National Nuclear Laboratory

Addendum to NNL(11)11620 - Assessment of advanced reactor systems against UK performance metrics

NNL (11) 11620
ADDENDUM Issue 1 DE06742/06/09/02

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

 Mar 2012

National Nuclear Laboratory

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Work Order No.	06742.100

KEYWORDS:

EXECUTIVE SUMMARY

In January 2012 the National Nuclear Laboratory (NNL) produced a report (NNL (11) 11620 Issue 4) under contract to the Department for Energy and Climate Change (DECC), which assessed nine advanced reactor systems and two reference LWR systems against the 42 metrics identified in NNL (11) 11491. In March 2012, NNL was awarded a follow-up contract for which one of the deliverables was to produce an addendum to NNL 11491 which progresses the analysis further. Specifically, the follow-up work was to rationalise the 42 metrics, by eliminating duplications and to group the metrics in a way that would allow a meaningful system of weighting factors to be applied.

A second deliverable was to apply the rationalised metrics to re-score the advanced reactor systems of NNL 11620. The deliverable would be an addendum to NNL 11620 and the intention is that after discussion and agreement with DECC, an Issue 6 of NNL 11620 will be produced which will incorporate this addendum within it.

This addendum proposes assesses the nine advanced reactor systems against the seven metrics groups identified in the Addendum to NNL 11491.

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
1	30 March 2012	Issued to DECC for initial discussion

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1. Introduction

In January 2012 the National Nuclear Laboratory (NNL) produced a report (NNL (11) 11620 Issue 4 [1]) under contract to the Department for Energy and Climate Change (DECC), which assessed nine advanced reactor systems and two reference LWR systems against the 42 metrics identified in NNL (11) 11491. In March 2012, NNL was awarded a follow-up contract for which one of the deliverables was to produce an addendum to NNL 11491 which progresses the analysis further. Specifically, the follow-up work was to rationalise the 42 metrics, by eliminating duplications and to group the metrics in a way that would allow a meaningful system of weighting factors to be applied.

A second deliverable was to apply the rationalised metrics to re-score the advanced reactor systems of NNL 11620 [2]. The deliverable would be an addendum to NNL 11620 and the intention is that after discussion and agreement with DECC, an Issue 5 of NNL 11620 will be produced which will incorporate this addendum within it.

This addendum re-assesses the nine advanced reactor systems against the seven metrics groups identified in the Addendum to NNL 11491. These groupings are: Generating cost; Inherent Proliferation Resistance and Physical Protection (PRPP); Safety; Strategic; Deployability; Sustainability and Waste. Section 2 describes how the weighted scores were calculated and Sections 3 to 9 present and discuss the results for each of the seven groupings in turn.

2. Scoring method

The approach used for this Addendum was to take the scores evaluated previously in NNL 11620 Issue 5 as givens and to combine the scores for the seven metrics groupings using the weighting factors identified in the Addendum to NNL 11491. In NNL 11620 Issue 5, scores of 4, 3, 2 and 1 points are assigned against each metric according to whether the performance of a system is assessed as VERY HIGH, HIGH, MEDIUM and LOW respectively. These scores are then used to produce a weighted average using the weighting factors from the Addendum to NNL 11491.

The weighting factors used all add up to 100 and are used to calculate a weighted average where the maximum possible score is 100% (corresponding to a system being assessed at VERY HIGH (4 points) on all the metrics). Because the lowest possible score is 1 point, the minimum possible score is 25% score (corresponding to a system being assessed at LOW on all the metrics). As explained in the Addendum to NNL 11491, attempts have been made to assign the weighting factors in an objective way as far as possible.

3. Generating cost metrics

3.1. Results

Table 1 shows the systems scores and the weighted scores for the four Generating Cost metrics. The individual scores are exactly as given previously in NNL 11620, with 4, 3, 2 and 1 representing scorings of VERY HIGH, HIGH, MEDIUM and LOW respectively. The weighting factors are taken from the Addendum to NNL 11491 and are applied according to the prescription described in Section 2. Figure 1 shows the weighted scores in the form of a bar chart.

Table 1: Generating cost scores

	Overnight construction costs	Production costs (O&M + fuel)	Decommissioning costs	R&D costs	Weighted score (%)
System					
SFR	1	2	2	2	36.3
GFR	1	2	2	1	33.8
LFR	1	2	2	2	36.3
VHTR	2	2	3	3	55.0
SCWR	2	2	3	1	50.0
MSR	2	1	2	1	41.3
ADSR	1	2	2	1	33.8
HPM	2	2	4	1	52.5
Small LWR	2	1	3	4	51.3
LWR once-through	2	2	3	4	57.5
LWR recycle	2	2	3	4	57.5
Weighting factors	55	25	10	10	

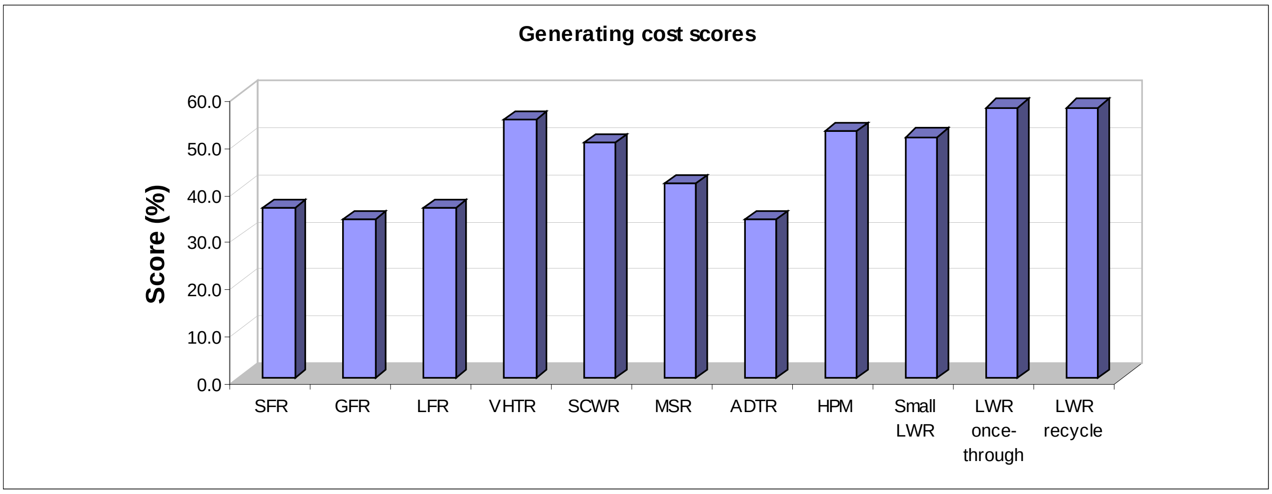

Figure 1: Generating cost scores

3.2. Commentary

SFR, GFR and LFR all score relatively poorly on generating cost, reflecting a widely held view that it will be a major challenge for these systems to match the economic performance of current generation LWRs, given the complex reactor designs and complex fuel cycle. The Gen IV Project is actively exploring strategies for improving the generating cost, for example by considering supercritical CO_2 power conversion to eliminate the possibility of sodium/water interaction and the need for a secondary coolant circuit.

The score for VHTR is closer to that of current generation LWRs. However, this reflects the design intent for VHTR, which maybe difficult to achieve in practice. Capital and operating costs for VHTR are intended to benefit from not having to provide extensive nuclear safety grade systems to assure decay heat removal, because the design is intended to radiate decay heat passively without fuel damage. There is a theoretical generating cost benefit from the high thermal efficiency of HTGRs, though it needs to be acknowledged that the PBMR Project reverted at a late stage to a conventional steam cycle, in place of the direct gas cycle originally intended, because the direct cycle technology was insufficiently mature at the time. The modular deployment of VHTRs is also cited as factor that should reduce generating costs by allowing phased investment with short module construction times and earlier payback on investment.

SCWR and MSR are relative unknowns, being at a very immature stage of development and it is fair too comment that it is probably far too soon to be able to assess the cost of generation for them.

ADSR is a complex system, sharing many of the complexities of LFR, but with the addition of the accelerator beam, the spallation target and the complications caused by the rapid spatial attenuation of neutron flux in a sub-critical reactor, all of which have the potential to adversely affect generating costs unless there are other mitigating factors.

HPM scores the same as current generation LWRs on overnight construction costs and production costs, the assumption on production costs being that for an autonomous reactor very few people would be needed to run it. Small LWR loses out on the latter consideration because it is assumed to be adversely affected by requiring a large number of operating staff in relation to its low electrical output.

Relative to current generation LWRs, most of the Gen IV systems are penalised on decommissioning costs, largely because they are potentially more complex systems to decommission. Similarly, the Gen IV systems are penalised by the need for extensive R&D expenditure. However, both decommissioning cost and R&D cost are lightly weighted.

3.3. Sensitivities

The relative rankings of the 11 systems is not very sensitive to weighting factors use. In particular, the relative ranking remains the same if all four metrics are assigned equal weights. This gives confidence that more detailed justification of the preferred weighting scheme is unnecessary.

4. Proliferation Resistance and Physical Protection (PRPP) metrics

4.1. Results

Table 2 shows the systems scores and the weighted scores for the four Proliferation Resistance and Physical Protection (PRPP) metrics. The individual scores are exactly as given previously in NNL 11620. Figure 2 shows the weighted scores.

Table 2: PRPP scores

	Separated materials	Spent fuel characteristics	Sabotage resistance	Weighted score (%)
System				
SFR	2	2	3	57.8
GFR	2	2	3	57.8
LFR	2	2	3	57.8
VHTR	4	4	4	99.0
SCWR	3	2	3	66.0
MSR	3	4	1	66.0
ADSR	2	2	3	57.8
HPM	3	2	4	74.3
Small LWR	3	2	3	66.0
LWR once-through	3	2	3	66.0
LWR recycle	1	2	3	49.5
Weighting factors	33	33	33	

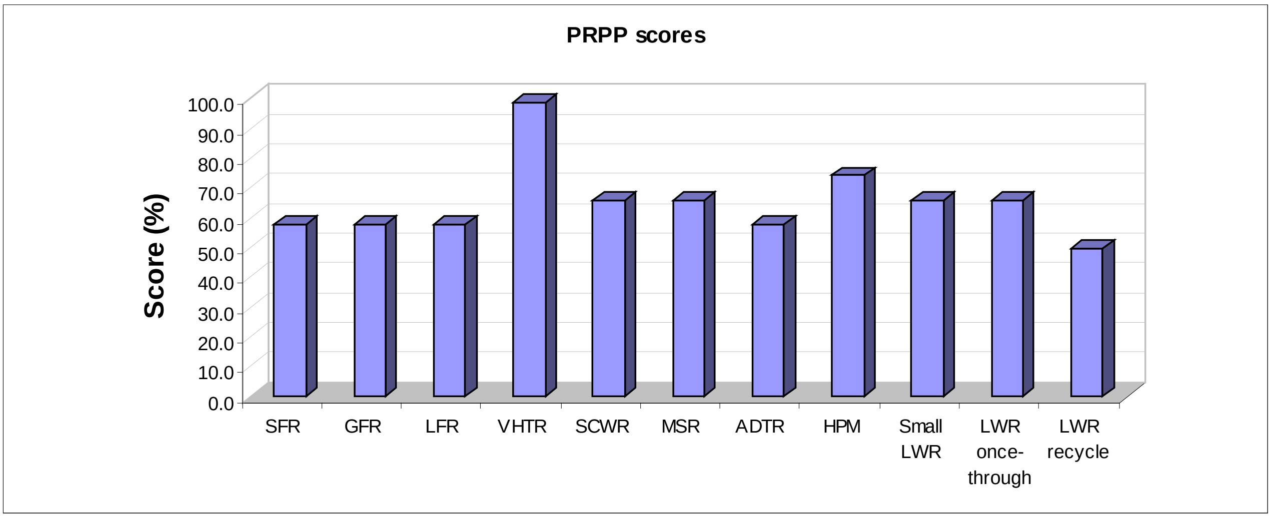

Figure 2: PRPP scores

4.2. Commentary

All the closed cycle Gen IV systems, SFR, GFR, LFR and ADSR, score the same on proliferation resistance and physical protection (PRPP) and at a level which is intermediate to the LWR once-through and LWR recycle cases. This recognises that recycle makes fissile materials more accessible to potential diversion by a state or theft by a sub-national organisation. The Gen IV systems are all score slightly higher than LWR recycle, recognising that the recycle schemes for Gen IV systems will have to be improved in terms of inherent PRPP in order to meet the proliferation resistance goal that is one of the underlying driving factors for Gen IV.

Of the other systems, HPM benefits from the fact that is an autonomous system with no access to the fuel and core in-situ, which therefore improves inherent PRPP. VHTR stands out as the best performing system with the maximum 100% score. This is because VHTR is a once-through fuel cycle, which reduces accessibility to fissile materials. Moreover, VHTR fuels encapsulate the fissile material in SiC coated microspheres. The fuel microspheres are dispersed in a graphite matrix that increases the bulk of the fuel and would need to be separated before the fuel could be reprocessed. Additionally, the SiC shells make the fuel difficult reprocesses as they are insoluble in acid and need to be mechanically crushed. The graphite matrix and the SiC shells are therefore credited with giving VHTR a high level of intrinsic PRPP.

4.3. Sensitivities

Increasing the weighting for the separated materials metric has no effect on the relative rankings of the 11 systems.

Increasing the weighting of the spent fuel characteristics metric has a strong polarising effect, with VHTR and MSR all scoring the maximum. This reflects the very robust fuel form for VHTR and the fact that MSR produces no spent fuel – only immobilised fission products.

Increasing the sabotage resistance metric also strongly polarises the results, with VHTR and HPM scoring very highly. For VHTR, the high scoring reflects the robust fuel form and the passive safety capability. For HPM it is because the reactor is mostly sited underground and therefore less vulnerable to external missiles. MSR is strongly penalised because of its low assessment for sabotage resistance on account of the molten fuel, which is assumed here to increase its vulnerability to fission product release. This interpretation could be challenged on the grounds that the volatile fission products would be preferentially retained in the molten salt and a robust containment could be designed around the reactor. For the time being, this MSR scoring is retained as a small penalty when considering its overall ranking on PRPP.

5. Safety metrics

5.1. Results

Table 3 shows the systems scores and the weighted scores for the Safety metrics. The individual scores are exactly as given previously in NNL 11620. Figure 3 shows the weighted scores.

Table 3: Safety scores

System	Reliability	Worker exposures	Reactivity control	Decay heat removal	Low uncertainties on dominant phenomena	Fuel thermal response	Integral experiment scalability	Source term	Energy release mechanisms	System response times	Effective hold-up	Weighted score (%)
SFR	3	2	2	2	3	3	3	1	1	3	1	52.5
GFR	3	2	2	2	1	1	1	1	3	1	1	42.5
LFR	3	2	2	2	2	3	2	1	3	3	1	55.0
VHTR	4	4	3	4	3	4	3	4	4	4	4	95.0
SCWR	3	3	2	2	1	1	1	2	1	1	2	42.5
MSR	2	2	3	3	1	3	1	1	3	2	2	58.8
ADSR	2	2	2	2	1	3	2	1	3	3	1	52.5
HPM	3	3	2	4	2	3	2	2	3	3	1	71.3
Small LWR	3	3	2	2	3	1	4	2	1	1	2	48.8
LWR once-through	3	3	2	2	3	1	4	2	1	1	2	48.8
LWR recycle	3	3	2	2	3	1	4	2	1	1	2	48.8
Weighting factors	5	5	10	25	5	10	5	10	10	10	5	

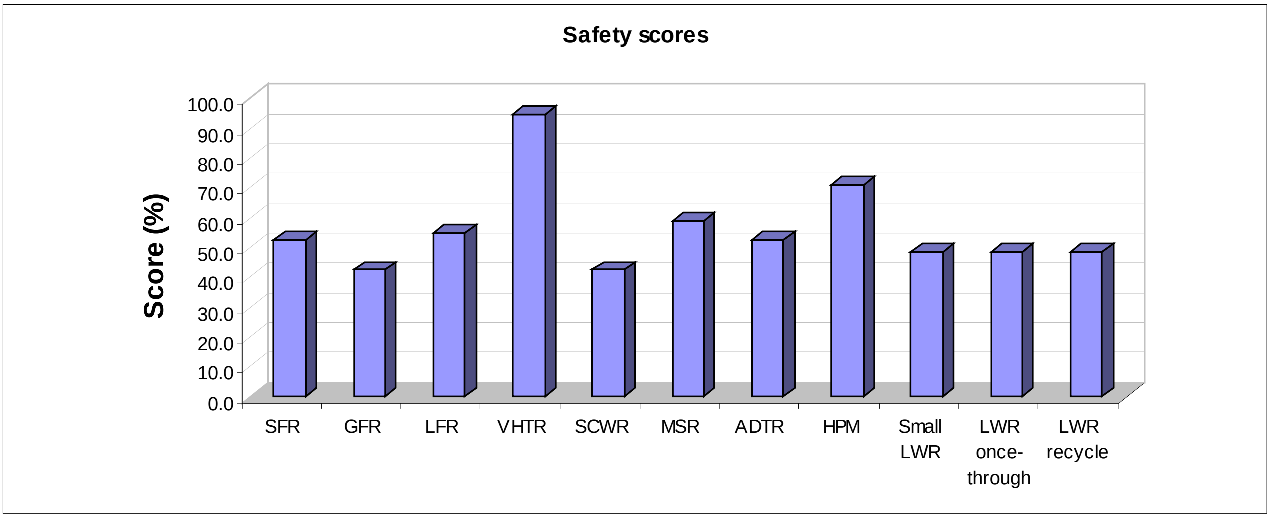

Figure 3: Safety scores

5.2. Commentary

For the safety metrics there is a little to differentiate between the majority of the systems, with VHTR and HPM excepted. VHTR performs very well on account of its passive safety capability. HPM is the next highest rated, again because of its passive safety capability.

SFR, LFR and ADSR all score about the same on safety, these systems all benefiting from a large coolant thermal inertia and natural coolant circulation.

GFR and SCWR both score a little lower because GFR still has to demonstrate safe recovery from loss of coolant accidents (LOCA) and the approach to safety in SCWR has yet to be demonstrated.

5.3. Sensitivities

Again, the weighting scheme has relatively little impact on the relative rankings, unless individual safety metrics are weighted very highly. Replacing the weighting scheme indicated in the table above with a set of uniform weights has no effect on the relative rankings.

6. Strategic metrics

6.1. Results

Table 4 shows the systems scores and the weighted scores for the four Strategic metrics. The individual scores are exactly as given previously in NNL 11620. Figure 4 shows the weighted scores.

Table 4: Strategic scores

	Scalability	Timescales to deployment	Technology Readiness Level	Weighted score (%)
System				
SFR	2	3	3	70.0
GFR	2	1	1	30.0
LFR	2	2	2	50.0
VHTR	3	2	3	65.0
SCWR	2	1	1	30.0
MSR	3	1	1	35.0
ADSR	2	1	1	30.0
HPM	3	1	1	35.0
Small LWR	3	3	3	75.0
LWR once-through	2	4	4	90.0
LWR recycle	2	4	4	90.0
Weighting factors	20	40	40	

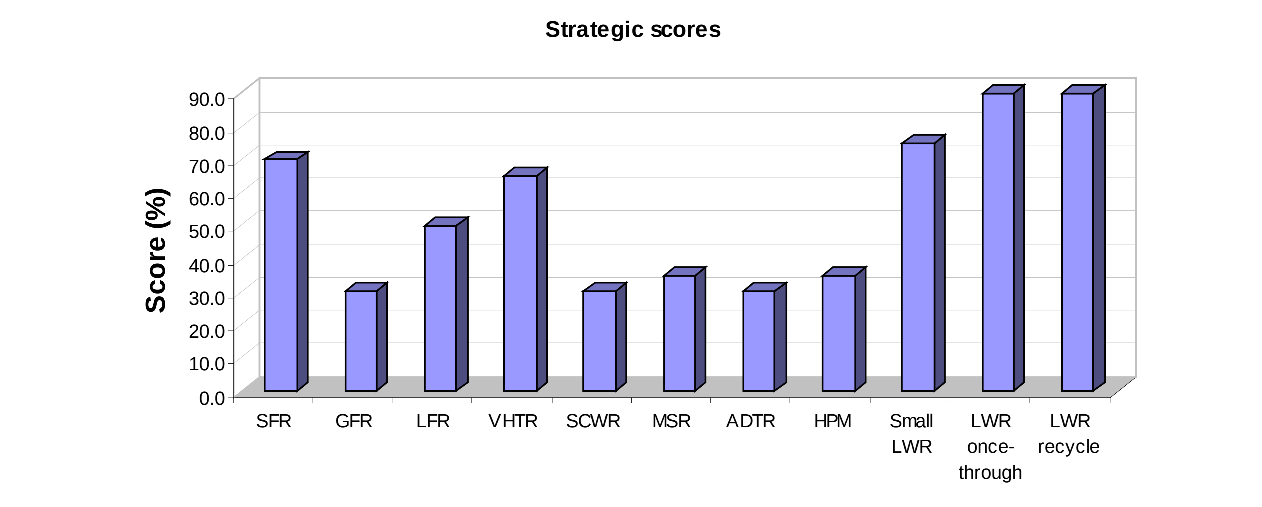

Figure 4: Strategic scores

6.2. Commentary

Current LWRs score the highest in the strategic metrics grouping, largely because they represent mature technology that is available commercially, with minimal technical risk. Small LWR is penalised slightly because, though the technology base is demonstrated, full system integration has yet to be achieved in the form of commercially available systems. Of the remaining systems, SFR and VHTR are ranked the highest, because both technologies have been demonstrated at prototype scale. LFR is less technologically mature than SFR and in turn GFR is less mature than either. The other systems all score low on both technical maturity metrics.

6.3. Sensitivities

Replacing the preferred weighting factors in the table above with uniform weightings has no impact on the relative rankings. Increasing the weighting factors for either timescales to deployment or technology readiness level again has no impact on the relative rankings. However, increasing the weighting for scalability makes the small modular systems stand out with high scores, these being VHTR, MSR, HPM and small LWR.

7. Deployability metrics

7.1. Results

Table 5 shows the systems scores and the weighted scores for the six Deployability metrics. The individual scores are exactly as given previously in NNL 11620. Figure 5 shows the weighted scores.

Table 5: Deployability scores

	Load follow capability	Flexibility of location	Number and size of reactors needed	Associated fuel cycle	Potential to drive thermal processes	Weighted score (%)
System						
SFR	2	2	2	1	2	45.0
GFR	2	2	2	1	3	50.0
LFR	2	2	2	1	2	45.0
VHTR	3	3	1	1	4	60.0
SCWR	2	2	2	3	2	55.0
MSR	3	2	3	1	3	60.0
ADSR	4	3	2	1	2	60.0
HPM	2	3	1	1	2	45.0
Small LWR	2	3	1	3	1	50.0
LWR once-through	2	2	2	3	1	50.0
LWR recycle	2	2	2	3	1	50.0
Weighting factors	20	20	20	20	20	

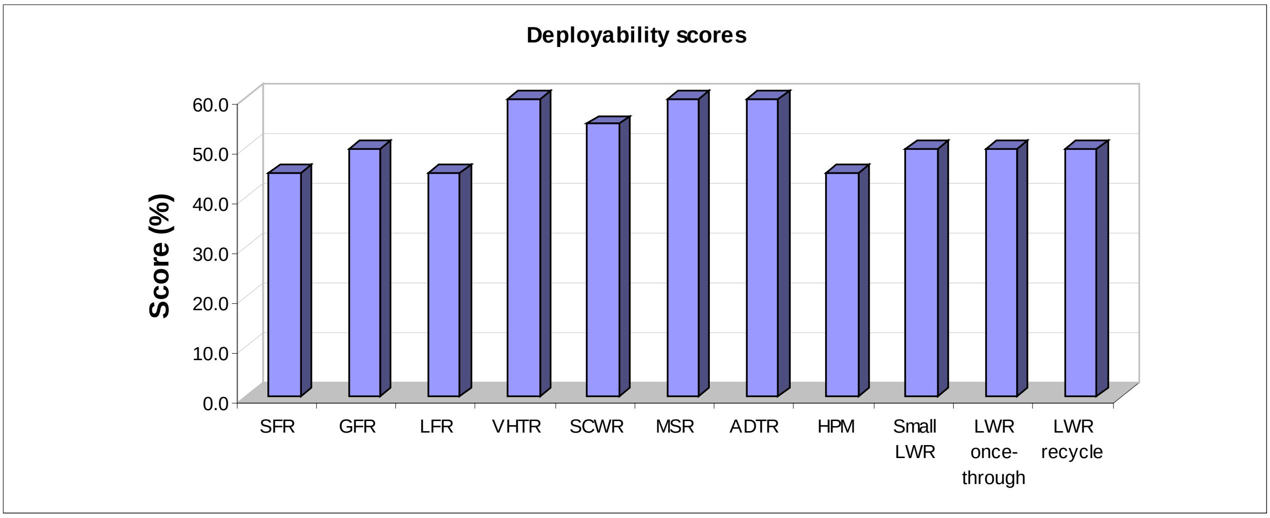

Figure 5: Deployability scores

7.2. *Commentary*

VHTR, SCWR, MSR and ADSR all stand out as high scoring systems on the Deployablity metric grouping. VHTR scores highly on its high temperature heat capability. SCWR has fairly average scores apart from the fuel cycle metric, which is assumed to be compatible with the existing LWR fuel cycle. ADSR scores highly on load follow capability, where the reactor power would scale with beam power, though there would be some impact on core spatial power distributions resulting from reactivity feedback effects.

7.3. *Sensitivities*

Weighting the individual deployability metrics more heavily results in some strong polarizations. For example, weighting load follow capability favours VHTR, MSR and especially ADSR. Weighting flexibility of location favours the small modular systems VHTR, HPM and small LWR and also ADSR, which has a relatively low output on 600 MWe. Weighting the number of reactors metric is unfavourable for the small modular systems, though MSR scores highly, because it is assumed that the design could be scaled for small modular or large scale generation (assuming that passive decay heat removal can be achieved over the whole range). Weighting the associated fuel cycle metric favours the LWRs and SCWR, since current fuel cycle facilities would apply. Finally, weighting the potential to drive thermal processes metric heavily favours the high operating temperatures of VHTR, GFR and MSR.

8. Sustainability metrics

8.1. Results

Table 6 shows the systems scores and the weighted scores for Sustainability metric. The individual scores are exactly as given previously in NNL 11620. Figure 6 shows the weighted scores.

Table 6: Sustainability scores

	Fuel utilisation	Weighted score (%)
System		
SFR	4	100.0
GFR	4	100.0
LFR	4	100.0
VHTR	1	25.0
SCWR	1	25.0
MSR	4	100.0
ADSR	4	100.0
HPM	1	25.0
Small LWR	1	25.0
LWR once-through	1	25.0
LWR recycle	1	25.0
Weighting factors	100	

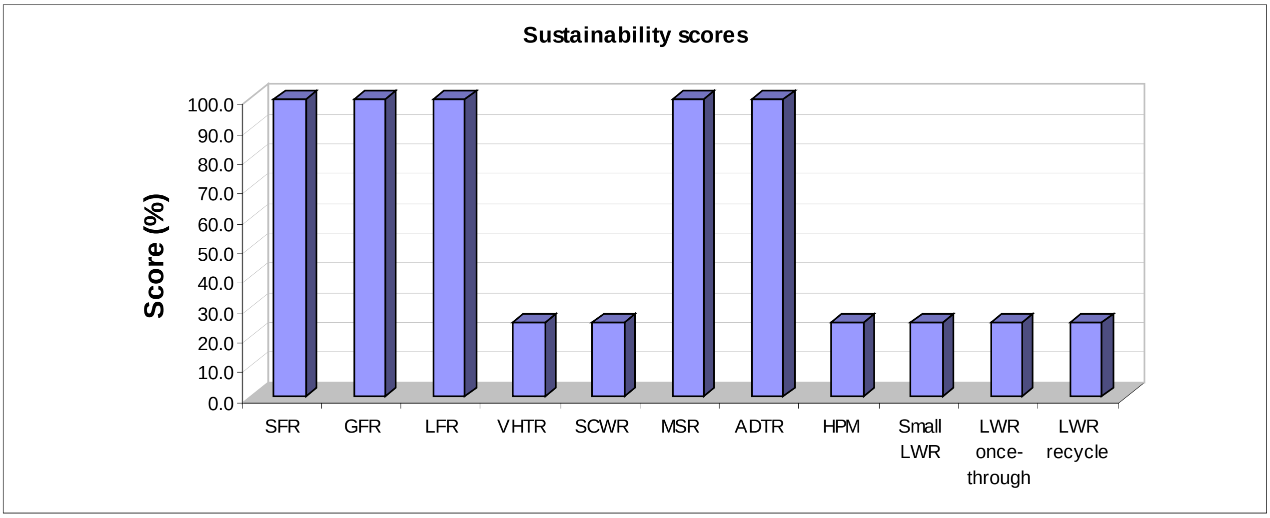

Figure 6: Sustainability scores

8.2. Commentary

With there being only a single metric, the various systems are completely polarised into the recycle breeding systems which are not dependent on uranium availability and once-through fuel cycles.

9. Waste metrics

9.1. Results

Table 7 shows the systems scores and the weighted scores for the Waste metrics. The individual scores are exactly as given previously in NNL 11620. Figure 7 shows the weighted scores.

Table 7: Waste scores

	Spent fuel mass	VHLW volume	Long term heat output	Long term radiotoxicity	Environmental impact	Plutonium and minor actinide management	Weighted score (%)
System							
SFR	3	3	3	3	4	3	80.0
GFR	3	3	3	3	4	3	80.0
LFR	3	3	3	3	4	3	80.0
VHTR	1	1	2	2	3	3	50.0
SCWR	2	2	2	2	3	2	55.0
MSR	2	3	3	3	4	4	80.0
ADSR	3	3	3	3	4	3	80.0
HPM	2	2	2	2	3	1	52.5
Small LWR	2	2	2	2	3	2	55.0
LWR once-through	2	2	2	2	3	2	55.0
LWR recycle	2	3	1	2	3	2	52.5
Weighting factors	10	20	30	10	20	10	

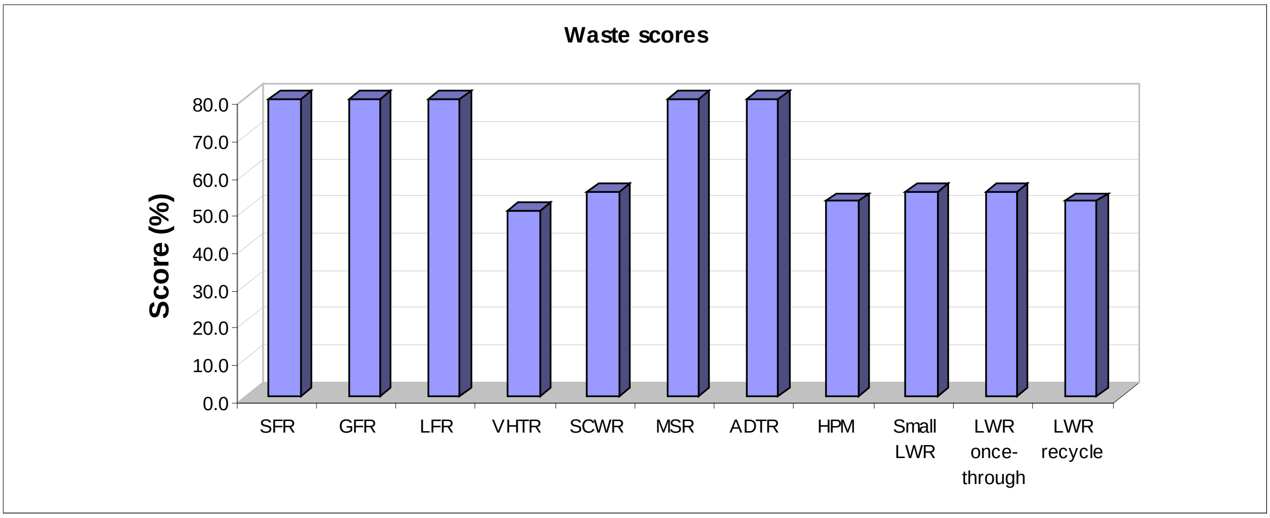

Figure 7: Waste scores

9.2. Commentary

With the waste metrics grouping, there is a strong polarisation in favour of the sustainable recycle systems, SFR, GFR, LFR, MSR and ADSR. There are strong benefits from sustainable recycle in relation to all six of the metrics.

9.3. Sensitivities

The relative ranking is not affected if uniform weightings are used instead of the preferred weightings. Moreover, if each of the individual metric is weighted more heavily in turn, the relative ranking again remains mostly unchanged, except for some small anomalies caused by the low score for LWR once-through on long term heat output and the low score for HPM on plutonium and minor actinide recycle.

10. Summary

This section provides a brief commentary on the relative ranking of the nine advanced nuclear systems against the seven metrics.

10.1. SFR, GFR & LFR

It is helpful to treat SFR, GFR and LFR together, because these are all breeder recycle systems with close similarities. In the original analysis in NNL 11620, all three systems were ranked quite closely overall, with SFR marginally ahead of LFR and GFR a little behind. In this re-assessment, the three systems have identical scores under Generating cost, PRPP, Sustainability and Waste. Under Safety, SFR and LFR have similar scores, but with GFR scoring low on technological maturity and transient response time. Under the Strategic grouping SFR scores the highest on account of its higher technological readiness (with commercial-scale prototypes having been built and operated), with GFR lowest of the three. GFR scores highest on deployability on account of its high operating temperatures and therefore suitability for process heat applications.

10.2. VHTR

In NNL 11620, VHTR emerged with the highest overall score. In this re-analysis, VHTR is the highest scoring system in three of the groupings: PRPP, Safety and Deployability. This is a result of the uniquely robust fuel form which offers clear benefits for inherent PRPP and passive safety. VHTR is especially well suited to high temperature heat applications and this is beneficial under Deployability. VHTR also scores quite highly on Generating cost and Strategic (but with the proviso that further development is needed to ensure it is competitive compared with LWRs). However VHTR scores relative poorly on Sustainability and Waste, because it is a once-through fuel cycle. VHTR is at a relatively high stage of Technology Readiness, with commercial-scale prototypes having been built and operated, but further development is needed for it to be regarded as technologically mature.

10.3. SCWR

The SCWR scores for PRPP, Sustainability and Waste are equivalent to those of the LWR once-through reference. SCWR performance is slightly penalised on Generating cost and Safety and heavily penalised on Strategic because of its low technological readiness. On Deployability, SCWR shows a slight advantage over the reference LWR on account of its high operating temperature.

10.4. MSR

MSR scores highly on Deployability, Sustainability, Waste and Safety. On PRPP MSR is equivalent to once-through LWR. MSR is penalised on production costs and R&D costs, which leads to a middling rating on Generation Cost. On Strategic, MSR scores poorly because of its very low technology readiness and very long development timescale.

10.5. ADSR

ADSR scores very highly on Deployability, Sustainability and Waste. However ADSR scores poorly on Generating cost (because of the additional complexity and cost of the accelerator system) and Strategic (because of its low technology readiness and long timescale to deployment). On PRPP and Safety ADSR is assessed to be equivalent to the mainstream Gen IV breeder systems

10.6. HPM

On PRPP and Safety HPM scores highly, while on Sustainability and Waste it is ranked the same as the LWR once-through reference.

10.7. Small LWR

Small LWR is equivalent to the LWR once-through reference for all metrics groupings apart from Generating Cost (where there is a scaling penalty) and Strategic, where there are small penalties on technology readiness and timescale to deployment, with no designs being commercially proven at present.

11. Recommendations

It is recommended that the metrics groupings and weightings used here should be used as the basis of any future UK assessment of advanced reactor systems. Ideally, future analyses should involve getting the reactor system vendors to provide evidence to support the scores for their specific system, though with appropriate independent assessment used to ensure a fair overall balance.

12. References

1. “Review of Metrics Relevant to Reactor Systems”, NNL(11) 11491 Issue 3, March 2011

2. “Assessment of advanced reactor systems against UK performance metrics”, NNL (11) 11620 Issue 5, March 2012