National Nuclear Laboratory

Review of Metrics Relevant to Reactor Systems

NNL (11) 11491
Issue 3

A report prepared for and on behalf of
Department of Energy and Climate Change

 Jan 2012

National Nuclear Laboratory

Review of Metrics Relevant to Reactor Systems

NNL (11) 11491
Issue 3

Checked by :	Christopher Grove
Approved by :	Andrew Worrall
Work Order No.	04944.100

KEYWORDS:

Gen IV; Metrics;

EXECUTIVE SUMMARY

The UK National Nuclear Laboratory has been contracted by the Department for 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: 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).

These nine systems span a very wide range, 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.

An important requirement for the UK is to be in a position to assess the relative merits of different advanced nuclear systems, for which a systematic approach is preferable. For this purpose it would be helpful to establish first a set of agreed metrics for the assessment. For this purpose, a preliminary list of metrics has been compiled. Although some of the metrics can be in principle be evaluated quantitatively, others are necessarily qualitative in nature and will require judgement to be applied. Even for the former, quantitative assessments may not be possible for all of the systems considered unless the systems are well enough developed. The priorities and drivers will likely change with time and will differ between countries and it is important that the metrics should not be applied too rigidly without recognising the likelihood of change.

This report provides initial suggestions for a set of metrics (42 in total), together with an initial assessment as to their relevance to the UK and the extent to which they are likely to be effective at discriminating between the different nuclear systems.

The metrics compiled here will be used in next phase of the study when the nine reactors technologies of interest will be evaluated. It should be noted that the metrics identified in this paper should only be regarded as preliminary. The study and the approach developed was deliberately limited in scope due to time and in particular budget constraints.

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

The above is a minimum requirement. Add any additional appropriate criteria

HISTORY SHEET

Issue Number	**Date**	**Comments**
Issue 1	4 March 2011	Issued to DECC for comment
Issue 2	5 Jan 2012	Re-issue taking account of comments received from reviewers
Issue 3	27 Jan 2012	Correction of minor typographical errors

CONTENTS

LIST OF TABLES

1. Introduction

The UK National Nuclear Laboratory has been contracted by the Department for 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, 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.

A recent position paper from NNL [2] has highlighted how, in some scenarios of UK energy development, there may be a role for fast reactors from about 2040 onwards. There are credible scenarios with fast reactors operating alongside new build PWRs where fast reactors would become of the highest strategic importance to the UK. Maintaining these long term strategic options is a strong reason why the UK should retain interest in advanced reactor systems and might prove a determining factor in policy decisions regarding UK fuel cycle policies. The timescales are difficult to gauge and there are large uncertainties regarding when fast reactors might become commercially available and it is not certain that fast reactors will be available in time for deployment alongside new build LWRs. Despite the uncertainties, it is important to investigate the strategic possibilities, which will identify potential future vulnerabilities.

In order to systematically assess the relevance of advanced nuclear systems to the UK, it is necessary to first identify what are the relevant metrics and a list of metrics is developed in this report. This will provide the framework for assessing the various systems in a second report. Finally, a third report will discuss the potential role of thorium fuels, particularly with relevance to UK plutonium management. DECC specifically requested an assessment of thorium fuel cycles because in recent years there has been a lot of activity in this area. The discussion in the thorium report will consider the merits and disadvantages of thorium in a hopefully more balanced way than it is often portrayed by proponents, building on another position paper from NNL [3].

2. Metrics

GIF has published a list of 26 metrics that it will using to assess the six Gen IV systems against its high level goals [1]. These are a good starting point for the UK to assess potential future reactor systems and are listed here in Table 1 (Labels 1 to 26). Some additional metrics that are important to the UK were identified in the specification for this review task and are also listed in Table 1 (Labels 27 onwards).

The complete list of metrics contains 42 separate items. This section provides a brief discussion of all 42 metrics. This is done in the tabular form, with one table per metric. Each table lists:

1. The metric number and name.
2. An indication of what general category heading the metric comes under (sustainability, economics, safety and reliability and proliferation resistance).
3. An assessment of the discriminating power of the metric for the UK, assigned High, Medium or Low, meaning the extent to which the particular metric discriminates between different systems.
4. As assessment of the relevance of the metric to the UK, assigned High, Medium or Low.
5. A discussion as to the significance of the metric, meaning an explanation of its meaning and importance, as well as the reasoning for assigning discriminating power and UK relevance.

The 42 metrics will be used in a later stage of this work to assess nine reactors systems identified in Section 1. The various metrics are categorised into groups under the headings: resource utilisation; waste minimisation, waste management; proliferation resistance; vulnerability; operational safety & reliability; economics; operational requirements and strategic that might prove useful at a later stage.

Although this paper is intended to focus on reactors and not fuel cycle options, the two cannot be completely separated.

Table 1: 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

1. Fuel utilisation					
Category: Resource utilisation					
Discriminating power	H	UK relevance	H		
Significance	Fuel utilisation is the mass of uranium ore needed to meet the fuelling requirements of the reactor. It is a measure of the strategic dependence on uranium ore supplied from overseas. Fuel utilisation is usually expressed in tU per GWye, which for a PWR is typically in the region of 200 tU/GWye. All of the thermal reactor systems have similar uranium requirements. The fast reactor systems in Gen IV (SFR, GFR and LFR) are capable of a self-sustaining (breeding) fuel cycle, with a virtually zero uranium requirement. The discriminating power is high because it is a strong distinguishing factor between the thermal and fast reactor options. Although fuel utilisation is not considered an important consideration for UK new build in the immediate future, there are scenarios of high world nuclear capacity where it may become a significant issue. This applies particularly to UK scenarios with high nuclear dependence, such as the Level 4 nuclear trajectory postulated in the recent 2050 Pathways Analysis Report published by DECC. The relevance to the UK is therefore considered high, on account of its potential impact in the medium to long term future.				

2. Spent fuel mass					
Category: Waste minimisation					
Discriminating power	L	UK relevance	L		
Significance	This is the mass of spent fuel arisings. The spent fuel arising is most meaningfully expressed as the heavy metal (HM) mass of fuel per GWye (tHM/GWye). The spent fuel arising has only low discriminating power for the once-through options, because it is determined by the fuel discharge burnup and the system thermal efficiency and these do not vary greatly. For the recycle options the spent fuel arising is important only in that it determines the throughput and capacity of reprocessing plants, which again is only a low discriminator. In the UK, the mass of spent fuel for disposal is not the limiting factors in waste management. The overall relevance to the UK is therefore classified low.				

3. VHLW volume					
Category: Waste minimisation					
Discriminating power	H	UK relevance	H		
Significance	This is the volume of high activity (heat generating) waste, expressed in m^3 per GWye. For once-through fuel cycle options, it is the volume of spent fuel. In the initial stages where the spent fuel is stored either in ponds or interim dry storage canister, the relevant volume is the overall volume of the spent fuel assemblies discharged per GWye. At a later stage, the volume becomes that of the spent fuel conditioned and packaged for geological disposal. For the options under consideration, the spent fuel volume per GWye is governed by the mean discharge burnup and thermal efficiency, which do not vary greatly. For the recycle options, the relevant measure is the volume of vitrified waste canisters, which in turn is determined by the incorporation rate of fission product and actinide oxide in the glass matrix. The incorporation rate is typically limited by the neutron source, which can vary depending on the reactors system. Therefore, there is the potential for the waste volume to have high discriminating power and is of high relevance in the UK, because it may determine capacity requirement of the geological repository.				

4. Long term heat output					
Category: Waste management					
Discriminating power	H	UK relevance	H		
Significance	The long term heat output of spent fuel or of heat producing nuclear waste, measured most meaningfully in kW per GWye, is a key discriminating factor. There are potentially significant differences in decay heat per GWye depending on the reactor system and whether a once-through or recycle option is chosen. Because the capacity of the geological disposal for heat generating waste is limited by the heat output, this makes both the discriminating power and relevance to the UK high. Consideration of long term heat outputs is a complex technical issue and great care is needed to ensure that comparisons between different reactors and fuel cycles are fair and meaningful. Long term heat output will be a major determining factor in the design and justification of a geological disposal facility, which is why the discriminating power and relevance have been set to high.				

5. Long term radiotoxicity					
Category: Waste management					
Discriminating power	M	UK relevance	M		
Significance	The radiotoxicity is a measure of the hazard potential of radioactive material. The most logical units to measure radiotoxicity are in Sieverts (Sv) per GWye, the Sievert being the unit of biological dose, which accounts for energy deposition in biological tissue, weighted by biological damage factors for different tissues, different types of radiation and depending on the retention of different radionuclides in the body. There are potentially significant differences in radiotoxicity per GWye between the once-through and recycle options, depending on the reactor systems and the specific scenarios considered. Radiotoxicity is a complex technical issue and great care is needed to ensure that comparisons between different reactors and fuel cycles are fair and meaningful. Although radiotoxicity is often cited as an important discrimination parameter, its relevance to a geological disposal facility is questionable. The more important consideration for a geological disposal facility is the combination of the radiotoxicities of the different nuclides and their mobilities in the immediate vicinity of the facility and the surrounding geology. The design of a geological repository is influenced primarily by heat load and not radiotoxicity and therefore radiotoxicity is not likely to be a major determining factor in the design of a geological disposal facility However, in the absence of a specific site for the geological disposal facility, radiotoxicity is often cited as the best available measure and indeed has been used in UK reactor and fuel cycle options studies. On balance, radiotoxicity is assigned medium discriminating power and medium relevance to the UK.				

<table>
<tr><td colspan="6">6. Environmental impact</td></tr>
<tr><td colspan="6">Category: Waste minimisation and waste management</td></tr>
<tr><td>Discriminating power</td><td>M</td><td>UK relevance</td><td>M</td><td></td><td></td></tr>
<tr><td>Significance</td><td colspan="5">The direct environmental impact of nuclear power stations and their associated fuel cycle facilities is generally quite low.

The environmental impacts can be identified as:

➢ Visual impact of reactors and fuel cycle plants
➢ Direct gaseous and aqueous radioactive emissions discharge to air and sea respectively
➢ Carbon footprints
➢ Environmental impact of uranium mining and other fuel cycle facilities

Any nuclear system under consideration in the UK would have to meet very stringent environmental requirements, and the likelihood is that there would be relatively little to distinguish the different systems in this respect. However, it is widely accepted that with conventional uranium mining methods (open cast and deep mining), uranium mining is the largest single contributor to the overall environmental impact of nuclear power plants. Therefore, self-sustaining fast reactor fuel cycles, for which no uranium mining is required, would score more highly in this respect.

For these reasons, the discriminating power and UK relevance are assigned medium categorisations.</td></tr>
</table>

7. Separated materials					
Category: proliferation resistance, meaning susceptibility of nuclear materials to diversion, theft or undeclared production					
Discriminating power	M	UK relevance	H		
Significance	One of the goals of GIF is that the nuclear systems should avoid producing at any stage nuclear materials such as high enriched uranium (HEU), weapons-grade plutonium (WG-Pu) or reactor-grade plutonium (RG-Pu) that could be used (with minimal processing) as the fissile material for a nuclear weapon. A definitive analysis of the proliferation resistance impact of different separation flowsheets has yet to be carried out, but NNL's judgement is that the discriminating power is likely to be moderate, hence the medium designation against this parameter. Nevertheless, it should be acknowledged that proliferation resistance is a very important political consideration and it is likely that any decision on future UK reactor systems and reprocessing plants will need to address the political sensitivities and this is why relevance to the UK has been assigned high.				

<table>
<tr><td colspan="6">8. Spent fuel characteristics</td></tr>
<tr><td colspan="6">Category: proliferation resistance, meaning susceptibility of nuclear materials to diversion, theft or undeclared production</td></tr>
<tr><td>Discriminating power</td><td>H</td><td>UK relevance</td><td>H</td><td></td><td></td></tr>
<tr><td>Significance</td><td colspan="5">The proliferation resistance characteristics of spent fuel are determined by the combination of the isotopic composition of the fissile material and the physical and radiological characterisation of the fuel material that would constitute inherent barriers to accessing the fissile material.

For most of the reactor systems considered here, the spent fuel characteristics are mostly quite similar, but there are exceptions:

VHTR fuel consists of fissile material encapsulated in small ceramic microspheres and dispersed in a graphite matrix. VHTR fuel microspheres are difficult to break down mechanically and are impervious to acid dissolution. Combined with the fuel microspheres being diluted in the graphite matrix, the net result is a fuel form in which it is very difficult to access the fissile material for diversion.

On the other hand, MSR fuel comprises molten salt where the fissile material is relatively easily separated in an on-line reprocessing plant.

The discriminating power is therefore categorised as high. The relevance to the UK is also categorised as high, on the grounds that for the UK as a nuclear weapons state the direct relevance of the accessibility of fissile material is low. Nevertheless, the need to comply with international best practice elevates the relevance to high.</td></tr>
</table>

9. Sabotage resistance					
Category: vulnerability of installations					
Discriminating power	M	UK relevance	H		
Significance	This refers to the vulnerability of the nuclear plant and fuel cycle facilities to external threats such as missile attack or aircraft impact. Any design constructed in the UK would need to meet very stringent standards with respect to external hazards and the discriminating potential between most of the designs would be expected to be low. However, in some of the systems considered (small modular LWRs and Hyperion) the nuclear island is largely sited underground and therefore exceptionally well protected. This is why the discriminating power is set to medium. Vulnerability to external attack is an area which has come under close scrutiny in the UK and this is why its relevance is set to high.				

10. Reliability					
Category: operational safety and reliability/economics					
Discriminating power	M	UK relevance	H		
Significance	This is the forced outage rate, which should be very low. It is classified in GIF as an operational safety and reliability issue, but it is also important for economics. Best operational practice at modern LWRs gives spurious reactor trip frequencies considerably less than 1 per year. Forced outages due to equipment failures are rare. For example, in Sizewell B there has only been one significant forced outage in 15 years of operation. Any new nuclear plant built in the UK would need to be able to demonstrate very low forced outage rates in order to be economically competitive. All of the systems considered in this report are designed to offer high reliability, though because some are not demonstrated the discriminating power of reliability is rated medium. It is assumed that the UK would only adopt reactor systems that are already mature and proven to be reliable. The importance of reliability for best operational practice and economics makes its relevance to the UK high.				

11. Radiological exposures					
Category: operational safety and reliability					
Discriminating power	H	UK relevance	H		
Significance	This covers radiological exposures to workers and the public from normal operations and from accidents. It is a fundamental safety aspect and is ranked high for UK relevance. Any new reactor system deployed in the UK would be expected to have very low radiological exposures in normal operation to workers and virtually zero exposure to the public. In this respect there would be little to distinguish different systems and low discriminating power. However, radiological releases in accident conditions may be a strong discriminator. Some of the systems considered here rely on passive safety and are expected to demonstrate low radiological release even in the most limiting accident conditions consistent with not having to put in place emergency evacuation arrangements. Other systems may not be able meet the same requirement.				

12. Safety					
Category: operational safety and reliability					
Discriminating power	M	UK relevance	H		
Significance	Any new reactor system deployed in the UK would need to meet very stringent safety standards and safety would not therefore be a strong discriminator. However, some of the systems considered here rely on passive safety and this might distinguish them from other systems that rely on conventional active safety systems. This is why the discriminating power has been set to medium. Safety is of high relevance to the UK and would be one of the main areas to be addressed in justifying a new reactor system.				

13. Reactivity control					
Category: operational safety and reliability					
Discriminating power	M	UK relevance	M		
Significance	Reliable reactivity control is an integral part of the overall approach to safety. It must be demonstrated that a reactor system can be shutdown safely from any operating condition with a specified margin and accounting for uncertainties. There is also a requirement for an independent shutdown mechanism. The reactivity control system of any reactor system deployed in the UK would be expected to meet stringent safety requirements and there should be only moderate discrimination between systems, since all different technical approaches will need to meet the same standards. This is why the discriminating power and UK relevance have been set to medium.				

14. Decay heat removal					
Category: operational safety and reliability					
Discriminating power	M	UK relevance	M		
Significance	Reliable decay heat removal is an integral part of the overall approach to safety. It must be demonstrated that a reactor system is able to dissipate decay heat following any normal or abnormal operating condition. Some of the systems considered here rely on passive decay heat removal systems, while others have active systems. The decay heat removal system of any reactor system deployed in the UK would be expected to meet stringent safety requirements and there should be little to discriminate between passive and active systems provided that the requirements are met. This is why the discriminating power and relevance have been set to medium.				

15. Low uncertainties on dominant phenomena					
Category: operational safety and reliability					
Discriminating power	L	UK relevance	L		
Significance	Low uncertainties on dominant phenomena refers to the uncertainties affecting the engineering parameters controlling safety at the plant. It is preferable if the dominant physical parameters controlling the safety behaviour of a nuclear power plant or fuel cycle plant are understood very well, with tightly defined uncertainty ranges. This allows the safe operating limits to be defined with high confidence and also maximises the headroom available for normal operation. Dominant phenomena uncertainties are also important during the development of new designs and systems where the dominant phenomena uncertainties are high might be expected to require more protracted R&D. Dominant phenomena uncertainties is a very detailed technical consideration that would not be expected to be a prominent issue in high level assessments such as these. Therefore this area is assigned low discriminating power and low relevance to the UK.				

16. Fuel thermal response					
Category: operational safety and reliability					
Discriminating power	L	UK relevance	L		
Significance	It is preferable from the point of view of safety if a reactor system has a long fuel thermal response time. This is the timescale on which the temperature of the fuel responds to off-nominal operation. If the response time is long, then this provides more time to sense the abnormal condition and take mitigating actions. Generally, a system which runs at a low specific rating would be expected to have a long response time. However, the specific rating is an important economic parameter – the higher the specific power the more compact the system and the lower are the construction costs. Therefore there is a balance between long fuel response time for safety and high power capability for more efficient and competitive operation. Fuel thermal response is a very detailed technical consideration that would not be expected to be a prominent issue in high level assessments such as these. Therefore this area is assigned low discriminating power and low relevance to the UK.				

17. Integral experiment scalability					
Category: operational safety and reliability					
Discriminating power	L	UK relevance	L		
Significance	Integral experiment scalability is an important consideration during the R&D phase of a new reactor or fuel cycle plant. Scale model testing of components is an important part of the validation process of computational methods and it is preferable if the scale model results can be extrapolated to full scale with minimum uncertainty. Integral experiment scalability is important only during the R&D phase and any mature system ready for deployment in the UK would be expected to have already completed this development phase and already be at a High Technology Readiness Level (TRL). Integral experiment scalability is a very detailed technical consideration that would not be expected to be a prominent issue in high level assessments such as these. It is assumed that the UK would only adopt reactor systems that are already mature, for which this metric would no longer be relevant. Therefore integral experiment scalability has low discriminating power and low relevance to the UK.				

18. Source term					
Category: operational safety and reliability					
Discriminating power	H	UK relevance	H		
Significance	The source term is that part of the radiological inventory of a reactor core that can potentially be released in an accident condition. It is important because it determines whether there is a need for emergency response arrangements to be made outside the site boundary. In conventional LWR cores the releasable inventory consists of a small fraction (usually about 1%) of volatile radionuclides such as I-131 that are generated in the fuel. The main inventory of volatile radionuclides is retained in the fuel pellets and is not available for release and only the small fraction that is released from the porosity of the fuel pellets into the fuel rod open volume is available for release. In some of the systems considered (VHTR), the release fraction would be much lower because of the ceramic fuel used and its high robustness. In other systems, the passive approach to safety is expected to result in no accident sequences within the Design Basis that result in radiological release. In both these cases, off-site evacuation would not be a requirement. It is for this reason that the source term has been assigned high discriminating power. It is also a topic that is considered of high relevance to the UK.				

19. Energy release mechanisms					
Category: operational safety and reliability					
Discriminating power	M	UK relevance	M		
Significance	Energy release mechanisms are an important aspect of nuclear plant safety. Preferably, there should be no mechanisms that release energy during accident conditions. The different reactor systems are potentially different in respect of the energy release mechanisms that apply. Energy release mechanisms is a very detailed technical consideration that would not be expected to be a prominent issue in high level assessments such as these. Therefore this area is assigned only medium discriminating power and medium relevance to the UK.				

20. System response times					
Category: operational safety and reliability					
Discriminating power	L	UK relevance	L		
Significance	This is similar to the fuel thermal response time and refers to the time constants associated with the balance of the nuclear system design. Slow response times associated with large heat capacities and low specific ratings are desirable, but must be balanced against the economic penalties of low ratings and large masses. System response times is a very detailed technical consideration that would not be expected to be a prominent issue in high level assessments such as these. Therefore this area is assigned low discriminating power and low relevance to the UK.				

21. Effective hold-up					
Category: operational safety and reliability					
Discriminating power	M	UK relevance	M		
Significance	Effective hold-up refers to mechanisms in the design of a plant for containing radioactive material following an accident condition. In LWRs it is normal practice to have either a containment dome or a system of interconnected volumes that can contain steam released in the event of an accident condition leading to a depressurisation of the primary pressure circuit. The containment system is equipped with mechanisms for condensing the steam and preventing further pressure build-up and retaining any radiological inventory. The containment capability is an important input determining whether there is a requirement for off-site evacuation procedures to be in place. Effective hold-up is a very detailed technical consideration that would not be expected to be a prominent issue in high level assessments such as these. Therefore this area is assigned medium discriminating power and medium relevance to the UK.				

22. Overnight construction costs					
Category: economics					
Discriminating power	H	UK relevance	H		
Significance	The overnight construction cost is the cost that would be incurred if construction could be completed instantaneously ie without finance charges. The overnight construction cost is the substantive cost, meaning the actual cost of construction materials, components and labour. The overall construction cost combines the overnight cost with the cost of finance over the extended construction period. It is not unusual for the finance costs to represent up to 50% of the total construction cost. Minimising the overnight construction cost is the key to making nuclear power plants economic. The high capital investment and long period from start of construction to first revenue flow are strong penalising factors for nuclear plants. The various systems under consideration here range from small modular plants, with low construction costs and short installation times to large plants with high capital investment and long construction times. Therefore, there is high discriminating power. The economics of nuclear power is key to its deployment in the UK's competitive electricity market and therefore it is assigned high relevance.				

23. Production (O&M) costs					
Category: economics					
Discriminating power	H	UK relevance	H		
Significance	Production costs refers to the operating and maintenance (O&M) costs of nuclear plants. These are determined primarily by the cost of supporting the operational staff requirement and by the cost of equipment maintenance. There could be a very different O&M base for small modular systems compared with the more conventional systems. Therefore, there O&M costs have high discriminating power. The economics of nuclear power is key to its deployment in the UK's competitive electricity market and therefore it is assigned high relevance.				

24. Construction duration					
Category: vulnerability of installations					
Discriminating power	H	UK relevance	H		
Significance	The duration of plant construction has already been discussed under Item 22 (overnight construction cost) and the same assessment applies.				

25. Development costs					
Category: economics					
Discriminating power	H	UK relevance	H		
Significance	If the UK was to buy into mature technology that had been developed and demonstrated overseas, the development cost would already have been incurred by the reactor vendor and an allocation recovered in the selling price. In this case the development cost would be of low relevance to the UK and low discrimination power. However, if the UK was to buy into technology that was not being developed elsewhere (such as ADSR), the UK would incur the developments costs and risks and therefore the discriminating power and UK relevance would be high. To allow for this possibility, this is how the metrics have been assigned.				

26. R&D costs					
Category: economics					
Discriminating power	H	UK relevance	H		
Significance	If the UK were to buy into mature technology that had been developed and demonstrated overseas, the R&D cost would already have been incurred by the reactor vendor and an allocation recovered in the selling price. In this case the R&D cost would be of low relevance to the UK and low discrimination power. However, if the UK was to buy into technology that was not being developed elsewhere (such as ADSR), the UK would incur the R&D costs and risks and therefore the discriminating power and UK relevance would be high. To allow for this possibility, this is how the metrics have been assigned.				

27. Plutonium and minor actinide management					
Category: waste management					
Discriminating power	M	UK relevance	H		
Significance	Most of the systems considered here are capable in principle of recycling plutonium and some would also be capable of destroying minor actinides (principally neptunium and americium). Plutonium recycle is potentially very important for UK given the large stock of separated plutonium from historic fuel cycle operations and a capability to irradiate the plutonium and effectively disposition it as spent fuel is of high relevance to the UK. The capabilities of the various systems in this respect are expected to be very similar and only have moderate discriminating power. There is no immediate interest in the UK in minor actinide management and this situation is not expected to change in the foreseeable future. However, it should not be dismissed as irrelevant to the UK because there is considerable interest internationally and the UK needs to be aware of developments that could potentially result in minor actinide management eventually becoming established as best international practice for sustainable nuclear energy. At the very least, the UK may need to assess minor actinide management as part of the justification process and in would need to be fully informed.				

28. Load follow capability					
Category: operational requirements					
Discriminating power	M	UK relevance	H		
Significance	Most of the nuclear systems under consideration here would be able to operate in responsive mode to changes in grid demand. There are two basic requirements: 1) Frequency control. This is a requirement that applies to current nuclear plants such as Sizewell B. The plant must be able to make small changes in power output (a few percent) in response to changes in grid frequency, which contributes to stability of the grid. 2) Pre-programmed load-follow. In this regime, a plant would be expected to cycle its output from 100% down to as low as 30% and back again overnight as demand falls. Current LWRs such as Sizewell B are capable of pre-programmed load-follow, although Sizewell B has not been required to do so. At present, UK nuclear plants are not required to operate in load-follow mode, as they are operated in base load. This situation, however, may change if nuclear output rises above its current 20% contribution. If the total contribution of nuclear approaches 50% or so, a load-follow capability is likely to be required or at least some plants. An additional factor is the growth of renewables, with increased load-follow capability possibly being needed to respond to variations in renewables output. The different systems may have different load-follow capabilities and therefore there may be some degree of discrimination between them. Reactor systems that are capable of rapid power response rates (% power increase per hour) might be particularly favoured in a UK grid with a high proportion of renewables. The relevance to the UK is potentially high in scenarios with a large nuclear component.				

29. Scalability					
Category: Strategic/economic					
Discriminating power	M	UK relevance	M		
Significance	This metric refers to scalability effects relating to the construction and decommissioning of modular reactor systems. There are clear strategic and economic advantages to having multiple reactor modules. There will be construction and decommissioning cost savings because the equipment and workforce can move on from one module to another. Also, it is well established that multiple units can be run with only a small overhead on operating staff compared with a single unit. Examples might be the deployment of twin-unit large reactors or multiple-unit small modular reactors. The discriminating power is not considered high between the different systems and has been set to medium. The potential relevance to the UK is considered medium.				

30. Timescales to deployment					
Category: Strategic					
Discriminating power	H	UK relevance	H		
Significance	The timescales at which new reactor systems could realistically be deployed is a strong discriminator between the different systems, with some requiring more development than others. The timescale at which any new system could be deployed would be of high relevance to strategic planning in the UK.				

31. Technology Readiness Level					
Category: Strategic					
Discriminating power	H	UK relevance	H		
Significance	The Technology Readiness Level (TRL) of new reactor systems is a systematic method of assessing how mature the technology is and therefore is indicative of the timescale for commercial readiness, the investment needs and the risk of technological failure. The systems under consideration are likely to have widely different TRL values and therefore TRL has high discriminating power and will be highly relevant in the UK as a means of screening options. The nine TRL levels, which originated in NASA, are defined as follows: 1. Basic principles observed and reported 2. Technology concept or application formulated 3. Analytical and/or experimental critical function or characteristic proof-of-concept 4. Component or sub-system validation in laboratory 5. Component or sub-system validation in a relevant environment 6. System/subsystem/component model or prototype demonstration in a relevant environment 7. System prototype demonstration in an operational environment 8. Actual system completed and qualified through test and demonstration in an operational environment 9. Actual system proven				

32. Flexibility of location					
Category: Strategic					
Discriminating power	M	UK relevance	H		
Significance	Given the limited number of existing power station sites in the UK, availability of suitable sites will be of high relevance to the UK in any future scenarios in which nuclear expands significantly above its present level. Some of the reactor types considered in this report will have different siting requirements (eg such as low cooling water demand for small modular LWR) and therefore there is potentially some discriminating power. Although there are many potentially suitable coastal sites in the UK, there may be local opposition especially at new sites, which may limit availability Therefore UK relevance is set to high.				

33. Waste arisings (volumes HLW, ILW, LLW)					
Category: Strategic					
Discriminating power	H	UK relevance	H		
Significance	The relative volumes of HLW, ILW and LLW is likely to be a strong discriminator between the different systems. The volumes and forms of the different waste streams are of high relevance to the UK, with respect to both storage and management and also eventual emplacement in a geological disposal facility.				

34. Benefits or risks for security					
Category: Operational safety					
Discriminating power	H	UK relevance	H		
Significance	Some of the reactor designs considered would use passive safety and some would locate the nuclear island underground. Other systems would use an integral fuel cycle, thereby avoiding the off-site transport of nuclear materials. There is therefore the potential for high discriminating power on security. The relevance to the UK is potentially high.				

35. Number and size of reactors needed					
Category: Strategic					
Discriminating power	H	UK relevance	H		
Significance	The UK's current and immediate future needs are best suited by large capacity plants (> 1 GWe), since these have clear economic advantages over small units. However, a scenario where smaller modules might fit is that of plutonium disposition and some of the reactor options may have capacities better suited for this application. The discriminating power of the different options is considered to be high and the relevance to the UK is potentially high as well.				

36. Associated fuel cycle					
Category: Strategic					
Discriminating power	H	UK relevance	H		
Significance	The fuel cycle plants needed for the various reactor system options are potentially very different and therefore the associated fuel cycle is potentially a strong discriminator. The requirements of the fuel cycle plants are of high relevance to the UK.				

37. Proliferation resistance					
Category: Security/non-proliferation					
Discriminating power	H	UK relevance	H		
Significance	There is increasing interest in international reactor systems development to be able to demonstrate increased proliferation resistance by design. The reactor systems considered here may potentially be strongly discriminating on inherent proliferation resistance. It is possible that in future best practice of deploying nuclear systems will require that consideration be given to inherent proliferation resistance and therefore this is potentially of some relevance to the UK, which is why the discriminating power and UK relevance are both set high.				

38. Ease of construction					
Category: Strategic/economic					
Discriminating power	H	UK relevance	H		
Significance	Reactor systems which are largely factory built and assembled on-site are considered advantageous because the construction phase is shortened and the investment cost reduced. There is also a reduced risk of construction over-runs. The SFR, GFR and MSR designs are likely to require large size pressure vessels that may not be compatible with factory construction and modular assembly and are therefore distinguished from the other six designs considered, all of which would be factory built. On this bases the discriminating potential and UK relevance are set to high.				

39. Sustainability					
Category: Strategic					
Discriminating power	H	UK relevance	H		
Significance	Sustainability is potentially a broad area encompassing the uranium ore requirement, environmental impact, waste arisings and others. With respect to fuel supply independence. The fast reactor systems, SFR, GFR and LFR (and MSR as well) are potentially capable of operating breeder fuel cycles with no dependence on overseas uranium supplies. In contrast, most of the other systems will be reliant on uranium supplies in the same way as the current generation of reactors. Similarly, the different systems have the potential for strong discrimination on environmental impact and wastes. Sustainability is therefore a high discriminator that may at some future date be of high relevance to the UK.				

40. Potential to drive thermal processes					
Category: Strategic					
Discriminating power	H	UK relevance	H		
Significance	In the longer term, the ability of nuclear reactors to provide heat sources for processes such as hydrogen production or petrochemical conversion may become strategically important. Certain of the systems considered (eg GFR, MSR and VHTR) have very primary circuit operating temperatures compatible with high temperature process heat applications. On this basis the discriminating power and UK relevance are set high.				

41. Decommissioning costs					
Category: Strategic					
Discriminating power	H	UK relevance	H		
Significance	Reactor systems which are inherently suited to in-situ dismantling would be regarded as having a strong strategic advantage. Systems such as LWRs are relatively easy to decommission because after defuelling the core contains only a relatively small number of structural components and the pressure vessel is relatively compact. Larger systems such as SFR, GFR and MSR may not be as straightforward to dismantle and would be disadvantaged. On this basis the discriminating power and UK relevance are set high.				

42. Primary purpose					
Category: Strategic					
Discriminating power	H	UK relevance	H		
Significance	The choice of reactor system would be driven largely by its primary purpose. Normally, this would be electricity production, but there are alternatives such as process heat production, plutonium management and minor actinide management that might be relevant in the UK. It is conceivable that if the UK opts to burn its plutonium stocks in reactors that the optimum system choice may be different to the systems chosen for large scale electricity production. On this basis the discriminating power and UK relevance are set high.				

3. Summary

A preliminary list of metrics has been compiled which could be used to assess the suitability of potential future reactors systems for deployment in the UK. Although some of the metrics can in principle be evaluated quantitatively, others are necessarily qualitative in nature and will require judgement to be applied. Even for the former, quantitative assessments may not be possible for all of the systems considered unless the systems are well enough developed. The priorities and drivers will likely change with time and will differ between countries and it is important that the metrics should not be applied too rigidly without recognising the likelihood of change.

The metrics compiled here will be used in next phase of the study when the nine reactors technologies of interest will be evaluated.

4. References

1. “A technology roadmap for Generation IV nuclear energy systems”, GIF-002-00, December 2002
2. “UK nuclear horizons - An independent assessment by the UK National Nuclear Laboratory”, January 2011, NNL position paper
3. “The thorium fuel cycle – An independent assessment by the UK National Nuclear Laboratory, August 2010”, NNL position paper

DISTRIBUTION

Name	Location
DECC	Climate & Energy: Science & Analysis, Department of Energy and Climate Change, London
NNL Corporate Memory	Strategic Assessments, Risley