High thermal inertia, especially for pool type
GFR	LOW	Low thermal inertia
LFR	HIGH	High thermal inertia, especially for pool type
VHTR	V HIGH	High thermal inertia
SCWR	LOW	Low thermal inertia
MSR	MED	Moderate thermal inertia
ADTR	HIGH	High thermal inertia
HPM	HIGH	High thermal inertia - low specific rating
Small LWR	LOW	Same as LWR
LWR once-through	LOW	Low thermal inertia - REFERENCE CASE
LWR recycle	LOW	Same

Explanatory notes

Table 30: Effective hold-up assessment

Attribute: Effective hold-up

UK Relevance	LOW
Discriminating powe**r**	LOW

System	**Performance**	**Comments**
SFR	LOW	100% release of fission gas from the fuel pellets into the fuel rod internal volume
GFR	LOW	Same
LFR	LOW	Same
VHTR	V HIGH	The ceramic fuel reliably retains fission products in all accident conditions
SCWR	MED	Assumed equivalent to LWR
MSR	MED	Equilibrium fission product inventory controlled, but fraction retained in salt to be demonstrated.
ADTR	LOW	Assumed 100% release of fission gas from the fuel pellets into the fuel rod internal volume
HPM	LOW	Assumed 100% release of fission gas from the fuel pellets into the fuel rod internal volume
Small LWR	MED	Equivalent to LWR
LWR once-through	MED	Retention of ~99% of volatiles in fuel plus double containment - REFERENCE CASE
LWR recycle	MED	Same

Explanatory notes

This metric refers to in-built mechanisms for retaining volatile fission products

Table 31: Overnight construction costs assessment

Attribute: Overnight construction costs

UK Relevance	HIGH
Discriminating powe	HIGH

System	Performance	Comments
SFR	LOW	Limited scope for modular construction & requirement for secondary circuit
GFR	LOW	Limited scope for modular construction
LFR	LOW	Limited scope for modular construction
VHTR	MED	Parity with LWR assumed, though to date this has not been demonstrated
SCWR	MED	Assumed equivalent to LWR
MSR	MED	Assumed equivalent to LWR
ADTR	LOW	Accelerator adds major capital cost element
HPM	MED	Assumed equivalent to LWR
Small LWR	MED	Equivalent to LWR
LWR once-through	MED	REFERENCE CASE
LWR recycle	MED	Same

Explanatory notes

Overnight costs for Gen IV systems assessed assuming that generic targets are attainable

ADTR costs assessed as HIGH or V HIGH on account of system complexity

Small LWR costs assessed as equivalent to LWR in best case where current LWR power density is retained

Table 32: Production costs assessment

Attribute: Production (O&M) costs

UK Relevance	HIGH
Discriminating power	HIGH

System	Performance	Comments
SFR	MED	Gen IV target is to be competitive wrt LWR
GFR	MED	Same
LFR	MED	Same
VHTR	MED	Same
SCWR	MED	Assumed equivalent to LWR
MSR	LOW	Gen IV target is to be competitive wrt LWR
ADTR	MED	Assumed equivalent to LWR
HPM	MED	Assumed equivalent to LWR
Small LWR	LOW	Small output may penalise O&M costs
LWR once-through	MED	REFERENCE CASE
LWR recycle	MED	Same

Explanatory notes

Production costs is taken here to be the operating and maintenance (O&M) costs
O&M costs for Gen IV systems assessed assuming that generic targets are attainable
Small LWR O&M costs penalised by low output

Table 33: Construction duration assessment

Attribute: Construction duration

UK Relevance	HIGH
Discriminating powe	HIGH

System	Performance	Comments
SFR	MED	Gen IV target is to be competitive wrt LWR
GFR	MED	Same
LFR	MED	Same
VHTR	HIGH	
SCWR	MED	Assumed equivalent to LWR
MSR	MED	Gen IV target is to be competitive wrt LWR
ADTR	MED	Assumed equivalent to LWR
HPM	HIGH	Same
Small LWR	HIGH	Assumed modular construction
LWR once-through	MED	REFERENCE CASE
LWR recycle	MED	Same

Explanatory notes

Table 34: Development cost assessment

Attribute: Development costs

UK Relevance	HIGH
Discriminating power	HIGH

System	Performance	Comments
SFR	MED	Technology known but not fully developed to required standards
GFR	LOW	Technology poorly developed
LFR	MED	Technology less mature than SFR
VHTR	HIGH	Further development required
SCWR	LOW	Technology poorly developed
MSR	LOW	Technology poorly developed
ADTR	LOW	Technology poorly developed
HPM	LOW	Technology poorly developed
Small LWR	V HIGH	Based on current LWR
LWR once-through	V HIGH	Mature technology - zero development costs - REFERENCE CASE
LWR recycle	V HIGH	Same

Explanatory notes

Table 35: R&D cost assessment

Attribute: R&D costs

UK Relevance	HIGH
Discriminating power	HIGH

System	Performance	Comments
SFR	MED	Technology known but not fully developed to required standards
GFR	LOW	Technology poorly developed
LFR	MED	Technology less mature than SFR
VHTR	HIGH	Further development required
SCWR	LOW	Technology poorly developed
MSR	LOW	Technology poorly developed
ADTR	LOW	Technology poorly developed
HPM	LOW	Technology poorly developed
Small LWR	V HIGH	Based on current LWR
LWR once-through	V HIGH	Mature technology - zero R&D costs - REFERENCE CASE
LWR recycle	V HIGH	Same

Explanatory notes

Table 36: Plutonium and minor actinide management assessment

Attribute: Plutonium and minor actinide management

UK Relevance	HIGH
Discriminating powe	MED

System	Performance	Comments
SFR	HIGH	Potential minor actinide burner
GFR	HIGH	Same
LFR	HIGH	Same
VHTR	HIGH	Potential minor actinide burner
SCWR	MED	Assumed equivalent to current LWR
MSR	V HIGH	Potential minor actinide burner
ADTR	HIGH	Potential minor actinide burner
HPM	LOW	Not intended as a minor actinide burner, though neutron spectrum is suitable
Small LWR	MED	Equivalent to current LWR
LWR once-through	MED	Limited but potentially useful minor actinide burning capability -REFERENCE CASE
LWR recycle	MED	Same

Explanatory notes

Table 37: Load follow capability assessment

Attribute: Load follow capability

UK Relevance	HIGH
Discriminating powei	MED

System	**Performance**	**Comments**
SFR	MED	Assumed equivalent to current LWR
GFR	MED	Same
LFR	MED	Same
VHTR	HIGH	Potentially very responsive core
SCWR	MED	Assumed equivalent to current LWR
MSR	HIGH	Assumed equivalent to current LWR
ADTR	V HIGH	Assumed high flexibility
HPM	MED	Assumed equivalent to current LWR
Small LWR	MED	Assumed equivalent to current LWR
LWR once-through	MED	Load follow capability demonstrated, but response time limited - REFERENCE CASE
LWR recycle	MED	Same

Explanatory notes

Load-follow capability is likely to become a requirement once nuclear capacity exceeds about 50% of grid capacity

Table 38: Scalability assessment

Attribute: Scalability

UK Relevance	HIGH
Discriminating powe	MED

System	Performance	Comments
SFR	MED	Range of core sizes envisaged
GFR	MED	Same
LFR	MED	Same
VHTR	HIGH	Modular core design
SCWR	MED	Assumed equivalent to current LWR
MSR	HIGH	
ADTR	MED	Assumed equivalent to current LWR
HPM	HIGH	Modular core design
Small LWR	HIGH	Modular core design
LWR once-through	MED	Range of core sizes from 600 MWe to 1600 MWe available - REFERENCE CASE
LWR recycle	MED	Same

Explanatory notes

Scalability is potentially an issue in the UK in a scenario of high nuclear capacity and limited site availability

Table 39: Timescales to deployment assessment

Attribute: Timescales to deployment

UK Relevance	HIGH
Discriminating power	HIGH

System	**Performance**	**Comments**
SFR	HIGH	Demonstrated technology base
GFR	LOW	Very immature design
LFR	MED	Needs some development
VHTR	MED	Needs some development
SCWR	LOW	Very immature design
MSR	LOW	Very immature design
ADTR	LOW	Very immature design
HPM	LOW	Very immature design
Small LWR	HIGH	Not commercially available, but mature technology base
LWR once-through	V HIGH	Available already - REFERENCE CASE
LWR recycle	V HIGH	Same

Explanatory notes

Table 40: Technology readiness level assessment

Attribute: Technology Readiness Level (TRL)

UK Relevance	HIGH
Discriminating power	HIGH

System	Performance	Comments
SFR	HIGH	Technology base demonstrated at industrial scale
GFR	LOW	Very immature technology
LFR	MED	Immature technology
VHTR	HIGH	Technology base demonstrated at inustrial scale
SCWR	LOW	Very immature technology
MSR	LOW	Very immature technology
ADTR	LOW	Very immature technology
HPM	LOW	Very immature technology
Small LWR	HIGH	Technology base mature, but no market penetration to date
LWR once-through	V HIGH	Available already - REFERENCE CASE
LWR recycle	V HIGH	Same

Explanatory notes

Table 41: Flexibility of location assessment

Attribute: Flexibility of location

UK Relevance	HIGH
Discriminating powe	MED

System	Performance	Comments
SFR	MED	Large scale plant
GFR	MED	Same
LFR	MED	Same
VHTR	HIGH	Modular deployment option
SCWR	MED	Assumed equivalent to LWR
MSR	MED	Assumed equivalent to LWR
ADTR	HIGH	600 MWe module
HPM	HIGH	Modular deployment option
Small LWR	HIGH	Modular deployment option
LWR once-through	MED	Large scale output (1 GWe+) - REFERENCE CASE
LWR recycle	MED	Same

Explanatory notes

Table 42: Waste arisings assessment

Attribute: Waste arisings (volumes HLW, ILW & LLW)

UK Relevance	HIGH
Discriminating power	HIGH

System	Performance	Comments
SFR	HIGH	Reduced inventory of higher actinides
GFR	HIGH	Same
LFR	HIGH	Same
VHTR	MED	Stable spent fuel form but increased HLW volume
SCWR	MED	Equivalent to current LWR
MSR	HIGH	Reduced inventory of higher actinides - no hulls and ends
ADTR	HIGH	Reduced inventory of higher actinides
HPM	HIGH	Reduced inventory of higher actinides
Small LWR	MED	Equivalent to current LWR
LWR once-through	MED	REFERENCE CASE
LWR recycle	MED	Same

Explanatory notes

Table 43: Benefits or risks for security assessment

Attribute: Benefits or risks for security

UK Relevance	HIGH
Discriminating power	HIGH

System	Performance	Comments
SFR	MED	Assumed equivalent to LWR
GFR	MED	Same
LFR	MED	Same
VHTR	V HIGH	Highly robust fuel form
SCWR	MED	Assumed equivalent to LWR
MSR	MED	Fewer containment barriers
ADTR	MED	Assumed equivalent to LWR
HPM	HIGH	Could be located underground
Small LWR	MED	Assumed equivalent to LWR
LWR once-through	MED	REFERENCE CASE
LWR recycle	MED	Same

Explanatory notes

Table 44: Number and size of reactors assessment

Attribute: Number and size of reactors needed

UK Relevance	HIGH
Discriminating power	HIGH

System	**Performance**	**Comments**
SFR	MED	Assumed equivalent to LWR
GFR	MED	Same
LFR	MED	Same
VHTR	LOW	Modular build offers increased flexibility wrt LWR
SCWR	MED	Assumed equivalent to LWR
MSR	HIGH	Basic design assumed scalable, but depends on passive heat removal capability scaling as well
ADTR	MED	600 MWe module
HPM	LOW	Very small system size does not fit UK requirements
Small LWR	LOW	Modular build offers increased flexibility wrt LWR
LWR once-through	MED	> 1 GWe capacity - REFERENCE CASE
LWR recycle	MED	Same

Explanatory notes

Table 45: Associated fuel cycle assessment

Attribute: Associated fuel cycle

UK Relevance	HIGH
Discriminating power	HIGH

System	Performance	Comments
SFR	LOW	New infrastructure needed
GFR	LOW	Same
LFR	LOW	Same
VHTR	LOW	New infrastructure needed
SCWR	HIGH	Assumed equivalent to LWR
MSR	LOW	New infrastructure needed
ADTR	LOW	New infrastructure needed
HPM	LOW	New infrastructure needed
Small LWR	HIGH	Equivalent to LWR
LWR once-through	HIGH	Matches existing infrastructure - REFERENCE CASE
LWR recycle	HIGH	Same

Explanatory notes

Table 46: Proliferation resistance assessment

Attribute: Proliferation resistance

UK Relevance	HIGH
Discriminating powe	MED

System	Performance	Comments
SFR	MED	Assumed equivalent to LWR recycle
GFR	MED	Same
LFR	MED	Same
VHTR	V HIGH	Highly proliferation resistant fuel form, using LEU fuel
SCWR	HIGH	Equivalent to LWR once-through
MSR	MED	Possible increased threat from real-time fission product separation
ADTR	MED	Assumed equivalent to LWR recycle
HPM	HIGH	Inaccessible fuel with no separated fissile materials
Small LWR	HIGH	Equivalent to LWR once-through
LWR once-through	HIGH	No separated fissile materials - REFERENCE CASE
LWR recycle	MED	Separated PuO2

Explanatory notes

Table 47: Ease of construction assessment

Attribute: Ease of construction

UK Relevance	HIGH
Discriminating powe	HIGH

System	Performance	Comments
SFR	LOW	Limited scope for modular construction
GFR	LOW	Same
LFR	LOW	Same
VHTR	HIGH	Modular construction
SCWR	MED	Assumed equivalent to LWR
MSR	LOW	New infrastructure needed
ADTR	LOW	New infrastructure needed
HPM	HIGH	Factory build small modules - new infrastructure needed
Small LWR	HIGH	Modular construction
LWR once-through	MED	REFERENCE CASE
LWR recycle	MED	Same

Explanatory notes

Table 48: Sustainability assessment

Attribute: Sustainability

UK Relevance	HIGH
Discriminating powe	HIGH

System	Performance	Comments
SFR	V HIGH	Independent of uranium ore supply
GFR	V HIGH	Same
LFR	V HIGH	Same
VHTR	LOW	Assumed equivalent to LWR
SCWR	LOW	Assumed equivalent to LWR
MSR	V HIGH	High conversion ratio
ADTR	V HIGH	
HPM	LOW	Assumed equuivalent to LWR
Small LWR	LOW	Modular construction
LWR once-through	LOW	REFERENCE CASE
LWR recycle	LOW	Marginal improvement on once-through

Explanatory notes

Table 49: Potential to drive thermal processes assessment

Attribute: Potential to drive thermal processes

UK Relevance	HIGH
Discriminating power	HIGH

System	Performance	Comments
SFR	MED	High operating temperature
GFR	HIGH	Very high operating temperature
LFR	MED	High operating temperature
VHTR	V HIGH	Very high operating temperature
SCWR	MED	High operating temperature
MSR	HIGH	High operating temperature
ADTR	MED	Potentially high operating temperature
HPM	MED	Potentially high operating temperature
Small LWR	LOW	Equivalent to LWR
LWR once-through	LOW	Low working temperature (300°c) - REFERENCE CASE
LWR recycle	LOW	Same

Explanatory notes

Table 50: Decommissioning costs assessment

Attribute: Decommissioning costs

UK Relevance	HIGH
Discriminating power	HIGH

System	Performance	Comments
SFR	MED	Bulky reactor structure & sodium decom/disposal adds cost?
GFR	MED	Bulky reactor structure
LFR	MED	Bulky reactor structure & Pb/Bi decom/disposal adds cost
VHTR	HIGH	Graphite decom/disposal adds cost ?
SCWR	HIGH	Equivalent to LWR
MSR	MED	Bulky reactor structure and graphite disposal
ADTR	MED	Bulky reactor structure
HPM	V HIGH	Disposable reactor module
Small LWR	HIGH	Equivalent to LWR
LWR once-through	HIGH	REFERENCE CASE
LWR recycle	HIGH	Same

Explanatory notes

Table 51: Primary purpose assessment

Attribute: Primary purpose

UK Relevance	HIGH
Discriminating power	HIGH

System	Performance	Comments
SFR	HIGH	Minor actinide burning and high operating temperature
GFR	HIGH	Same
LFR	HIGH	Same
VHTR	V HIGH	Minor actinide burning and very high operating temperature
SCWR	MED	High operating temperature
MSR	HIGH	Minor actinide burning
ADTR	HIGH	Minor actinide burning
HPM	MED	Possible heat source applications
Small LWR	MED	Possible improved match for plutonium disposition
LWR once-through	LOW	Electricity generation only - REFERENCE CASE
LWR recycle	LOW	Same

Explanatory notes

Table 52: Aggregate scores

	Fuel utilisation	Spent fuel mass	VHLW volume	Long term heat output	Long term radiotoxicity	Environmental impact	Separated materials	Spent fuel characteristics	Sabotage resistance	Reliability	Worker exposures	Safety	Reactivity control	Decay heat removal	Low uncertainties on dominant	Fuel thermal response	Integral experiment scalability	Source term	Energy release mechanisms	System response times	Effective hold-up
System	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
SFR	4	3	3	3	3	4	2	2	3	3	2	2	2	2	3	3	3	1	1	3	1
GFR	4	3	3	3	3	4	2	2	3	3	2	2	2	2	1	1	1	1	3	1	1
LFR	4	3	3	3	3	4	2	2	3	3	2	2	2	2	2	3	2	1	3	3	1
VHTR	1	1	1	2	2	3	4	4	4	4	4	4	3	4	3	4	3	4	4	4	4
SCWR	1	2	2	2	2	3	3	2	3	3	3	3	2	2	1	1	1	2	1	1	2
MSR	4	2	3	3	3	4	3	4	1	2	2	2	3	3	1	3	1	1	3	2	2
ADTR	4	3	3	3	3	4	2	2	3	2	2	2	2	2	1	3	2	1	3	3	1
HPM	1	2	2	2	2	3	3	2	4	3	3	3	2	4	2	3	2	2	3	3	1
Small LWR	1	2	2	2	2	3	3	2	3	3	3	3	2	2	3	1	4	2	1	1	2
LWR once-through	1	2	2	2	2	3	3	2	3	3	3	3	2	2	3	1	4	2	1	1	2
LWR recycle	1	2	3	1	2	3	1	2	3	3	3	3	2	2	3	1	4	2	1	1	2

	Overnight construction costs	Production costs (O&M?)	Construction duration	Development costs	R&D costs	Plutonium and minor actinide	Load follow capability	Scalability	Timescales to deployment	Technology Readiness Level	Flexibility of location	Waste arisings (volumes HLW, ILW,	Benefits or risks for security	Number and size of reactors needed	Associated fuel cycle	Proliferation resistance	Ease of construction	Sustainability	Potential to drive thermal processes	Decommissioning costs	Primary purpose			
System	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	**TOT1**	**TOT2**	**TOT3**
SFR	1	2	2	2	2	3	2	2	3	3	2	3	2	2	1	2	1	4	2	2	3	**99**	**81**	**29**
GFR	1	2	2	1	1	3	2	2	1	1	2	3	2	2	1	2	1	4	3	2	3	**88**	**80**	**28**
LFR	1	2	2	2	2	3	2	2	2	2	2	3	2	2	1	2	1	4	2	2	3	**97**	**83**	**28**
VHTR	2	2	3	3	3	3	3	3	2	3	3	2	4	1	1	4	3	1	4	3	4	**124**	**104**	**34**
SCWR	2	2	2	1	1	2	2	2	1	1	2	2	2	2	3	3	2	1	2	3	2	**82**	**76**	**24**
MSR	2	1	2	1	1	4	3	3	1	1	2	3	2	3	1	2	1	4	3	2	3	**97**	**88**	**32**
ADTR	1	2	2	1	1	3	4	2	1	1	3	3	2	2	1	2	1	4	2	2	3	**94**	**87**	**30**
HPM	2	2	3	1	1	1	2	3	1	1	3	3	3	1	1	3	3	1	2	4	2	**95**	**84**	**26**
Small LWR	2	1	3	4	4	2	2	3	3	3	3	2	2	1	3	3	3	1	1	3	2	**98**	**74**	**27**
LWR once-through	2	2	2	4	4	2	2	2	4	4	2	2	2	2	3	3	2	1	1	3	1	**97**	**72**	**25**
LWR recycle	2	2	2	4	4	2	2	2	4	4	2	2	2	2	3	2	2	1	1	3	1	**94**	**69**	**25**

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