Addendum to NNL(11)11491 - Review of Metrics Relevant to Reactor Systems

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National Nuclear Laboratory

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EXECUTIVE SUMMARY

In January 2012 the National Nuclear Laboratory (NNL) produced a report (NNL (11) 11491 Issue 3) under contract to the Department for Energy and Climate Change (DECC), which identified 42 metrics relevant to assessing advanced nuclear systems. 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. The deliverable would be an addendum to NNL 11491 that would describe the new work, which is the purpose of this report. The intention is that after discussion and agreement with DECC, an Issue 4 of NNL 11491 will be produced which will incorporate this addendum within it.

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) 11491 Issue 3 [1]) under contract to the Department for Energy and Climate Change (DECC), which identified 42 metrics relevant to assessing advanced nuclear systems. 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. The deliverable would be an addendum to NNL 11491 that would describe the new work, which is the purpose of this report. The intention is that after discussion and agreement with DECC, an Issue 4 of NNL 11491 will be produced which will incorporate this addendum within it.

An initial assessment of nine advanced nuclear systems using the 42 metrics was reported in NNL (11) 11620 Issue 5 [2]. The follow-up contract also provides for NNL to produce an addendum for NNL 11620 which will apply the revised metrics and weightings to the same nine systems.

This addendum proposes a scheme whereby the 42 metrics from NNL 11491 are rationalised down to a total of 33 metrics grouped under seven headings: Generating cost; Inherent Proliferation Resistance and Physical Protection (PRPP); Safety; Strategic; Deployability; Sustainability and Waste. This addendum explains the rationale for these groupings and also records the basis on which the weighting factors are allocated. In any multi-attribute analysis, such as this one, the choice of weighting factors is potentially very subjective. This addendum proposes, where practical, rationally informed choices of weighting factors that will hopefully minimise subjectivity.

Sections 2 to 8 describe each of the seven groupings in turn.

2. Group 1 : Generating cost metrics

The economics of nuclear power plants is clearly very important in determining whether they will be competitive compared with other energy sources. Combining all the metrics related to the cost of electricity under Generating cost constitutes an obvious grouping. The economics of power plants is usually expressed in terms of the levelised generating cost, normally measured in £/MWh with all component costs and the revenue from electricity generation discounted to a common reference date.

There are six metrics from NNL 11491 which are related to generating cost. Two of these are labeled “Development costs” and “R&D Costs” and are duplications. It is therefore appropriate to combine them under “R&D Costs” to give five remaining metrics grouped under Generating Cost:

1. Overnight construction costs.
2. Production costs.
3. Decommissioning costs.
4. Construction duration.
5. R&D costs.

The first three metrics are the components that make up the total generating cost. The overnight construction cost is the contribution to the levelised cost of electricity generation (in £/MWh) from substantive capital cost of the plant (meaning all the costs incurred in construction except for finance costs) plus the cost of financing the plant. The production costs are intended to cover all the costs of operating the plant, including the direct Operating and Maintenance (O&M) costs and the cost of procuring new fuel and of managing spent fuel. Included in the production costs are the costs of managing and disposing of wastes generated from plant operations and from spent fuel management. Decommissioning costs are included explicitly in the five metrics. These three costs between them make up the total generating cost of a mature plant design which is available on the market and does not require new research and development. Originally, the decommissioning cost metric was grouped under “Strategic”, but in this re-assessment it is thought more appropriate to include it in the Generating Cost grouping.

Implicit in the overnight construction costs is a finance cost that depends on the discount rate and the construction time for the plant, over which the interest on the capital is accrued. With typical annual discount rates between 5 and 10%, the cost of finance of current generation plants (which require 5 years or more to build) can typically amount to as much as 40 to 50% of the overnight cost. Therefore the construction time is a very important metric in choosing between competing reactor systems

R&D costs are relevant to the introduction of any reactor system which is not yet fully developed, which applies to many of the systems considered in NNL 11491. Depending on how the R&D is funded, there is the potential for this to add substantially to the overall generating cost of a first of a kind plant, if that happened to be sited in the UK.

The 2010 version of the IEA/NEA report “Projected Costs of Generating Electricity” [3], provides indicative breakdowns of the total generating cost for nuclear plants into the investment cost (which includes the substantive capital cost items plus the cost of finance); Operating and Maintenance (O&M) and fuel cycle. At 5% discount rate, the breakdown indicated is 60% investment; 24% O&M and 16% fuel cycle. At 10% discount rate, the breakdown indicated is 75% investment; 15% O&M and 9% fuel cycle. These items include allowances for refurbishment, waste treatment and decommissioning, all of which are sufficiently small in relative terms that they are not quoted separately in the IEA/NEA report.

The breakdowns from the IEA/NEA report are very similar to those resulting from various generating cost studies that NNL has carried out and are also broadly consistent with other studies quoted in the literature. Therefore the IEA/NEA cost breakdowns are very suitable for deciding the weighting factors for the Generating Cost grouping. Very simply, the weightings should strongly favour overnight construction costs, followed by production costs and lastly decommissioning costs. Construction duration directly affects the overnight costs and is included within it. Therefore if construction duration was included explicitly as a metric it would effectively be double counted along with overnight construction costs. For this reason, it is proposed to eliminate construction duration as an explicit metric and use only four metrics in this grouping.

Using the IEA/NEA generating cost breakdowns, the proposed weightings (which sum to 100) for the four generating cost items are as follows:

Table 1: Generating cost metrics and weights

Overnight construction costs	55%
Production costs	25%
Decommissioning costs	10%
R&D costs	10%

This choice assigns relative weights to overnight construction costs and production costs roughly in proportion to the breakdown indicated by IEA/NEA. Assigning 10% to decommissioning puts more weight on this item than the IEA/NEA report would suggest. The IEA/NEA report is consistent with a direct contribution from decommissioning costs nearer 1%, which is the range that NNL's past studies have indicated. In the UK, the direct contribution from decommissioning is not as relevant, as financial provisioning arrangements for decommissioning exist under which utilities are obliged to contribute to a segregated decommissioning fund that will be built up during the operating lifetime of the plant. Such provisioning fund arrangements are biased in the conservative sense and therefore a utility would make a higher contribution than the expected cost. For this reason and also to avoid dismissing decommissioning as a trivial item, a 10% weighting is proposed. Similarly, to avoid dismissing R&D costs, a 10% weighting is also applied here. For a mature nuclear system, the R&D cost could perhaps be regarded as not very relevant, but its inclusion at 10% weighting ensures that it is not dismissed completely.

The generating cost metrics therefore are amenable to a rational weighting scheme guided by their relative contributions to total generating cost. Therefore these weightings can be regarded as largely objective.

3. Group 2 : Inherent PRPP metrics

One of the key goals of the Gen IV International Forum [4] is to improve the inherent proliferation resistance and inherent physical protection (PRPP) of next generation nuclear systems. Proliferation Resistance is understood in GIF to refer the possibility of a state diverting nuclear materials for weapons purposes, while Physical Protection refers to risks posed by non-state actors such as terrorist groups attempting to sabotage a nuclear plant or steal nuclear material. This is an obvious metrics grouping.

The four metrics in NNL 11491 that are categorised under Proliferation Resistance and Vulnerability have been grouped under the heading PRPP. The four metrics are:

1. Separated materials.
2. Spent fuel characteristics.
3. Sabotage resistance.
4. Proliferation resistance.

The first three of these metrics are originally from GIF [4]. The first two of these capture the main aspects of inherent proliferation resistance with respect to the diversion of nuclear materials by a state for use in nuclear weapons development and acquisition. This largely overlaps what was intended with the proliferation resistance metric and for this reason it is proposed that the latter should be removed to avoid duplication.

The sabotage resistance metric refers to inherent protection against attack by a sub-national organisation or against the theft of nuclear materials for use either in a fission weapon or in a radioactive dispersal device. Again, this metric was taken from the GIF report and together with the other two GIF metrics fits into the PRPP category.

There is no obvious means of assigning weights to the three remaining metrics without a detailed assessment of the scope of the threats and therefore it is proposed to assign equal weighting to the three metrics:

Table 2: Inherent PRPP metrics and weights

Separated materials	33%
Spent fuel characteristics	33%
Sabotage resistance	33%

Assigning equal weights ensures all of the three areas are treated as equally important. For a specific threat, one of these metrics might play a more prominent role, but it is important to consider a range of potential threats that might apply and therefore it is a reasonable working assumption to assign equal weights. The PRPP metrics do not lend themselves to objective weighting and the equal weighting scheme should be regarded as necessarily subjective.

4. Group 3 : Safety metrics

Nuclear safety is an extremely important consideration and is a natural metrics grouping. There are 13 metrics in NNL 11491 that were categorised under Operational safety and reliability:

1. Reliability
2. Radiological exposures
3. Safety
4. Reactivity control
5. Decay heat removal
6. Low uncertainties on dominant phenomena
7. Fuel thermal response
8. Integral experiment scalability
9. Source term
10. Energy release mechanisms
11. System response times
12. Effective hold-up
13. Benefits or risks for security

The first 12 of these were all taken from the GIF report [4]. The third metric (safety) is covered already by the other metrics, so it is proposed to delete it. Also, Metric 13 (Benefits or risks for security) is difficult to reconcile with the others, which all relate to some specific aspect of nuclear plant safety and therefore it will also be deleted from the list.

This leaves 11 metrics for which the proposed weightings (which again sum to 100) are as follows:

Table 3: Safety metrics and weights

Reliability	5%
Worker exposures	5%
Reactivity control	10%
Decay heat removal	25%
Low uncertainties on dominant phenomena	5%
Fuel thermal response	10%
Integral experiment scalability	5%
Source term	10%
Energy release mechanisms	10%
System response times	10%
Effective hold-up	5%

These weightings are necessarily subjective, but they are guided by expert judgment the basis of which is as follows:

Decay heat removal is assigned the highest weighting on the grounds that managing decay heat is the principal safety objective of any nuclear reactor. All reactors are required to be operated in such a way that they can be made sub-critical (shutdown) on demand and maintained in a sub-critical condition. However, all reactors produce decay heat following shutdown that needs to be managed and there is a high degree of uniformity in that all reactor systems produce decay heat in proportion to their thermal output and these proportions hardly vary between reactor designs. Moreover, the time profiles of decay heat output vary little between different systems, so that decay heat can be regarded as a largely constant factor for all systems. All power reactors need to manage decay heat and it is the approach to dissipating decay heat that is the distinguishing factor between them.

Loss of decay heat removal capability was the underlying consideration that led to core damage in the Three Mile Island and Fukushima accidents. Modern power reactors are equipped with multiple lines of protection designed to ensure that decay heat removal can be assured, such as Residual Heat Removal Systems (RHRS), Emergency Core Cooing Systems (ECCS) and other Safety Injection (SI) systems. Together with the associated diverse power supply systems, these represent a very significant proportion of system costs that are incurred in recognition of the major threat posed by loss of decay heat removal. Many of the other safety metrics are irrelevant to the course of an accident if reliable decay heat removal can be assured. The capability of a complete passive decay heat removal mechanism, which is a design feature of High Temperature Gas Reactors (HTGR) and some other systems should merit a high overall rating on safety. On this basis, it is considered rational and justified to assign the highest weight to decay heat removal.

After decay heat, the next most important safety metrics are reactivity control, fuel thermal response, source term, energy release mechanisms and system response times.

The Chernobyl accident was triggered by a positive void coefficient resulting in prompt criticality, which is a reactivity control issue. While reactivity control can be the main initiating event, as at Chernobyl, a properly designed reactor with multiple reactivity shutdown mechanisms should not be especially vulnerable to severe reactivity insertion accidents. In both Three Mile Island and Fukushima, reactivity control did not feature at all, because the reactors all successfully tripped on demand and remained sub-critical.

In Three Mile Island and Fukushima, although the initiating event was loss of decay heat removal, the subsequent progression of the accidents was strongly influenced by:

1. The fuel thermal response, with fuel overheating being followed by clad oxidation and subsequent fuel melting.
2. Releases of volatile radionuclides (the source term) from the melted fuel determined the radioactive inventory released into the primary circuit in Three Mile Island and to the environment in Fukushima.
3. Corrosion of fuel cladding by superheated steam was an exothermic reaction that added to the heat source and accelerated the progression of fuel degradation.

4. System response times were important in the initial progression of the Three Mile Island and Fukushima accidents, since the thermal inertia of LWRs is low, leading to response timescales measured in minutes.

In any specific accident sequence, one of these metrics might play a more important role than the others and would therefore carry a higher weight. However, in practice reactor safety cases need to consider a wide range of accident sequences each with different lead metrics. For this reason it is difficult to discriminate between any of these four mechanisms and it is proposed to assign equal weights to them. This is a reasonable approach, given that none of these four metrics are associated with initiating events – they are all associated with the subsequent system response following some other initiating event.

The only contentious point is whether reactivity control should be given the same weight as the system response metrics or a higher weight. It is proposed here to adopt the first approach, of assigning it equal weight, for simplicity, as in the table above. The remaining five safety metrics can be considered as secondary safety metrics and are each assigned a 5% weighting. The following comments apply:

1. Reliability could be regarded as an operational issue or as a safety issue. Unreliable operation would adversely affect system availability and therefore impact on economics. Additionally, an unreliable system might lead to an increase in the frequency of initiating events. It could be argued that the economic impact of poor reliability would be captured in a low load factor leading to an increase in levelised generating costs and this aspect is already covered under the Generating Cost metrics. For this reason, reliability is only considered here as a third tier safety issue, with a possible influence on initiating event frequencies.
2. Worker exposures is normally regarded as a normal operating issue, but does also have a role in accident sequences involving radiological release.
3. Low uncertainties on dominant phenomena is a metric that is directly related to safety. If the underlying physical phenomena are well understood and their uncertainties are quantified, it is possible to assign uncertainty allowances and define operational limits with confidence that will protect against unwanted outcomes. It is potentially a strong discriminator especially for novel systems that are not well developed.
4. Integral experiment scalability is closely related to low uncertainties on dominant phenomena and is specifically designed to capture the uncertainty that applies to immature systems and whether the behaviour observed in small scale laboratory experiments can be extrapolated to a full scale plant.
5. Effective hold-up is intended to account for any mechanisms that would result in radionuclide release into the environment being prevented or delayed and controlled. This is the role of the containment systems in LWRs and there is the potential to discriminate between different systems on the basis of how many containment barriers there are and how effective each is.

The overall recommendation is therefore for three tiers of safety metrics, with decay heat removal ranked the highest and with reactivity control, fuel thermal response, source term, energy release mechanisms and system response times in the next tier and the secondary safety metrics in the lowest tier. With so many safety metrics and with reactor safety being a very complex area, it is considered that such simplification is necessary for a practicable approach.

5. Group 4 : Strategic metrics

The strategic fit of a nuclear system is an important and obvious grouping to use. In NNL 11491 there are 13 metrics classified as strategic:

1. Scalability
2. Timescales to deployment
3. Technology Readiness Level
4. Waste arisings (volumes HLW, ILW, LLW)
5. Ease of construction
6. Sustainability
7. Primary purpose
8. Load follow capability
9. Flexibility of location
10. Number and size of reactors needed
11. Associated fuel cycle
12. Potential to drive thermal processes
13. Decommissioning.

Items 4 to 7 above all overlap with other metrics and are eliminated here as duplicate metrics. Waste arisings is duplicated by the VHLW, ILW and LLW volumes metric considered later. Ease of construction is covered overnight construction costs and considered already under Generating cost metrics. Sustainability is now addressed explicitly under fuel sustainability. Items 7 to 12 above are now re-classified under Deployability. Item 13, decommissioning, is already considered under the Generating cost grouping and is therefore removed from this grouping.

Of the remaining three metrics, the key strategic metrics are considered to be timescales to deployment and technology readiness level. The timescale on which a system is expected to be deployed is a key strategic consideration sufficient to rule out systems requiring a long development time. The technology readiness level metric is important strategically because it can account for technical risks involved with developing immature systems to commercial readiness. Scalability captures whether a system can be scaled up or down to meet the strategic requirements and does not necessarily apply to all systems, so is regarded here as a secondary metric. For these reasons, the following weighting scheme is proposed:

Table 4: **Strategic metrics and weights**

Scalability	20%
Timescales to deployment	40%
Technology Readiness Level	40%

6. Group 5 : Deployability metrics

Deployability is an obvious metrics grouping that can be used to subsume several metrics that were originally classified under different categories. In NNL 11491 there are six strategic metrics which are now re-classified under the heading of deployability. Of these, primary purpose and potential to drive thermal processes can be regarded as duplicates and are combined here under the latter metric.

1. Primary purpose
2. Load follow capability
3. Flexibility of location
4. Number and size of reactors needed
5. Associated fuel cycle
6. Potential to drive thermal processes

Deployability concerns how flexible a system would be in meeting specific requirements. They mostly relate to the nuclear reactors deployed for roles other than large scale baseload generation and might be important in UK scenarios where nuclear plants are required to be more responsive, such as balancing loads from renewables. The associated fuel cycle metric is designed to capture the important possibility that a new reactor system may demand the construction of new fuel cycle facilities and/or may produce a spent fuel form that is not compatible with the existing fuel cycle infrastructure. The last metric is designed to capture potential non-electricity production roles for nuclear, including industrial heat applications and thermal hydrogen production.

There is no obvious rationale for weighting any of these metrics more heavily than the others and therefore a uniform weighting is proposed:

Table 5: Deployability metrics and weights

Load follow capability	20%
Flexibility of location	20%
Number and size of reactors needed	20%
Associated fuel cycle	20%
Potential to drive thermal processes	20%

7. Group 6 : Sustainability metrics

Only fuel utilisation is considered under sustainability metrics, this being the first question that usually arises when considering whether there will be fissile material available to fuel a fleet of reactors over their lifetimes at a price that is affordable. It could be argued that metrics such as environmental impact and waste arisings can also be regarded as falling under sustainability, but these are captured under the separate heading of waste, so that sustainability here means specifically fuel sustainability.

With just a single metric under this heading, there is no need for a set of weighting factors.

8. Group 7 : Waste metrics

The amount and type of nuclear waste produced by a nuclear system is an obvious grouping of metrics to use, given the importance of waste as a justification issue. In NNL 11491 there are six metrics that were previously categorised under waste minimization or waste management and which are now grouped under the simpler heading of waste:

1. Spent fuel mass
2. VHLW, ILW & LLW volumes
3. Long term heat output
4. Long term radiotoxicity
5. Environmental impact
6. Plutonium and minor actinide management

Similar to the safety metrics, a three tier system is proposed for weighting the waste metrics:

Table 6: Waste metrics and weights

Spent fuel mass	10%
VHLW, ILW & LLW volumes	20%
Long term heat output	30%
Long term radiotoxicity	10%
Environmental impact	20%
Plutonium and minor actinide management	10%

Long term heat output is assigned the highest weighting because this is the single most important factor determining the footprint of the geological disposal facility (GDF) which would receive the heat producing waste, usually either spent fuel or vitrified high level waste (VHLW).

There are strong arguments why waste volume minimization can be considered secondary to long term heat output, as the spacing between waste packages in a repository is not as much affected by the packaged volume as it is by heat production. There are environmental impacts from wastes produced in all stages of the fuel cycle, from front-end fuel cycle operations to reactor operations and back-end fuel cycle operations. Recognising the importance of these two metrics, they are assigned to the second tier of weights.

Spent fuel mass, radiotoxicity and plutonium and minor actinide management are all considered slightly less relevant and allocated the third tier weights. The spent fuel mass is perhaps most important when considering how much spent fuel must be held in interim storage. Radiotoxicity is often portrayed as a key parameter for repository performance, but a recent OECD-NEA report [5] has highlighted how peak radiological doses from a repository are largely decoupled from the total radiotoxic inventory (because the minor actinides which dominate the radiotoxic inventory after 500 years are immobile in all the repository geological conditions considered world-wide). While plutonium management is an important consideration in the UK, any strategy for dealing with separated plutonium is unlikely to be deferred to the very distant future, as would be necessary if an immature system with long development timescales was considered for this purpose. On this basis, plutonium (and minor actinide management to a greater extent) is allocated to the third tier.

9. Summary

The basis for the seven groupings and the rationale for assigning the weights has been explained. This provides a basis for the subsequent scorings that will be reported in the addendum to NNL 11620.

10. References

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

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

3. Projected Costs of Generating Electricity, OECD-NEA & IEA, 2010

4. “A technology roadmap for Generation IV nuclear energy systems”, GIF-002-00, December 2002

5. Potential benefits and impact of advanced fuel cycles with actinide partitioning and transmutation, OECD-NEA Task Force on Potential Benefits and Impacts of Advanced Fuel Cycles with Partitioning and Transmutation (TFPT), OECD-NEA 2012