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Work in Progress

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The Generic Feasibility Assessment:
An Essential Ingredient in Nuclear Policy making

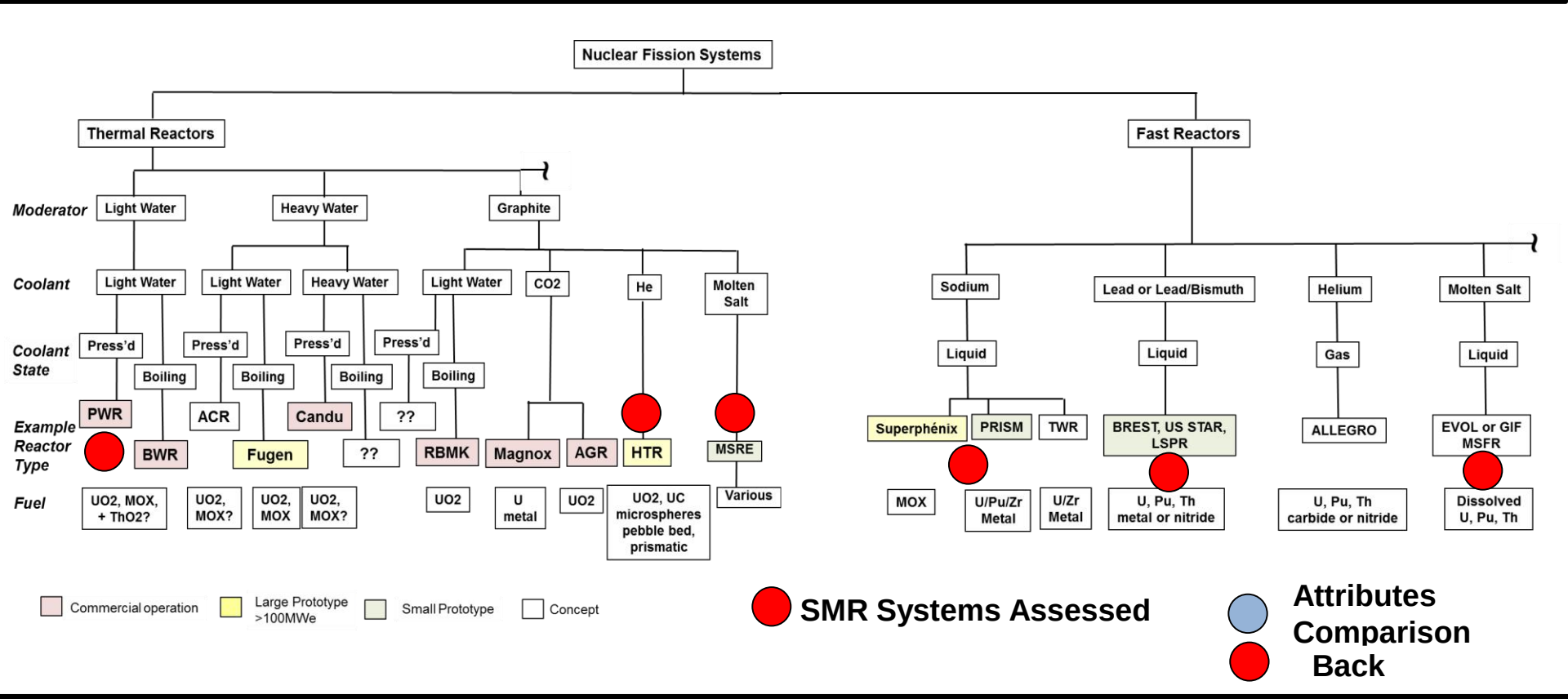
The Generic Feasibility Assessment of Small Modular Reactor Systems

SMR Techno-Economic Assessment
Project 3 – SMRs: Emerging Technology

March 2016

Start

IDM
integrated decision management



References

These Generic Feasibility Assessments draw upon extensive work by NNL on nuclear energy technology assessment, IAEA, OECD/NEA, USDOE and other international literature. Individual references have not been included in the current draft GFA. It is anticipated that as more information becomes available relating to specific Attributes or Metrics, this might either further validate or modify the GFA. This additional information can then be referenced in the appropriate places in the GFA Template.

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The Generic Feasibility Assessment:
An Essential Ingredient in Nuclear Policy making

Assessment Matrix with Descriptions

Subject System: **Generic SMR**

Reference System: **GWe-sized PWR**

Template: **14**

Date of Assessment: **15th March 2016**
Modified to generalise references to Regulators at 20th December 2017

Assessment

IDM
integrated decision management

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Reference and Subject Systems

Reference System:

GWe-sized PWR

Subject System:

A Generic SMR is a PWR having a capacity of less than 300MWe. It should be capable of being deployed in multiple units, is based on currently PWR technology and uses pumped cooling, which could be built, commissioned and operating in the UK from 2030 or soon thereafter.

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Version Development

2015.08.08 Initial GFA of Generic SMR based on 2014 assessment inserted into updated format Template 12

2015.08.19 Re-examined by Kevin Hesketh, Grace McGlynn, Gregg Butler

2015.08.27 Re-examination completed by Kevin Hesketh, Grace McGlynn, Gregg Butler

2016.01.11 Further additions/corrections by Kevin Hesketh subsequent to Workshop on 11.12.2015

2016.02.08 Minor connection glitches removed – slides 62-82

2016.02.24 Checked/mods accepted for Draft Report

2016.03.15 Mods to Flexibility wording

References

This Generic Feasibility Assessment draws upon extensive work by NNL on nuclear energy technology assessment, IAEA, OECD/NEA, USDOE and other international literature. Individual references have not been included in the current draft GFA. It is anticipated that as more information becomes available relating to specific Attributes or Metrics, this might either further validate or modify the GFA. This additional information can then be referenced in the appropriate places in the GFA Template.

IDM
integrated decision management

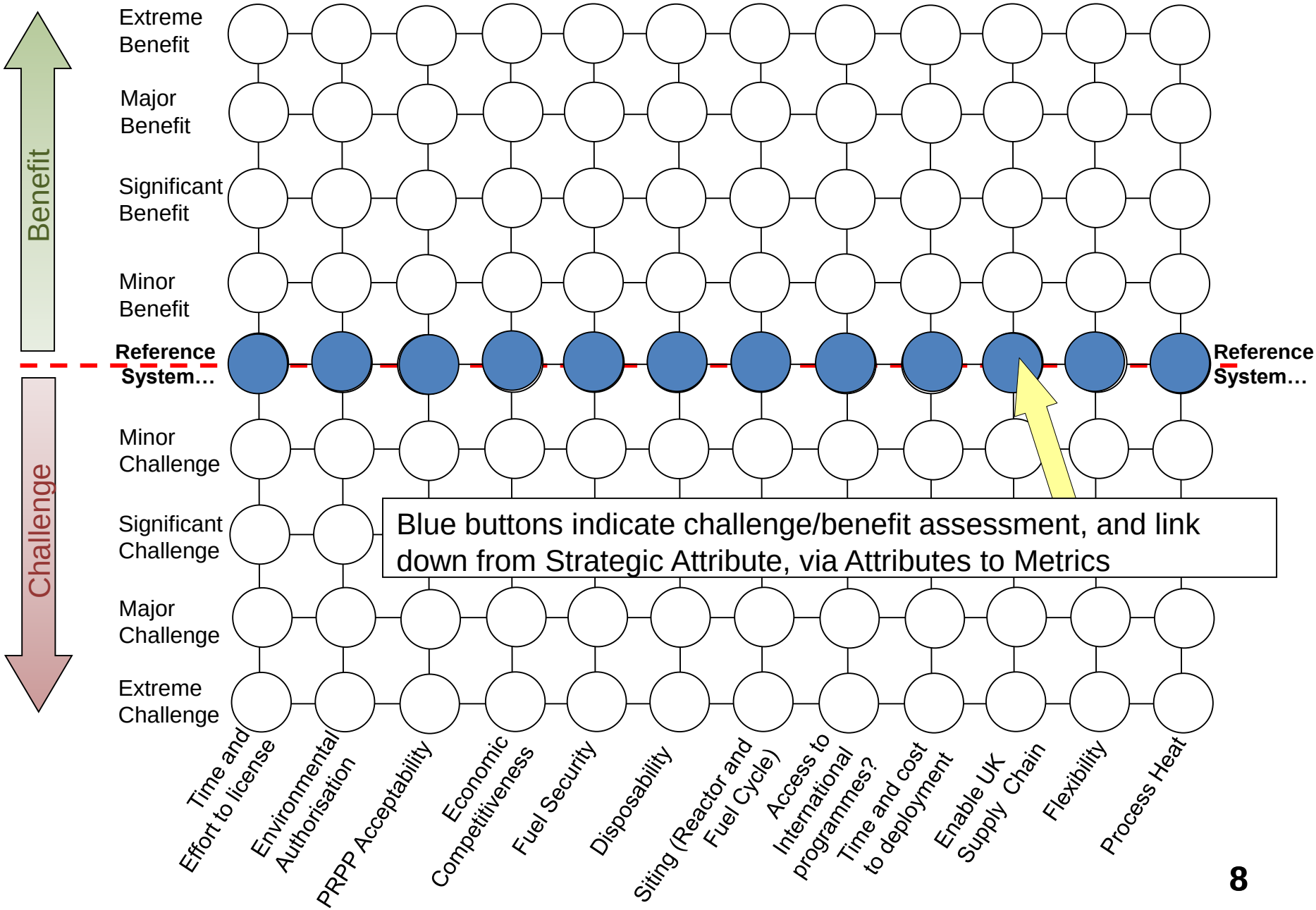
What is Generic Feasibility Assessment?

- GFA was developed for DECC to provide a high level strategic evaluation of nuclear reactor and fuel cycle systems
- It operates by making comparisons between the 'Subject System' and a Reference System, initially 'once-through LWR' as envisaged for new nuclear build in the UK
- The analysis uses 12 Strategic Attributes, using public domain information and informed professional judgement to assess the relative degree of benefit or challenge offered by the Candidate System.

What is Generic Feasibility Assessment?

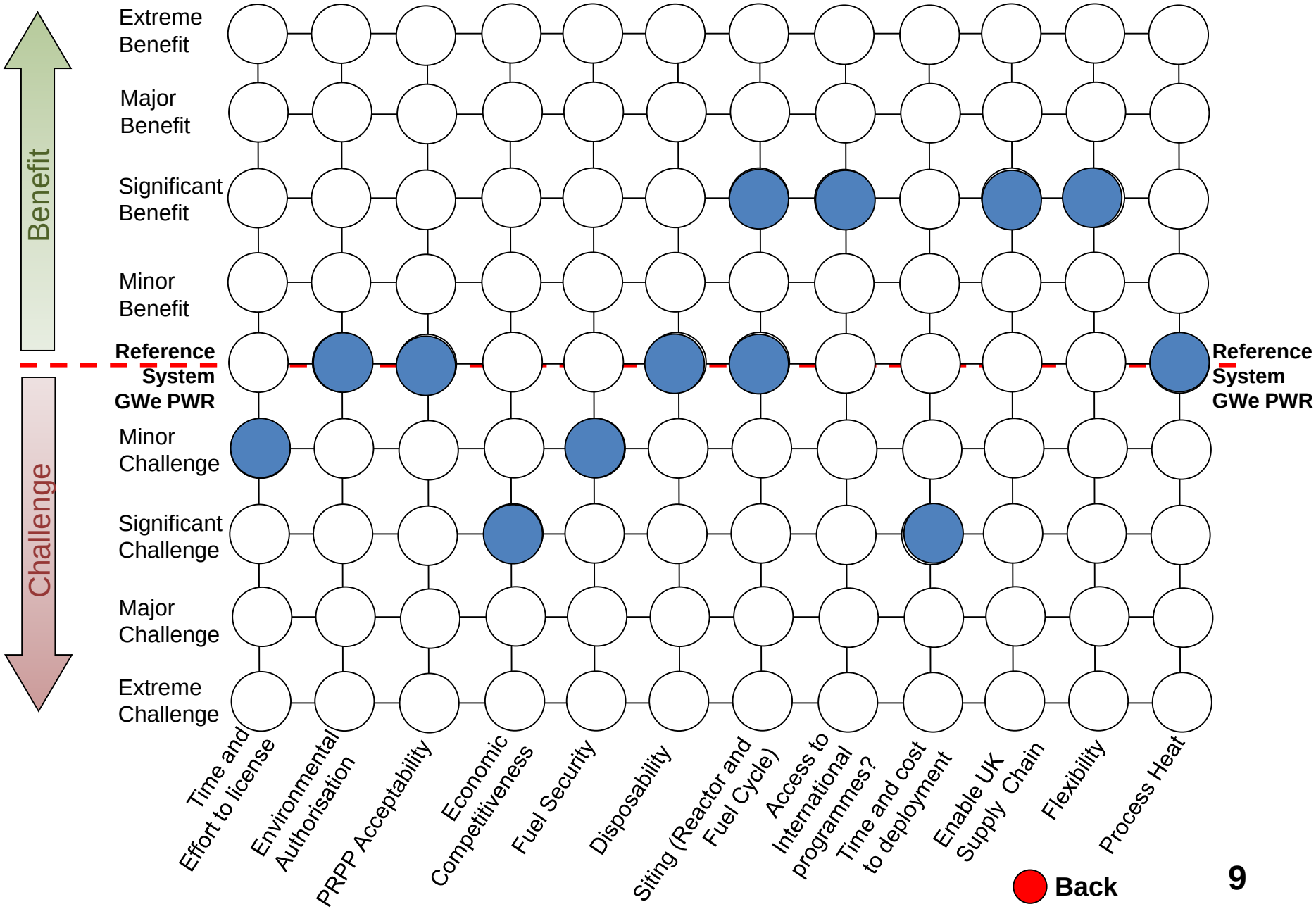
- GFA presents a high level, accessible visual representation of benefits and challenges, while allowing more detailed interrogation of the underpinning rationale and data
- As all information is public domain, any additional evidence can, and will, lead to modification of the assessment: GFA assessments are always 'Work in Progress'
- A full description of how GFA was derived and developed is available at: www.dalton.manchester.ac.uk/gfa
- This Visualisation provides a guide to how GFA is built up, the definitions of Strategic Attributes, Attributes and Metrics, and demonstrates how the information and logic tree can be navigated.

GFA Assessment Subject System: Generic SMR Reference System: GWe PWR – *Work in Progress*



Blue buttons indicate challenge/benefit assessment, and link down from Strategic Attribute, via Attributes to Metrics

GFA Assessment Subject System: Generic SMR Reference System: GWe PWR – *Work in Progress*



1a. Time and Effort to License

Summary

The overall assessment is that there is relatively little to distinguish SMRs from large scale plants with respect to demonstrating overall safety, though individual SMR units may need to achieve more stringent limits when installed as multiple units to meet the same overall safety performance for the entire site

Assessed as 'Minor Challenge'

Attributes

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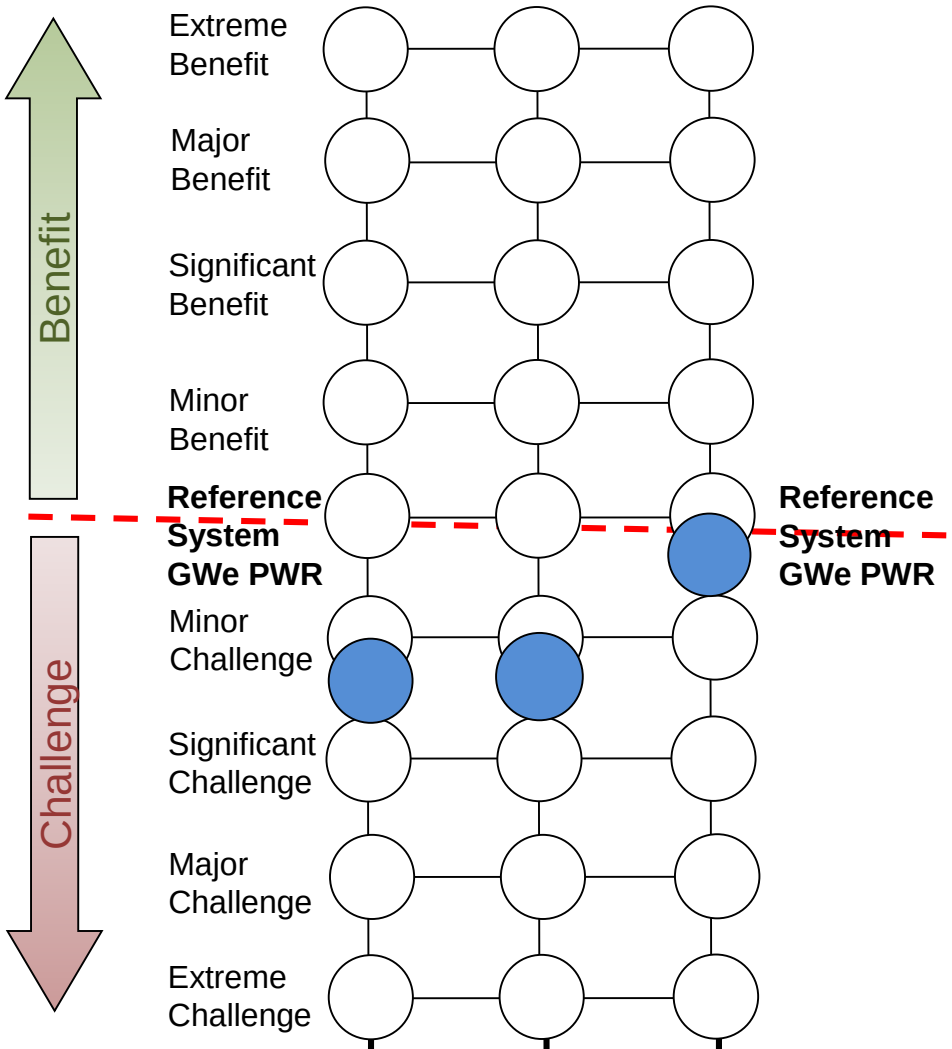
Description

GFA Assessment Subject System: Generic SMR Reference System: GWe PWR – *Work in Progress*

1a. Time and Effort to License



1a.3 Effort to meet radiological regulations

1a.2 Timescale required to demonstrate that Safety Regulation Requirements can be satisfied

1a.1 Effort to satisfy Safety Regulation Requirements

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Description

1a. Time and Effort to License

Nuclear facilities in the UK are required to comply with the requirements set down by the appropriate regulatory bodies. Safety and licensing requirements are the responsibility of the Office of Nuclear Regulation (ONR), which also sets the radiological protection requirements for occupational exposure and members of the public.

Any reactor system to be deployed in the UK must be demonstrated to be safe, and to do so the reactor system must adhere to the fundamental safety principles as laid down by the licensing regulator. ONR has defined a series of Safety Assessment Principles known by the acronym 'SAPs'. These SAPs are seen as the top level goals which any system for deployment in the UK must be able to meet. The SAPs framework provides ONR with a set of guidelines by which ONR inspectors can make consistent judgements on nuclear safety assessment.

The top level safety criterion can be posed as: ***How much time and effort will be involved to allow the reactor system to meet the various UK safety regulatory requirements?***

From this top level criterion, the following attributes are obtained:

- ***Nuclear safety and regulation. What challenges must be met to enable the reactor system to meet well developed*** **Safety Regulation Requirements** ***(Button 1a.1)and on what timescale can such compliance be demonstrated? (Button 1a.2)***
- ***Radiological regulation. What challenges must be met to enable the reactor system to comply with the radiological dose limits defined by regulators for workers and members of the public? (Button 1a.3)***

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1a.1 Effort to satisfy Safety Regulation Requirements

Licensing individual integral units may be an issue, and though passive safety is potentially a benefit, it does require different approaches to the regulators. Numbers of modules in close proximity may also present challenges.

Assessed as 'Minor Challenge'

Metrics

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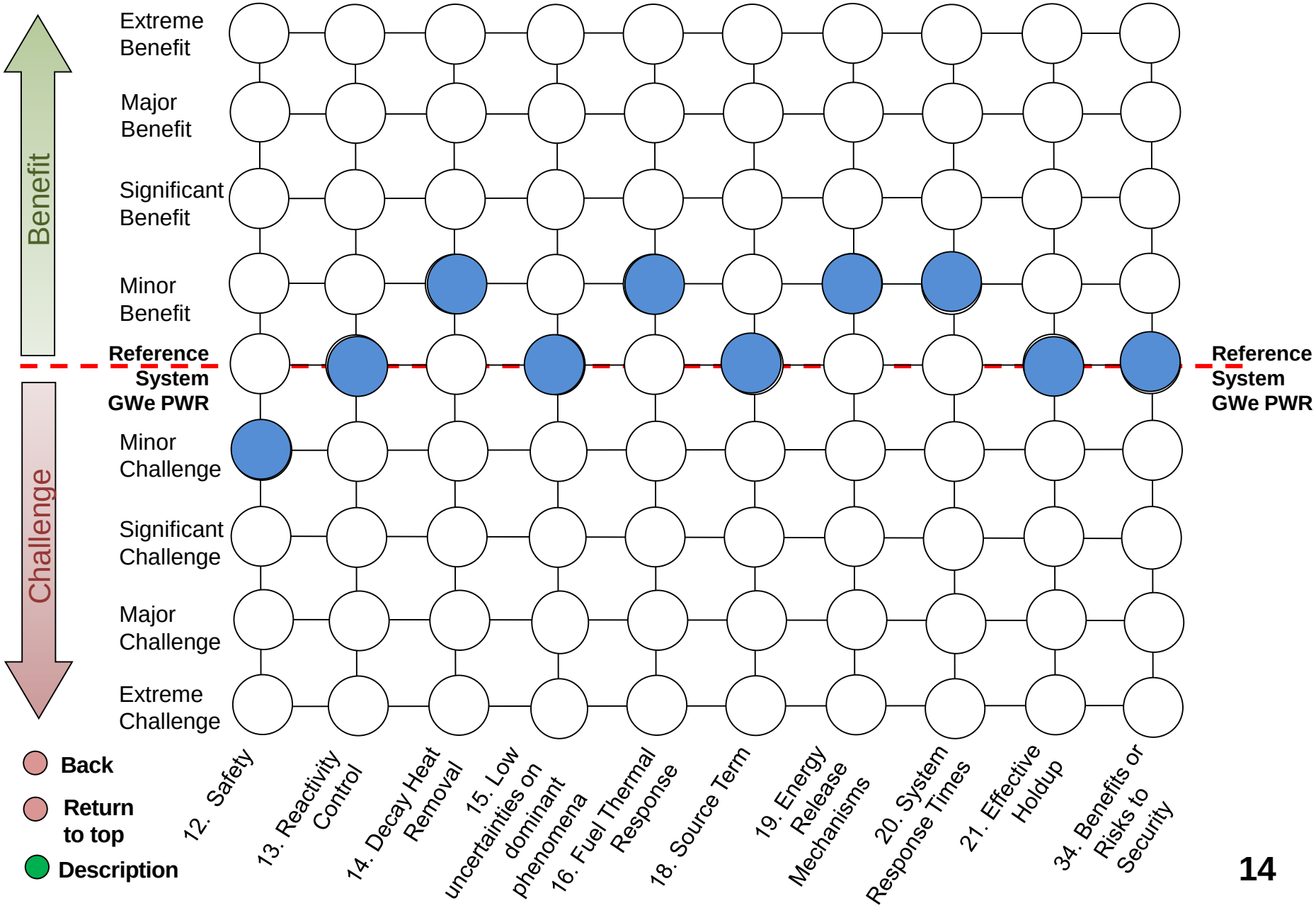
Description

References

GFA Assessment Subject System: Generic SMR Reference System: GWe PWR – *Work in Progress*

1a.1 Effort to satisfy Safety Regulation Requirements



1a.1 Effort to satisfy Safety Regulation Requirements

1a.1 assesses the challenge faced by a reactor system in meeting the goals defined by the Safety Regulation Requirements. Levels of challenge would be expected to increase as the system examined moves further away from current experience, for example:

- Systems which are already deployed commercially or whose designs are already licensed in other countries.
- Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.
- Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.
- Systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

Assessments will assume that regulatory effort is available when and as required

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12. Safety

Licensing individual integral units may be an issue, and though passive safety is potentially a benefit, it does require different approaches to the regulators. Numbers of modules in close proximity may also present challenges.

Assessed as 'Minor Challenge'

12. Safety

Any new reactor system deployed in the UK would need to meet very stringent safety standards. Some of the systems considered will rely on passive safety and this might distinguish them from other systems that rely on conventional active safety systems.

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12. Safety - references

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13. Reactivity Control

Reactivity control for small modular PWRs is equivalent to that of large PWRs with the exception that some designs do not use soluble boron control. SMRs with lower specific ratings are less sensitive to control rod insertion because the power margins to fuel performance limits are increased. With the exception of boration/dilution accidents, the reactivity insertion events that will need to be addressed in the safety case are equivalent. Demonstrating adequate cold zero power (CZP) shutdown margin may be an issue for small modular PWRs with no soluble boron system.

Assessed as 'Reference'

13. Reactivity Control

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.

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13. Reactivity Control - references

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14. Decay Heat Removal

Passive decay heat removal from LWRs is possible even for large scale LWRs (eg AP-1000) and is widely adopted for SMRs. It is helpful if the specific ratings are low, as is the case for many proposed SMRs.

Integral designs may require extensive testing programmes to validate decay heat removal mechanisms. This would be expected to be addressed as part of the engineering design process, the details of which would normally be accessible only to the reactor designers at the design stage, but which would later be made available to the licensing authority and prospective owner/operators.

Assessed as 'Minor 'Benefit'

14. Decay Heat Removal

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.

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14. Decay Heat Removal - references

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15. Low uncertainties on dominant phenomena

LWR safety behaviour is well understood from current large scale plants and mostly carries over to SMRs. Therefore the dominant phenomena should have low uncertainties for designs with forced circulation.

Integral plant layouts may require extensive testing to validate overall system behaviour, even if the individual components are already well understood.

Assessed as 'Reference'

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Description

References

15. Low uncertainties on dominant phenomena

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.

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15. Low uncertainties on dominant phenomena - references

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16. Fuel Thermal Response

Essentially same as for large scale LWRs. Small beneficial effect of lower specific ratings

This observation is based on a detailed understanding of the design of current large LWRs and are valid because the basic operating principles carry over to small modular LWRs. The issues raised would be expected to be addressed as part of the engineering design process, the details of which would normally be accessible only to the reactor designers at the design stage, but which would later be made available to the licensing authority and prospective owner/operators.

Assessed as 'Minor Benefit'

16. Fuel Thermal Response

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.

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16. Fuel Thermal Response - references

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18. Source Term

Maximum inventory at End-of-Cycle depends on the number of refuelling batches. Maximum effect for a single-batch core is to increase the inventory of long-lived fission products (LLFP), such as Cs-137, by a factor 2. For a long-life core, the LLFP source term could be increased by a factor 10.

Assessed as 'Reference'

18. Source Term

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.

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18. Source Term - references

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19. Energy Release Mechanisms

This is interpreted to mean significant energy release mechanisms such as Zircaloy cladding oxidation which in LWRs is a significant to energy inputs in certain accident sequences.

Essentially same as large scale LWRs. Possible extended timescales for designs with low specific ratings and/or large thermal inertias. Significant improvement for small modular LWR would require development and irradiation testing of accident tolerant fuel. Accident tolerant fuel might be expected to be compatible with retro-fitting most small modular PWRs (lifetime fuelled cores would be an exception).

Assessed as 'Minor Benefit'

19. Energy Release Mechanisms

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.

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19. Energy Release Mechanisms - references

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20. System response times

LWRs typically have very short transient response times, which a consequence of the compact high power density cores and the relatively small primary coolant inventories. Transit times for the primary coolant are a few seconds and transient response times from a few seconds to a few minutes are typical. Automated system responses are needed to ensure that ONR's 30 minute non-intervention requirement is met.
Possible extended timescales for designs with low specific ratings and/or large thermal inertias. This may be helpful in providing extra time for accident mitigating systems to take effect.

Assessed as 'Minor Benefit'

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Description

References

20. System response times

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.

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20. System response times - references

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21. Effective Holdup

This refers to the holdup of volatile fission products in accident scenarios. Conventional PWR designs are able to retain a large proportion of fission products by condensation on internal surfaces. Holdup of volatile fission products will depend on the details of each specific design. There are large uncertainties associated with holdup calculations that may require integral systems testing

Assessed as 'Reference'

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Description

References

21. Effective Holdup

Effective hold-up refers to mechanisms in the design of a plant for containing radioactive material following an accident condition. In PWRs 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.

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21. Effective Holdup - references

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34. Benefits or challenges for security

The physical security requirements that small modular PWRs will need to comply with are equivalent to those of current large PWRs. The nuclear material that is to be protected from unauthorised access is essentially equivalent and any detailed differences in terms of assembly masses, spent fuel inventory, burnup and specific activities are considered at most of marginal importance for security..

Some SMPWR reactors use passive safety and some would locate the nuclear island underground. This apart, for individual modules, security challenges would be broadly similar to large scale PWRs. The security implications of a distributed network of many SMR sites would require evaluation, and may be a challenge.

Assessed as 'Reference'

34. Benefits or challenges for security

This attribute assesses the security implications of reactor deployment

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34. Benefits or challenges for security - references

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1a.2 Timescale required to demonstrate that Safety Regulation Requirements can be satisfied

In the UK the Generic Design Approval (GDA) process is new and only EPR has been through it in its entirety. The process for EPR took almost 6 years, but the experience gained should allow future LWRs to gain approval within 4 years or so. Small PWRs will benefit from this prior experience because many of the system components are the same and existing experience in large reactors will apply. However, the systems integration aspects are very different for small PWRs, since they typically have an integral primary system layout. Integral systems will need specific testing to demonstrate satisfactory design.

The conclusion is that the minimum timescale for a small modular PWR to gain UK approval would be determined by the time required for the integral systems testing and a 4 year minimum time assumed for the GDA process. The integral systems testing could overlap with the GDA process, but it is difficult to envisage any of the small modular PWR designers being in a position to begin the GDA process in less than 5 to 6 years, because of the need to further develop the designs and to design, implement and analyse the integral systems tests. This leads to an estimate of 10 years minimum (2025+) for a small modular PWR to complete the GDA process.

Most current small modular PWR designs use proven fuel designs. Any system which uses a novel fuel design will need an estimated 15 years minimum to qualify the fuel. This is governed by test irradiation timescales and post-irradiation examination requirements.

Assessed as 'Minor Challenge'

1a.2 Timescale required to demonstrate that Safety Regulation Requirements can be satisfied

1a.2 assesses how long it might reasonably be expected to take to demonstrate that the system can satisfy stringent Safety Regulation Requirements. Levels of challenge would be expected to increase as the system examined moves further away from current experience, for example:

- Systems which are already deployed commercially or whose designs are already licensed in other countries.
- Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.
- Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.
- Systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

Assessments will assume that regulatory effort is available when and as required

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1a.2 Timescale required to demonstrate that stringent Safety Regulation Requirements can be satisfied - references

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1a.3 Effort to meet radiological regulations

Essentially same as large scale LWR, but details will be design specific. There may be benefit if the design eliminates the need for soluble boron reactivity control, by avoiding worker exposure in Chemical and Volume Control System (CVCS) maintenance activities associated with the boron resin beds. However, there may be compensating factors elsewhere, for example, maintenance and inspection exposures for integral pumps and steam generators.

Assessed as 'Reference'

Metric - 11. Worker Exposures

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Description

References

1a.3 Effort to meet radiological regulations

1a.3 assesses the difficulty likely to be experienced in meeting the worker radiological protection requirements defined by regulators, noting that this includes the reactor and its fuel cycle. Levels of challenge would be expected to increase as the system examined moves further away from current experience, for example:

- Systems which are already deployed commercially or whose designs are already licensed in other countries.
- Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.
- Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.
- Systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

Assessments will assume that regulatory effort is available when and as required

1a.3 Effort to meet radiological regulations - references

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11. Worker Exposures

Essentially same as large scale PWR, but details will be design specific. There may be benefit if the design eliminates the need for soluble boron reactivity control, by avoiding worker exposure in Chemical and Volume Control System (CVCS) maintenance activities associated with the boron resin beds. However, there may be compensating factors elsewhere, for example, maintenance and inspection exposures for integral pumps and steam generators.

Assessed as 'Reference'

11. Worker Exposures

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.

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11. Worker Exposures - references

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1b. Time and Effort for Environmental Permitting

Summary

Essentially same as large scale PWRs, but details of environmental impacts will be design specific, and will vary with the number of units on a site, and the site location, particularly if a distributed network of SMRs is envisaged.

Assessed as 'Reference'

Attribute – 1b.1 Effort to meet environmental regulations

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Description

References

1b. Time and Effort for Environmental Permitting

Nuclear facilities in the UK are required to comply with the requirements set down by the appropriate regulatory bodies. Environmental regulations are the responsibility of the Environment Agencies (EA,NRW, SEPA) and are implemented through the granting of site aerial and liquid Discharge Authorisations. The Environment Agencies are also responsible for the authorisation of solid waste disposal.

1b. Time and Effort for Environmental Permitting - References

Insert

1b.1 Effort to meet environmental regulations

Small modular PWRs are likely to be capable of meeting environmental regulations. In terms of discharges to the environment and doses to members of the public, they are likely to an equivalent performance to large PWRs.

With respect to doses to the workforce, it is possible that small modular PWRs will display substantial differences. This is because the integral system layout will result in significant changes to operator doses. An example would be steam generator inspection and maintenance, which would be different in an integral reactor. There is the potential for radiological doses to be increased for some specific tasks, while in other tasks there is the potential for dose commitments to reduce (eg elimination of soluble boron system in some designs).

The details will be design specific.

Assessed as 'Reference'

Metric – 06 Environmental Impact

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Description

References

1b.1 Effort to meet environmental regulatory requirements

1b.1 assesses the challenge faced by a reactor system in meeting the environmental impact requirements defined by the regulators, noting that this includes the reactor and its fuel cycle. This parameter is assumed to refer to routine operational environmental discharges. Levels of challenge would be expected to increase as the system examined moves further away from current experience, for example:

- Systems which are already deployed commercially or whose designs are already licensed in other countries.
- Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.
- Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.
- Systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

Assessments will assume that regulatory effort is available when and as required

1b.1 Effort to meet environmental regulatory requirements - references

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06. Environmental Impact

Small modular PWRs are likely to be capable of meeting environmental regulations. In terms of discharges to the environment and doses to members of the public, they are likely to an equivalent performance to large PWRs.

With respect to doses to the workforce, it is possible that small modular PWRs will display substantial differences. This is because the integral system layout will result in significant changes to operator doses. An example would be steam generator inspection and maintenance, which would be different in an integral reactor. There is the potential for radiological doses to be increased for some specific tasks, while in other tasks there is the potential for dose commitments to reduce (eg elimination of soluble boron system in some designs).

The details will be design specific.

Assessed as 'Reference'

06. Environmental Impact

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.

06. Environmental Impact - references

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1c. Proliferation Resistance and Physical Protection (PRPP) Acceptability

Summary

The once-through PWR fuel cycle is internationally recognised as the reference system for PRPP assessments. Small modular PWRs are essentially the same, with any differences being very minor and in terms of PRPP largely inconsequential. Examples are: initial enrichments; discharge burnups; spent fuel mass per GWyear & fuel assembly mass.

PRPP is taken to have a dual meaning, with Proliferation Resistance referring to state involvement in diversion of fissile materials and Physical Protection concerned with the threat of acquisition of nuclear materials by a sub-national group. The assessments are potential different for the two aspects.

Assessed as 'Reference'

Attributes

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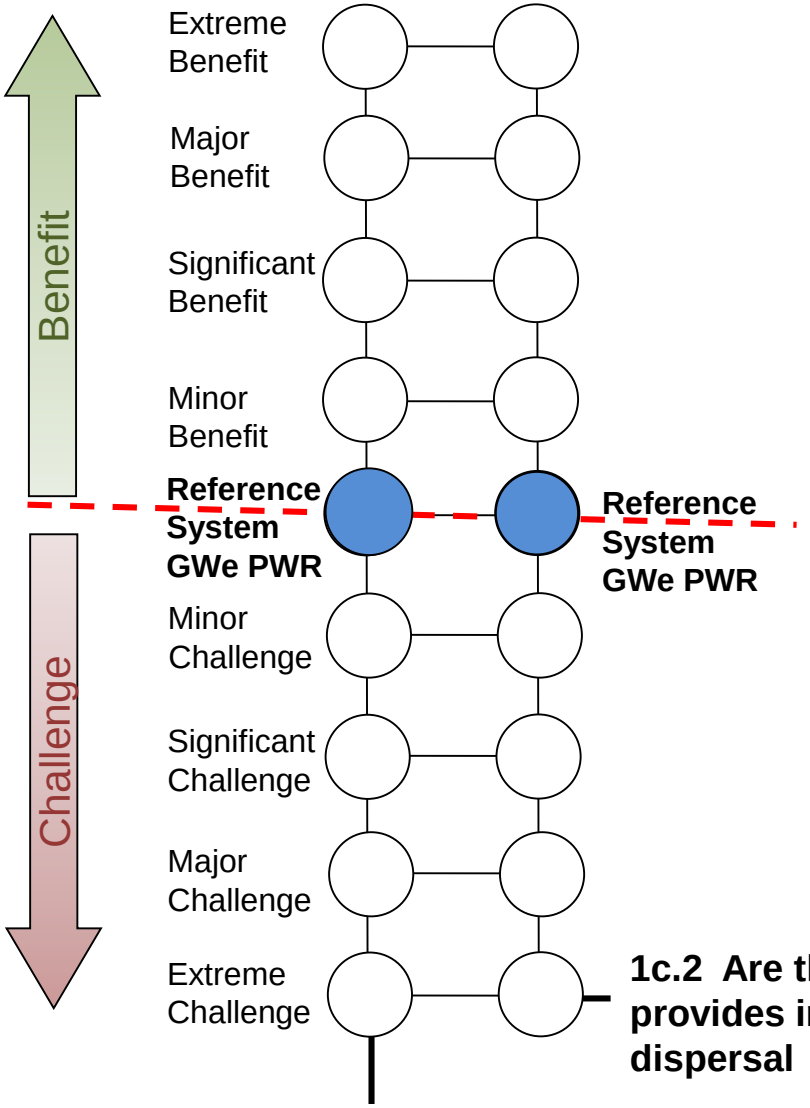
Description

1c. Proliferation Resistance and Physical Protection (PRPP) Acceptability



1c.2 Are the nuclear materials in a form that provides inherent self-protection against theft or dispersal

1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage

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1c. Proliferation Resistance and Physical Protection (PRPP) Acceptability

Any new system deployed in the UK will be required to satisfy the Nuclear Industries Security Regulations 2003. This is a system which responds to the nuclear processes being carried out and the amount and form of nuclear materials being used, and ensures that a system is in place which will "prevent the theft or sabotage of nuclear material or the sabotage of nuclear facilities". The Office of Civil Nuclear Security (OCNS) is the responsible regulator.

UK situation is that, while systems may not accord with the ideals of PRPP, yet there are systems, monitored and enforced by OCNS, which ensure risks of theft or sabotage are maintained at acceptably low levels. Thus while it is highly relevant to monitor the PRPP characteristics of nuclear reactor systems, the value of this Attribute in the UK context is predominantly to be judged by policy makers. The assessment will, however, give an indication of the challenges to be met in order to generate an approved Security Plan for the candidate system.

The top level PRPP criterion can be posed as: *"Are the nuclear materials produced in the fuel cycle difficult to access?"*

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1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage

Essentially same as large scale PWRs, but details will be design specific.

Assessed as 'Reference'

Metrics

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Description

References

1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage

This attribute accounts for the physical forms of fissile materials in the fuel cycle. The levels of challenge will vary between:

Fuel cycles in which high grade fissile materials are present at any stage, for example high enriched uranium (HEU) or plutonium, which will be considered to present considerable PRPP challenges. Examples would include a fuel cycle based on HEU fuel or the separation of pure plutonium for recycle (as in conventional PUREX reprocessing).

A LWR fuel cycle with low enriched uranium (LEU) and a once-through fuel cycle will present a lower level of PRPP challenge.

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1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage - references

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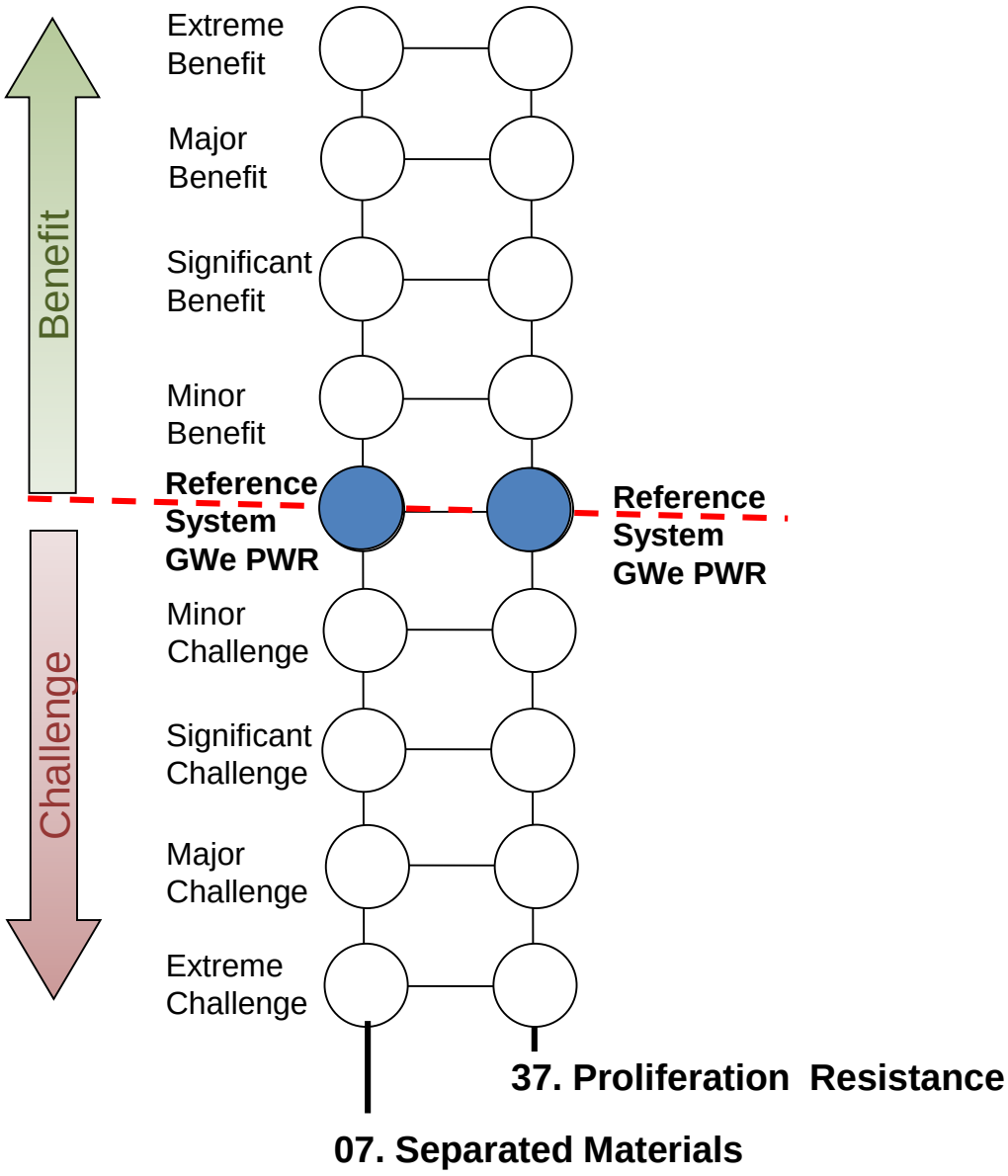
1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage



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07. Separated Materials

Essentially same as large scale PWRs, but details will be design specific.

Assessed as 'Reference'

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Description

References

07. Separated Materials

One of the PRPP goals of advanced systems is that they 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.

07. Separated Materials - references

Insert

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37. Proliferation Resistance

Essentially same as large scale PWRs for batch refuelling. Minor challenge for single-batch refuelling because of reduced self-protection at low burnup and increased fissile quality.

Assessed as 'Reference'

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Description

References

37. Proliferation Resistance

There is increasing interest in international reactor systems development to be able to demonstrate increased proliferation resistance by design, and different reactor systems may be considerably differentiated by inherent proliferation resistance.

37. Proliferation Resistance – references

Insert

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to top

1c.2 Are the nuclear materials in the fuel cycle in a form which provides inherent self-protection against theft or dispersal

Essentially same as large scale PWRs, but details will be design specific.

Assessed as 'Reference'

Metrics

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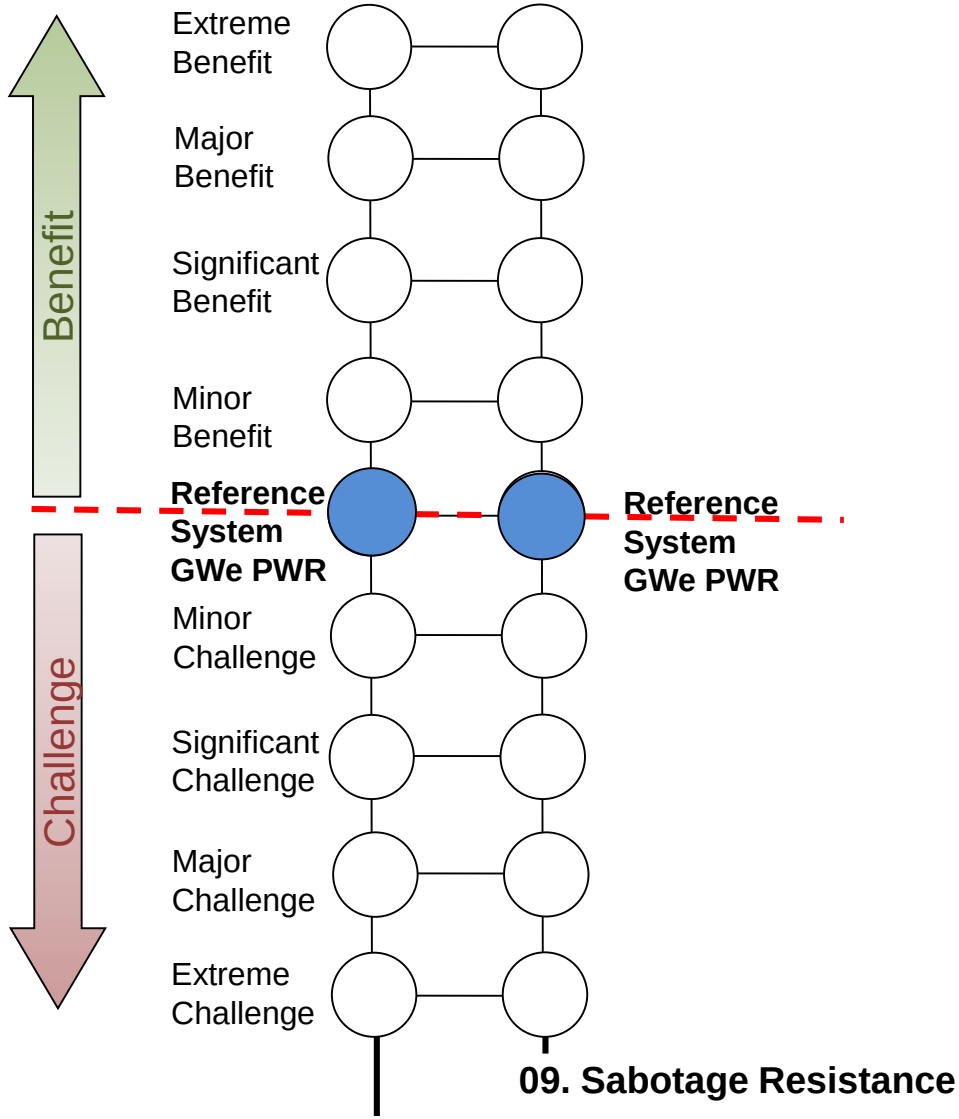
Description

References

1c.2 Are the nuclear materials in the fuel cycle in a form which provides inherent self-protection against theft or dispersal



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Description

1c.2 Are the nuclear materials in the fuel cycle in a form which provides inherent self-protection against theft or dispersal

1c.2 (Inherent PRPP). This attribute tests whether nuclear material is inherently protected by physical or chemical form, or by a strong self-protective radiation field. It is also intended to test whether the material is in a form that could be readily dispersed. Illustrations of levels of challenge are:

- a once-through fuel cycle with uranium oxide fuel in which there are multiple inherent barriers to accessing fissile material.
- fuel cycles which involve the production at some stage of unirradiated HEU fuel or plutonium oxide powder which present no inherent barriers.

Back

1c.2 Are the nuclear materials in the fuel cycle in a form which provides inherent self-protection against theft or dispersal - references

Insert

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08. Spent fuel characteristics

For multiple-batch refuelling essentially same as large scale PWRs, but details will be design specific. Lower burnup and higher spent fuel mass (approx x 2) for single-batch refuelling.

Assessed as 'Reference'

08. Spent fuel characteristics

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.

There is a range of spent fuel characteristics, for example:

High Temperature Reactor (HTR) fuel consists of fissile material encapsulated in small ceramic microspheres and dispersed in a graphite matrix. HTR 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, Molten Salt Reactor (MSR) fuel comprises molten salt where the fissile material is relatively easily separated in an on-line reprocessing plant.

08. Spent fuel characteristics - references

Insert

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09. Sabotage resistance

Essentially same as large scale PWRs. Possible slight benefit from underground siting with respect to aircraft impact or missile attack.

Assessed as 'Reference'

09. Sabotage resistance

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 but in some of the systems, for example small modular PWRs, the nuclear island is largely sited underground and therefore exceptionally well protected.

09. Sabotage resistance - references

Insert

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2a. Economic Competitiveness

Summary

Although SMRs have the theoretical potential to improve economic competitiveness, there are some significant challenges that will need to be addressed. SMRs are likely be penalised by historic scaling laws that favour large plants and will need to rely on new compensating mechanisms, such as cost savings from factory replication, lower risk financing and more favourable grid connection charges.

Assessed as 'Significant Challenge'

Attributes
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Description

2a. Economic Competitiveness

The electrical generation cost is one of the principal criteria against which a nuclear system will be assessed – without a demonstrably economically competitive system, utilities are unlikely to invest.

The top level economics Attribute can be posed as: *Will the reactor system be economically competitive in the electricity generation market or in possible future heat generation markets?*

From this Strategic Attribute, the following Criteria are obtained:

Overnight construction cost. The cost of building and financing the nuclear system, usually expressed as £/MWe.

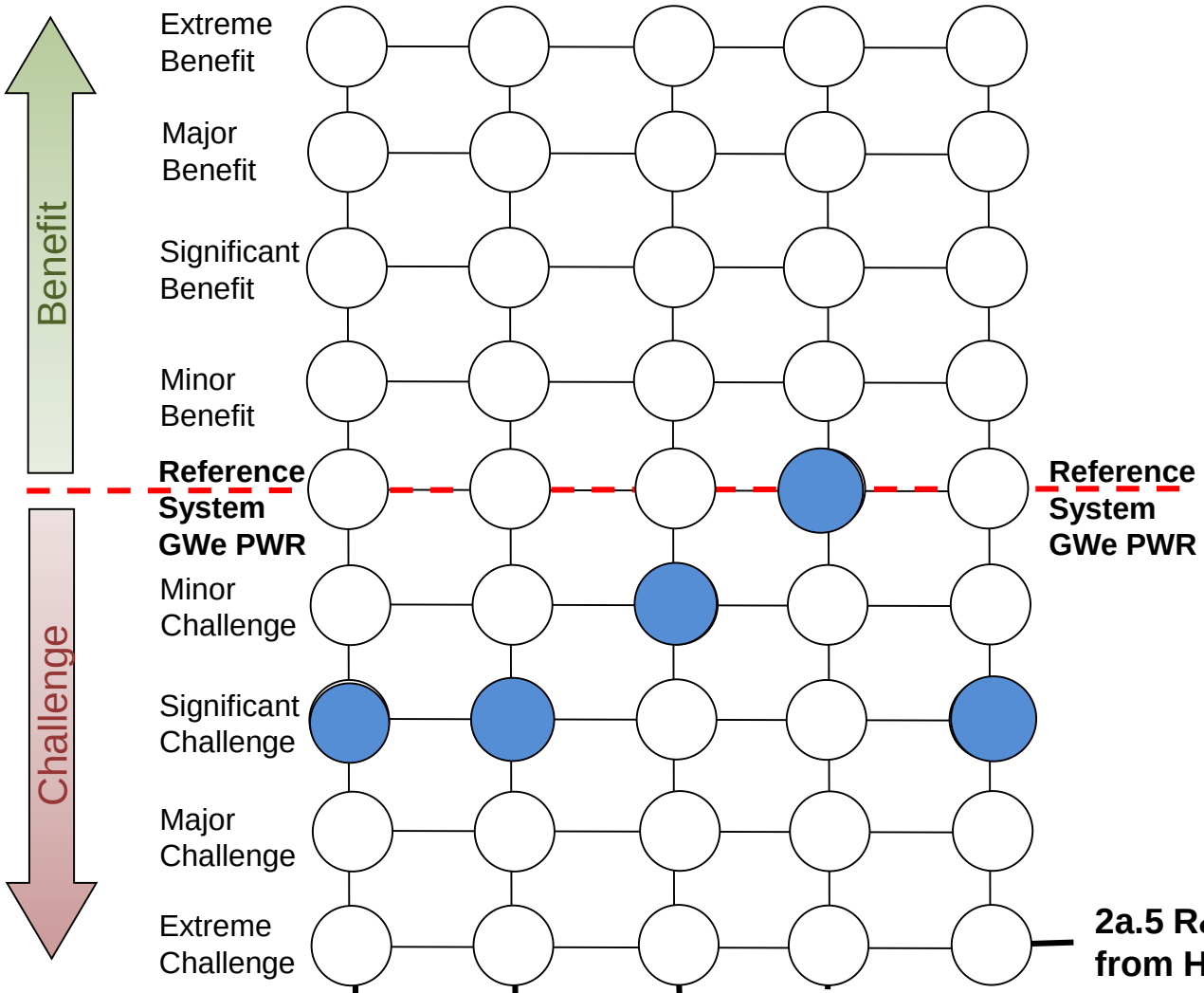
Operating and maintenance cost: This is the cost of operating and maintenance (O&M), taken to include staffing costs, operating costs (excluding fuel), the cost of routine maintenance and other related costs, usually expressed as a levelised cost in £/MWh.

Fuel cycle cost: This criterion is intended to capture the cost of operating the fuel cycle, both procuring new fuel and all the back-end costs associated with spent fuel management or reprocessing/recycle, usually expressed as a levelised cost in £/MWh.

Decommissioning cost: This is the actual cost of decommissioning *without* applying financial discounting, expressed as £/MWe.

R&D cost: This is the cost of the research and development programme needed to bring a system to commercial readiness. This will generally be an infeed into this attribute from High Level Discriminator 1 – Regulatory Challenges and Timescales.

2a. Economic Competitiveness



2a.5 R&D cost – feed from HLD1

2a.4 Decommissioning cost

2a.3 Fuel cycle cost – front and back end combined

2a.2 Operating and Maintenance cost

2a.1 Overnight construction cost

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Return to top

Description

2a1. Overnight construction cost

Economy of scale penalty (for which there is a consensus) with potential for savings from replication, factory build and increased modularisation. Potential for first module to finance later modules but note need for common infrastructure to be in place for the first module. Needs demonstrating with fully costed designs (Class 1 cost estimate)

Assessed as 'Significant Challenge'

Metrics

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Description

References

2a.1 Overnight construction cost

2a.1 (Overnight construction cost). The cost of building and financing the nuclear system, usually expressed as £/MWe. This attribute is the cost of construction and of financing construction, usually taken as the overnight construction cost with all financing costs discounted to the date at which the plant becomes operational. Included in this context, is the construction cost of any fuel cycle plants needed for fuel reprocessing, recycle or waste management. Illustrations of levels of challenge are:

- Plants with a high degree of modularisation and short construction times.
- Plants with a limited degree of modularisation and moderate construction times. This might apply to current large PWRs operating a once-through fuel cycle, for example.
- Complex plants with long and difficult construction demands. This might apply to systems involving extensive reprocessing and recycle.

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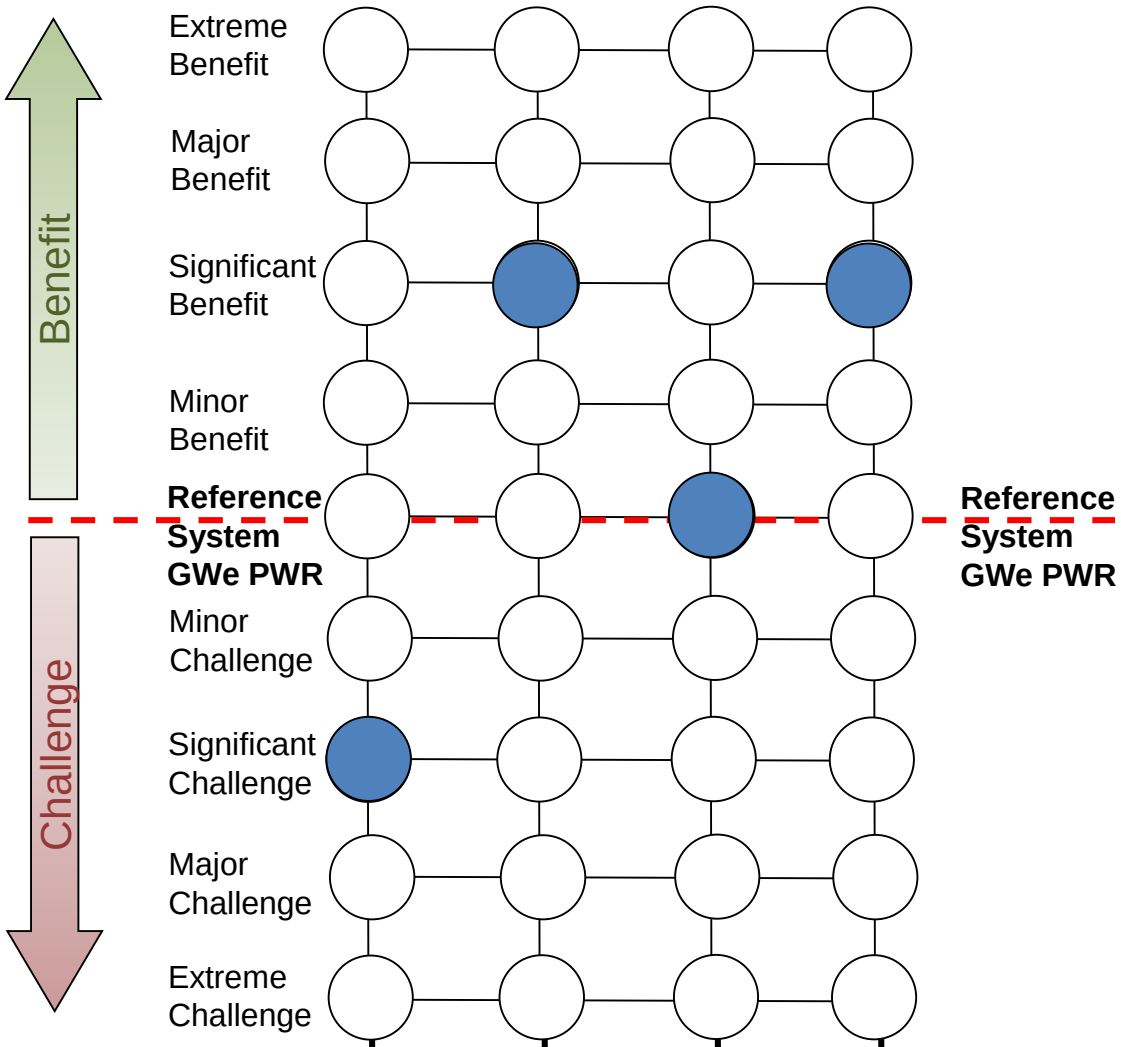
2a.1 Overnight construction cost



34. Ease of Construction

29. Scaleability

24. Construction Duration

22. Overnight construction cost

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Return to top

Description

22. Overnight construction cost

There is a general consensus that small reactors will suffer a penalty on construction costs measured expressed as £/kWe, because of simple scaling considerations. There is no evidence in the literature that this will not be the case. The challenge for SMR vendors will be to demonstrate that there are effective compensating mechanisms, specifically grouping of modules into large power stations, shorter construction times, favourable financing mechanisms and infrastructure savings. Small modular LWRs do not necessarily need to undercut large plants, but the levelised generating cost should not be too far removed.

Assessed as 'Significant Challenge'

22 Overnight construction cost

22 (Overnight construction cost). The cost of building and financing the nuclear system, usually expressed as £/MWe. This attribute is the cost of construction and of financing construction, usually taken as the overnight construction cost with all financing costs discounted to the date at which the plant becomes operational. Included in this context, is the construction cost of any fuel cycle plants needed for fuel reprocessing, recycle or waste management. Illustrations of levels of challenge are:

- Plants with a high degree of modularisation and short construction times.
- Plants with a limited degree of modularisation and moderate construction times. This might apply to current large PWRs operating a once-through fuel cycle, for example.
- Complex plants with long and difficult construction demands. This might apply to systems involving extensive reprocessing and recycle.

Back

22. Overnight construction costs - references

Insert

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24. Construction duration

Short construction times would reduce finance cost and risk with theoretically lower £/kWe. This will need to be demonstrated with fully costed designs (Class 1 cost estimate)

Assessed as 'Significant Benefit'

24. Construction duration

The duration of plant construction has already been discussed under Item 22 (overnight construction cost) and the same assessment applies.

References

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24. Construction duration - references

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29. Scaleability

SMRs would be a better fit to small grid systems, though currently not a powerful consideration in the UK, the transition to ‘smart grids’ may change this.

Assessed as ‘Reference’

29. Scaleability

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.

29. Scaleability - references

Insert

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34. Ease of Construction

Potential to reduce finance costs through shorter duration and lower risk.

Assessed as 'Significant Benefit'

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Description

References

34. Ease of Construction

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.

34. Ease of Construction - references

Insert here

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2a.2 Operating and maintenance cost

Operating and Maintenance costs will be strongly affected by manning levels. For SMRs, at least initially, manning levels are likely to be higher than a GWe reactor on a 'Per MWe installed' basis.

Assessed as 'Significant Challenge'

Metrics

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Description

References

2a.2 Operating and maintenance cost

This Attribute covers the cost of operating and maintenance, taken to include staffing costs, operating costs (excluding fuel), the cost of routine maintenance and other related costs. Illustrations of levels of O&M costs are:

- Plants such as LWRs with long operating lives and no requirement for mid-life refurbishment of major plant items
- Plants with a requirement for through-life replacement of major components
- Complex plants with difficult operational requrements

2a.2 Operating and maintenance cost - references

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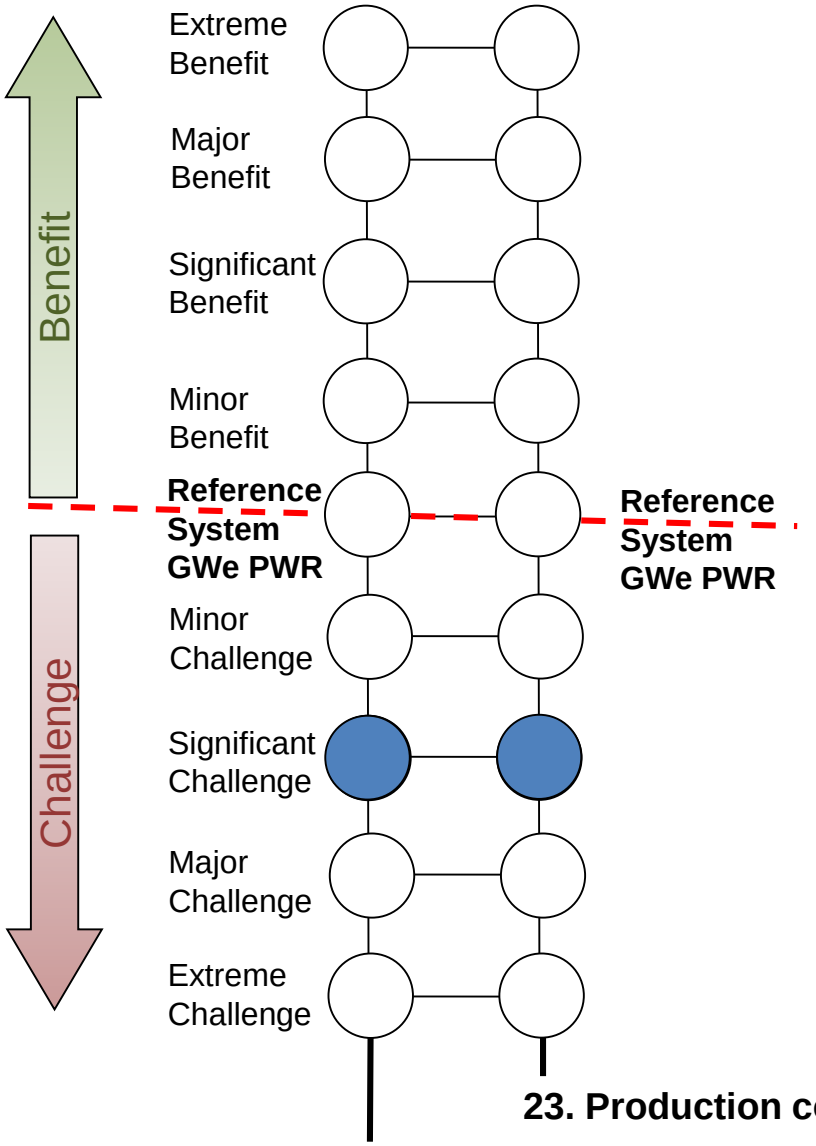
2a.2 Operating and maintenance cost



23. Production costs (O&M)

10. Reliability

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10. Reliability

Outage rates for SMRs would need to be demonstrated to be equivalently low to GWe PWRs if an economic penalty is to be avoided. In the early years of new designs, this might be expected to be a significant challenge.

Assessed as 'Significant Challenge'

10. Reliability

This is the forced outage rate, which should be very low. It is an operational safety and reliability issue, but it is also important for economics. Best operational practice at modern PWRs 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.

10. Reliability - references

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to top

23. Production costs (O&M)

For all nuclear plants the detailed breakdown of operating and maintenance (O&M) costs is regarded by the reactor vendor as commercially sensitive and must be assumed not available for the GFA. The best that GFA can achieve is to identify what the generic challenges are.

There is a general consensus that small reactors will suffer a penalty on O&M costs measured expressed as £/kWe, because of simple scaling considerations. There is no evidence in the literature that this will not be the case. The challenge for SMR vendors will be to demonstrate that there are effective compensating mechanisms, specifically grouping of modules into large power stations (spreads fixed staff costs over larger output), simplifications to equipment and maintenance requirements (minimise use of nuclear safety grade equipment and maximise use of passive equipment).

Small modular PWRs do not necessarily need to undercut large plants, but the levelised generating cost should not be too far removed.

Assessed as 'Significant Challenge'

23. Production costs (O&M)

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.

23. Production costs (O&M) - references

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2a.3 Fuel cycle costs (front and back-end combined)

Fuel cycle costs will show a small penalty for multiple batch schemes with lower specific rating. There would be a major penalty for single batch schemes. This is a direct consequence of the relationship between the equilibrium discharge burnup (Bu_n) in a n-batch fuel management scheme and the infinite batch equilibrium discharge burnup (Bu_∞): $Bu_n = [n/(n+1)]Bu_\infty$. The fuel throughput for a single-batch scheme approaches twice that for a multiple batch scheme at the same initial enrichment, resulting in a fuel cost penalty of about a factor 2. Overall the Attribute is assessed as presenting a Minor Challenge.

Assessed as Minor Challenge

2a.3 Fuel cycle costs (front and back-end combined)

2a.3 (Fuel cycle cost). This attribute is intended to capture the cost of operating the fuel cycle, both procuring new fuel and all the back-end costs associated with spent fuel management or reprocessing/recycle. Illustrations of varying levels of challenge with choice of fuel cycle are:

- the once-through LWR fuel cycle
- the closed LWR fuel, cycle (i.e. thermal recycle)
- a fast reactor system with recycle, especially if there was recycle of minor actinides.

2a.3 Fuel cycle costs (front and back-end combined) - references

Insert

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2a.4 Decommissioning costs

41. Decommissioning costs

Modular construction may lend itself to reduced decommissioning costs per unit, but the number of units will mean that the cost per GWe installed will be more problematic. Very small effect on LCOE because of discounting.

Assessed as 'Minor Benefit'

2a.4 Decommissioning costs

41. Decommissioning costs

2a.4 (Decommissioning cost). This attribute is intended to represent the actual cost of decommissioning without applying financial discounting. The decommissioning cost represents a significant risk element in financial analysis, even though the discounted cost is usually very low. Levels of challenge are illustrated by:

- A nuclear system with small, modular components compatible with disposal as self-contained units.
- Current LWRs where, after defueling, there are only medium active components that need to be decommissioned in the core.
- Systems with graphite moderation, such as the UK's legacy gas cooled reactors, due to the need to deal with large masses of material.

2a.4 Decommissioning costs - references

41. Decommissioning costs

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2a.5 R&D cost

At the current level of development, development costs up to completion of licensing are likely to be very considerable, especially as R&D costs are unlikely to be scaled on MWe output. This is unlikely to present less than a significant challenge.

Assessed as Significant Challenge

Metrics

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Description

References

2a.5 R&D cost

This Attribute covers the cost of the research and development programme needed to bring a system to commercial readiness. Illustrations of levels of R&D cost are:

- Those associated with an existing system or a minor development of an existing system
- Those associated with the evolution of a current system
- Those associated with novel systems involving significant innovations and long and extensive R&D

2a.5 R&D cost - references

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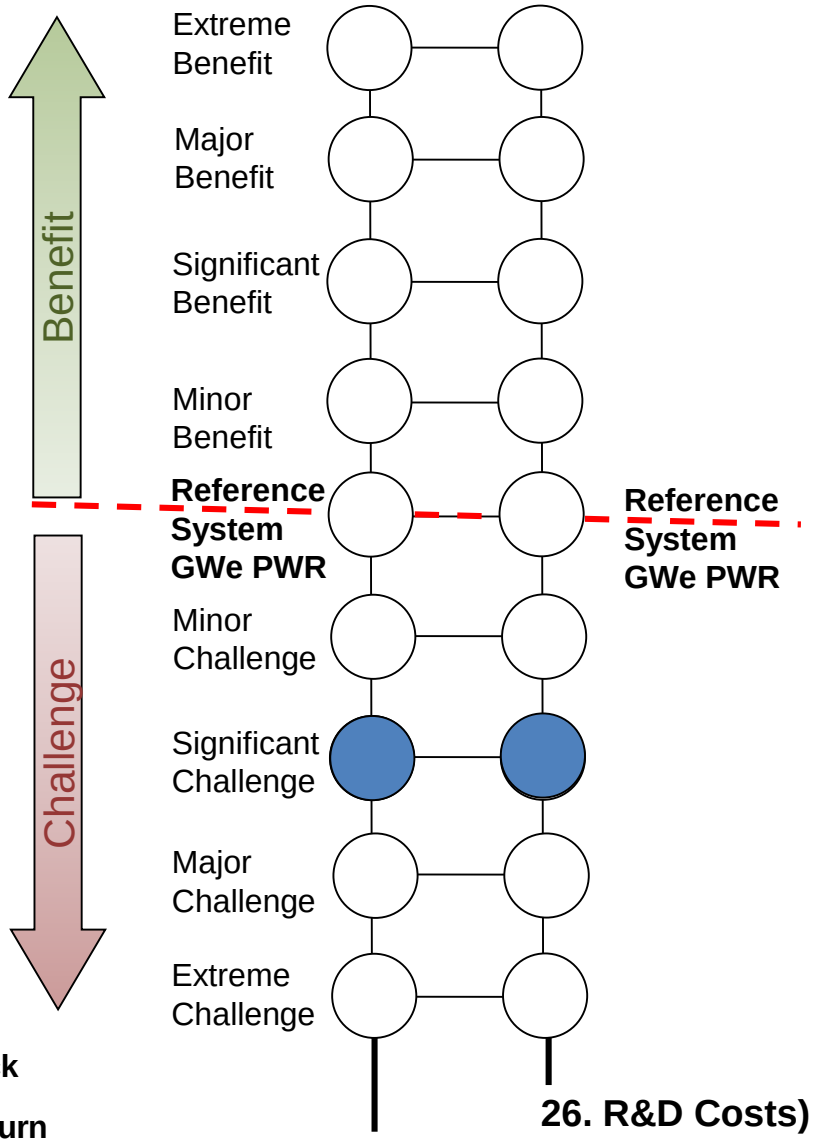
2a.5 R&D cost



26. R&D Costs)

17. Integral experiment scaleability

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17. Integral experiment scaleability

Data from large PWR integral experiments should be scaleable to small PWRs, potentially speeding up R&D timescales. However, some small PWR systems may be novel and require specific experiments (eg IRIS experimental programme). Integral plant layouts represent a significant departure from current PWRs and that fact that the performance of individual components may be supported by existing experience doesn't necessarily carry over to integral system performance.

Assessed as 'Significant Challenge'

17. Integral experiment scaleability

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.

17. Integral experiment scaleability - references

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26. R&D costs

At the current level of development, development costs up to completion of licensing are likely to be very considerable, especially as R&D costs are unlikely to be scaled on MWe output. This is unlikely to present less than a significant challenge.

Assessed as 'Significant Benefit'

26. R&D costs

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. However, if the UK was to buy into technology that was not being developed elsewhere, the UK could incur the R&D costs and risks.

26. R&D costs - references

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3a. Fuel Security

Summary

Essentially same as large scale PWRs for batch refuelling. Significant penalty for single-batch refuelling. A once-through fuel cycle with spent fuel disposed of in the Geological Disposal Facility (GDF) is assumed.

Assessed as 'Minor Challenge'

Attributes

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Description

References

3a. Fuel Security

Summary

This Strategic Attribute assesses whether fissile materials are available to start up a reactor system, and whether the supplies are sufficient and secure enough to fuel the reactor(s) over their projected lifetime

3a. Fuel Security - references

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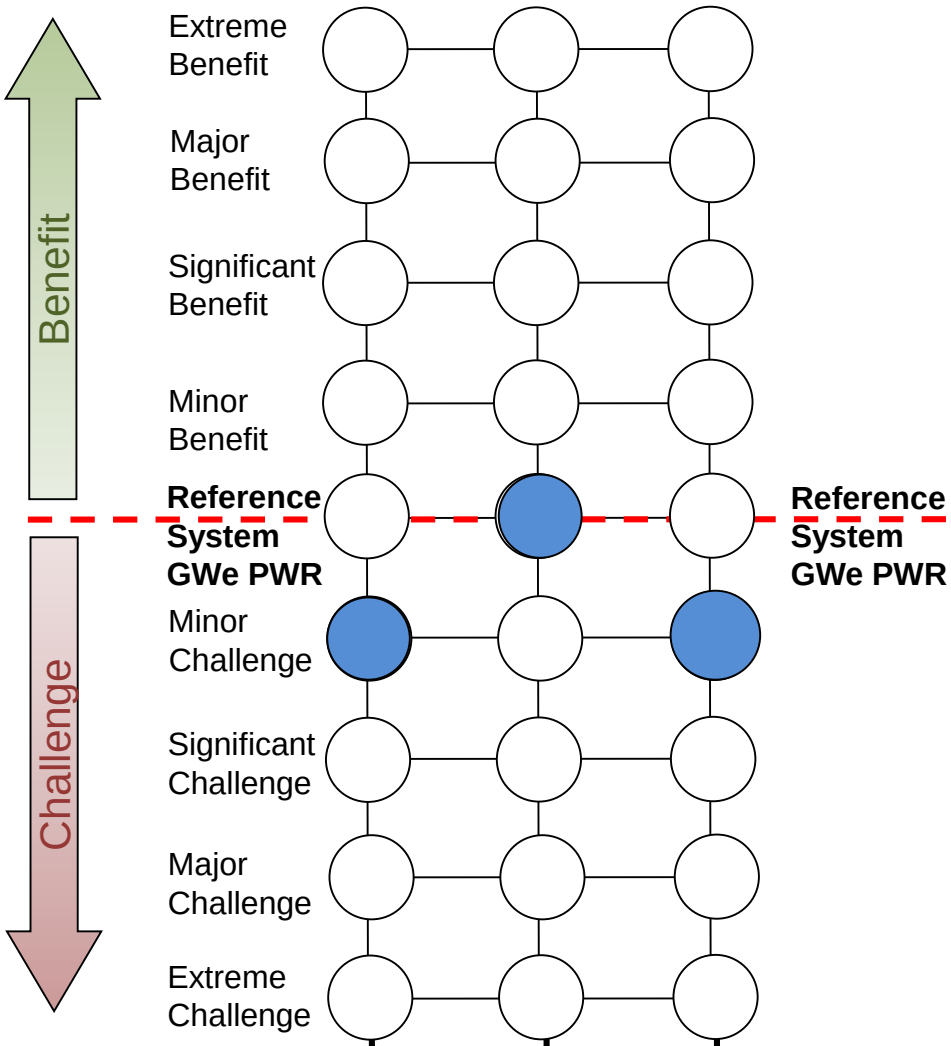
3a. Fuel Security



3a.3 Uranium dependence

3a.2 Spent fuel characteristics – compatible with existing reprocessing technology?

3a.1 Ability to deploy – fissile material availability

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Description

3a.1 Ability to deploy – fissile material availability

Essentially same as large scale PWRs for batch refuelling. Significant penalty for single-batch refuelling.

Assessed as 'Minor Challenge'

3a.1 Ability to deploy – fissile material availability

3a.1 (Fissile material availability) applies specifically to closed fuel cycle systems which may have limitations on the rate at which new reactors could be deployed because of the need to acquire and/or build up the necessary fissile material. The levels of challenge vary between open and closed fuel cycle systems:

OPEN - this designates an open fuel cycle in which reactors are fuelled by LEU, which as natural uranium or LEU is available on the world market. In this instance the deployment rate would not be restricted, provided that world market supplies are sufficient and sufficient reactor build capacity was available.

CLOSED – this designates a closed fuel cycle which will eventually operate virtually independently of uranium availability, but which may be subject to constraints on the initial rate of deployment depending on the availability of fissile material. Limitations to closed cycle deployment can be calculated for any assumed future nuclear generation scenario.

3a.1 Ability to deploy – fissile material availability - references

Insert

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3a.2 Spent fuel characteristics – compatible with existing reprocessing technology?

As the fuel is the same as that for GWe-sized PWRs, it is compatible with existing reprocessing technology

Assessed as 'Reference'

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Description

References

3a.2 Spent fuel characteristics – compatible with existing reprocessing technology?

3a.2 (Spent fuel characteristics).
Spent fuel characteristics: Is the spent fuel of a form that is compatible with established reprocessing methods, or are there features that would preclude its reprocessing using current reprocessing methods? This Attribute tests whether or not the spent fuel form is compatible with established reprocessing technologies and gives a measure of the accessibility of the contained fissile material and hence the ability to affect any closed cycle deployment limitations in 3a.1.

Conventional spent oxide or metallic fuel, irrespective of whether the main fissile material is uranium or plutonium, are compatible with existing reprocessing technologies.

Unconventional fuels, such as fuels based on thorium matrix or coated particle TRISO fuels (used in high temperature gas reactors) are incompatible with established reprocessing methods. Fuel which is not straightforward to reprocess represents an intrinsic barrier to accessing fissile material.

3a.2 Spent fuel characteristics – compatible with existing reprocessing technology?

References

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3a.3 Uranium dependence

Essentially same as large scale PWRs for batch refuelling. Significant penalty for single-batch refuelling.

Assessed as 'Minor Challenge'

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3a.3 Uranium dependence

The uranium usage Attribute poses the questions: "*Will there be sufficient uranium available on the world market to meet the requirements of the reactor system over its operational lifetime?"* and therefore *"Is the system more or less dependent on uranium ore availability/supply on the world market?*"

3a.3 therefore categorises the dependence of the nuclear system on uranium obtained from the world market. Illustrations of levels of uranium usage are:

LWRs have a specific uranium requirement of approximately 200 tU/GWye. CANDU reactors have a lower specific uranium requirement of approximately 160 tU/GWye.

Systems with high conversion ratios or with partial recycle of fissile materials are less dependent on uranium ore, defined as specific uranium requirements in the range 20 to 160 tU/GWye.

The lower range is set arbitrarily to 20 tU/GWye to allow for systems with high conversion ratios that are not quite self-sustained. Systems which have full recycle of fissile materials and operate a breeding cycle totally independent of external uranium supplies.

3a.3 Uranium dependence - References

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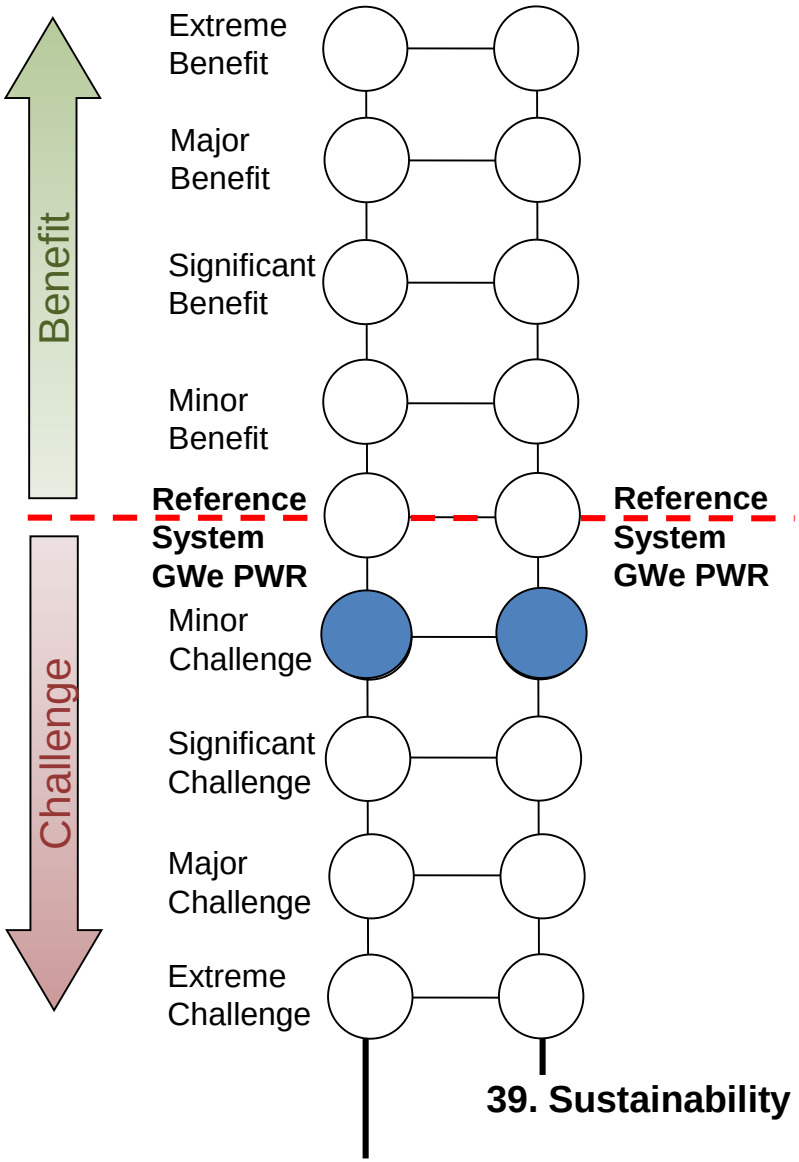
3a.3 Uranium dependence



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Description

01. Fuel utilisation

Essentially same as large scale PWRs for batch refuelling, but a significant penalty for single-batch refuelling.

Assessed as 'Minor Challenge'

01. Fuel utilisation

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 eventually capable of a self-sustaining (breeding) fuel cycle, with a virtually zero natural uranium requirement.

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..

01. Fuel utilisation - references

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39. Sustainability

This 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.

Assessed as 'Minor Challenge'

39. Sustainability

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.

39. Sustainability - references

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3b. Waste storage and disposability

Summary

Largely equivalent to large scale PWR, but with details which are design dependent.

Assessed as 'Reference'

Attributes

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Description

References

3b. Waste storage and disposability

Summary

All nuclear reactors generate nuclear waste that needs to be managed as part of the fuel cycle. The management and disposability of nuclear waste is one of the key long term considerations for the nuclear power industry. The current solution sought for long term disposability is to encapsulate waste into solid forms which are then protectively packaged and placed into a geological disposal facility (GDF). It is therefore required that any spent fuel, high level or intermediate level waste arising must be suitable for encapsulation and safe long term disposal in a GDF.

The waste management Strategic Attribute can be posed as: *Can the waste arisings from reactor systems be managed and eventually disposed of in a safe manner that is compatible with the acceptance criteria for existing or anticipated waste treatment plants and disposal facilities?*

From this top level Strategic Attribute, the following attributes are obtained:

Compatibility of waste forms: The masses and volumes of waste forms for disposal.

Suitability for disposal in GDF: Waste incorporation rate, long term decay heat and radiotoxicity.

3b. Waste storage and disposability - References

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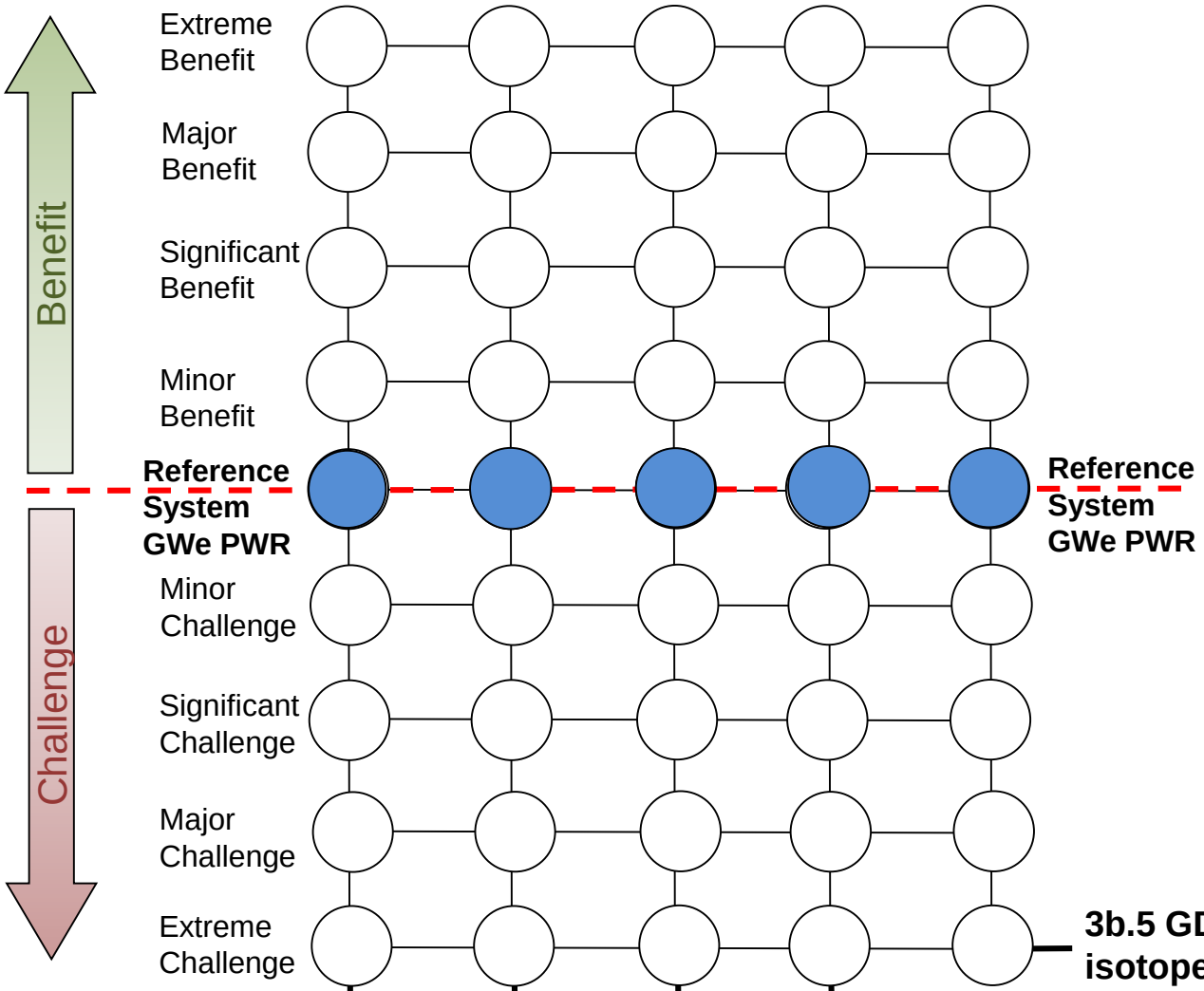
3b. Waste storage and disposability



3b.5 GDF disposal impact – isotopes driving safety case

3b.4 GDF disposal impact – long term radiotoxicity

3b.3 GDF disposal impact – long term decay heat

3b.2 GDF disposal impact – waste incorporation rate

3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology?

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3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology?

SM-PWR fuel is essentially equivalent to conventional – the same basic designs are used for both, with the assembly length shortened. Disposal of complete assemblies may require a modification to disposal canisters to avoid wasting capacity (the disposal canisters as currently envisaged are designed to accommodate four 14 foot assemblies).

If reprocessed, the reprocessing waste arisings are likely to be equivalent, with a slight modification for single-batch cores.

Assessed as 'Reference'

3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology?

3b.1 (Number and type of waste forms). This attribute accounts for the number of different waste forms produced. It is intended to take account of waste forms that are incompatible with existing or expected future waste packaging and disposal facilities. Any incompatible waste forms produced will require the construction and operation of new facilities to deal with them, and this will be noted..

01/39. Essentially same as large scale LWRs for batch refuelling. Significant penalty for single-batch refuelling.

3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology? References

Insert

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3b.2 GDF disposal impact – waste incorporation rate

Largely equivalent to large scale PWRs, but with design specific details. Single- batch cores will have slightly lower long term radiotoxicity, neutron source and decay heat per teHM.

Assessed as 'Reference'

Metric - 33. Waste arisings – volumes of HLW, ILW, LLW

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Description

References

3b.2 GDF disposal impact – waste incorporation rate

3b.2 (Waste Incorporation rate). Waste packages for disposal in the GDF mass may consist of spent fuel assemblies or immobilised high level waste forms (such as glass blocks) depending upon the fuel cycle. For the disposal of spent fuel assemblies, disposal canisters would normally be designed to accommodate uranium fuel assemblies with a relatively low long term decay heat output. Other types of fuel assemblies, for example MOX assemblies, would have a higher long term decay heat output and the disposal canister might be able to accommodate fewer of them, giving a low incorporation rate. Immobilised high level waste from reprocessing of low burnup fuels contains relatively low amounts of transuranics contributing to heat and neutron output and therefore can give a high incorporation rate. High burnup fuels are characterised by high transuranic content, with high heat and neutron outputs that may results in reduced incorporation rates. Illustrations of levels of waste incorporation rate are:

HIGH – Applies to reactor systems producing waste forms with relatively low heat and neutron outputs compatible with current waste forms.

LOW – Applies to reactor systems producing waste forms with relatively high heat and neutron outputs that are incompatible with current waste forms.

3b.2 GDF disposal impact – waste incorporation rate - references

Insert

33. Waste arisings – volumes of HLW, ILW, LLW

Largely equivalent to large scale PWRs, but with design specific details. Single- batch cores will have slightly lower long term radiotoxicity, neutron source and decay heat.

Assessed as 'Reference'

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Description

References

33. Waste arisings – volumes of HLW, ILW, LLW

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.

33. Waste arisings – volumes of HLW, ILW, LLW - references

Insert

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3b.3 GDF disposal impact – long term decay heat

Largely equivalent to large scale PWRs, but with design specific details. Single- batch cores will have slightly lower long term radiotoxicity, neutron source and decay heat. However, decay heat is likely to be similar on a ‘per TWh’ basis

Assessed as ‘Reference’

Metrics

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Description

References

3b.3 GDF disposal impact – long term decay heat

This is a measure of the long term decay heat of spent fuel or high level waste in interim storage pending disposal and in the GDF. Decay heat is important, because it determines how long spent fuel or immobilised high level waste will need to be held in interim storage prior to final disposal. Also, decay heat loading is the principal determinant of repository footprint. Spent uranium fuel or immobilised high level waste derived from uranium fuels sets the baseline for low long term decay heat. Spent fuel containing higher inventories of transuranics (such as MOX fuels) or immobilised high level waste originating from such fuels will have elevated decay heat output. Immobilised high level waste from fast spectrum systems with recycle of transuranics and from thorium systems would be expected to have a low inventory of transuranics and therefore low decay heat.
Illustrations of levels of long term decay heat are:

LOW – Applies to reactor systems producing waste forms with relatively low long term decay heat output consistent with long, but manageable interim storage times.

HIGH – Applies to reactor systems producing waste forms with relatively high long term decay heat output that would lead to unfeasibly long interim storage times.

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3b.3 GDF disposal impact – long term decay heat - references

Insert

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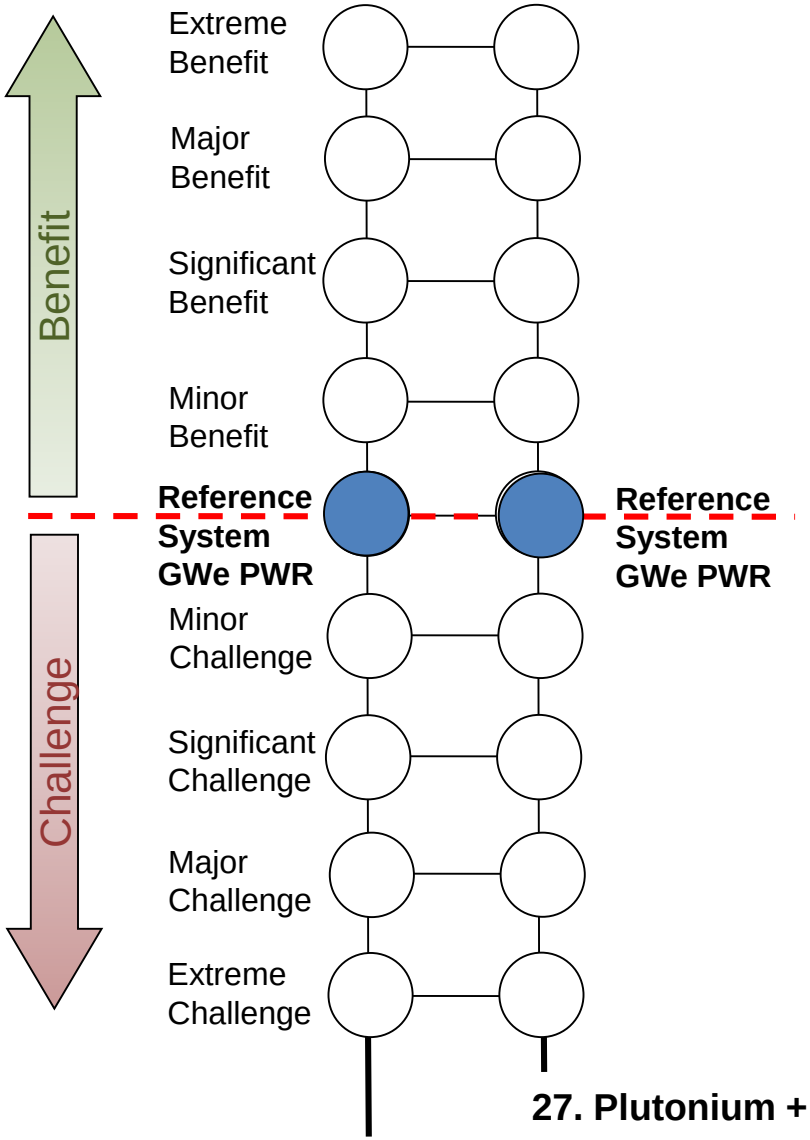
3b.3 GDF disposal impact – long term decay heat



27. Plutonium + minor actinide management

04. Long term heat output

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04. Long term heat output

Largely equivalent to large scale PWRs, but with design specific details. Single- batch cores will have slightly lower long term radiotoxicity, neutron source and decay heat. However, decay heat is likely to be similar on a ‘per TWh’ basis

Assessed as ‘Reference’

04. Long term heat output

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.

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

04. Long term heat output - references

Insert

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27. Plutonium and minor actinide management

Essentially same as large scale PWRs. PWRs have limited ability to transmute Np and Am.

Assessed as 'Reference'

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Description

References

27. Plutonium and minor actinide management

Most systems are capable in principle of recycling plutonium and some would also be capable of destroying minor actinides (principally neptunium and americium). This ability to manage plutonium and minor actinides is assessed in this attribute.

27. Plutonium and minor actinide management - references

Insert

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3b.4 GDF Disposal Impact – Long Term Radiotoxicity

Largely equivalent to large scale PWRs, but with design specific details. Single- batch cores will have slightly lower long term radiotoxicity per teHM, but overall radiotoxicity is likely to be similar on a 'per TWh' basis

Assessed as 'Reference'

Metrics

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Description

References

3b.4 GDF Disposal Impact – Long Term Radiotoxicity

For cooling times up to approximately 500 years, it is the fission products that determine the radiotoxicity of spent fuel or immobilised high level waste and only marginal differences are expected between different systems. Beyond 500 years, where there are transuranics present in the spent fuel or immobilised high level waste, it is these that dominate radiotoxicity for up to 10^5 years. Low radiotoxicity on a timeframe of the order of 500 years is sometimes regarded as a desirable attribute of a fuel cycle because it might be feasible to argue that engineering barriers might retain their effectiveness up to that point. Spent uranium or MOX fuel assemblies and immobilised high level waste from uranium or MOX fuels will have high inventories of transuranics and therefore high long term radiotoxicity. Recycling transuranics in fast reactors can reduce the inventory in repository, possibly leading to low long term radiotoxicity. Fuel cycles based on the Th-232/U-233 fuel cycle have low transuranic inventories which give an intermediate level of radiotoxicity for spent thorium assemblies (in the once-through thorium cycle) and a lower level for immobilised waste from a closed Th-232/U-233 fuel cycle. Examples of the levels of long term radiotoxicity to be expected are:

Uranium or uranium/plutonium fuel assemblies or immobilised high level wastes from thermal reactors such as LWRs generally have a high long term radiotoxicity.

Uranium or uranium/plutonium fuel assemblies or immobilised high level wastes from fast reactors operating a closed, breeding fuel cycle, but without minor actinide recycle generally exhibit a medium long term radiotoxicity. This also covers a high converter Th-232/U-233 fuel cycle and possibly the once-through Th-232/U-233 fuel cycle.

Uranium or uranium/plutonium fuel assemblies or immobilised high level wastes from fast reactors operating a closed, breeding fuel cycle with minor actinide recycle or a closed breeder Th-232/U-233 fuel cycle generally exhibit low long term radiotoxicity.

3b.4 GDF Disposal Impact – Long Term Radiotoxicity - references

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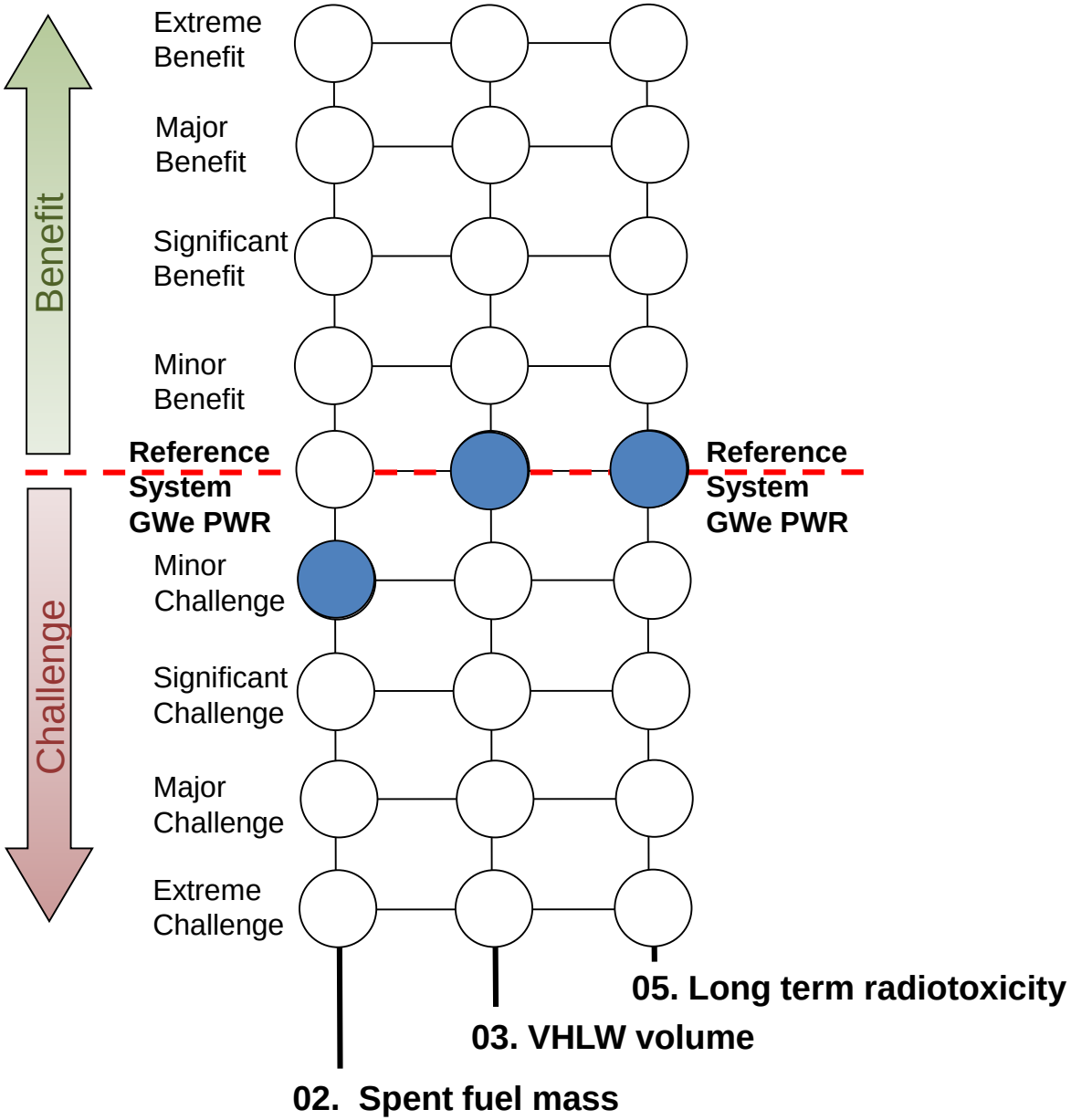
3b.4 GDF disposal impact – long term radiotoxicity



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02. Spent fuel mass

Spent fuel arisings essentially same as large scale LWRs for multiple batch refuelling. Significant penalty for single-batch refuelling, with close to a factor 2 penalty applying (see 2a.3 Fuel Cycle Costs).

Assessed as 'Minor Challenge'

02. Spent fuel mass

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).

For the recycle options the spent fuel arising is important only in that it determines the throughput and capacity of reprocessing plants,

02. Spent fuel mass - references

Insert

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03. VHLW volume

If fuel was reprocessed, VHLW arisings would be essentially same as large scale PWRs for multiple batch refuelling. Possible slight benefit for single-batch refuelling due to lower transuranic content (lower neutron source), which would affect the waste incorporation rate.

Assessed as 'Reference'

03. VHLW volume

This is the volume of high activity (heat generating) waste, expressed in m3 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.

03. VHLW volume - references

Insert

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05. Long term radiotoxicity

Essentially same as large scale PWRs. Minor sensitivity to refuelling scheme (multiple or single batch).

Assessed as 'Reference'

05. Long term radiotoxicity

The radiotoxicity is a measure of the hazard potential of radioactive material. Radiotoxicity can be measured as the potential dose from the waste in Sieverts (Sv) per Gwye, or by Toxic Potential, which measures the dilution required to allow dissolved waste to meet dose standards if used for drinking.

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 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.

05. Long term radiotoxicity - references

Insert

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3b.5 GDF disposal impact – isotopes driving safety case

Essentially equivalent to large PWRs.

Assessed as 'Reference'

3b.5 GDF disposal impact – isotopes driving safety case

As GDF safety cases are generally driven by long-lived mobile fission and activation products rather than by radiotoxicity per se, this attribute assesses any material differences in mobile isotope yields on a per Gwy basis.

3b.5 GDF disposal impact – isotopes driving safety case - references

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3c. Siting

Summary

There is a range of potential SMR siting scenarios from a dispersed network of low capacity (one or a few SMR modules) to GWe-sized groupings. There is a tension between dispersed siting (lower demands on cooling water and grid connections) and economics (with dispersed siting likely to involve more manpower for GWe installed, at least initially).

Both extremes will be assessed for this Attribute, and also for overall economics..

Assessed as 'Significant Benefit' (dispersed network) to 'Reference' (GWe-sized groupings)

Attributes

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Description

References

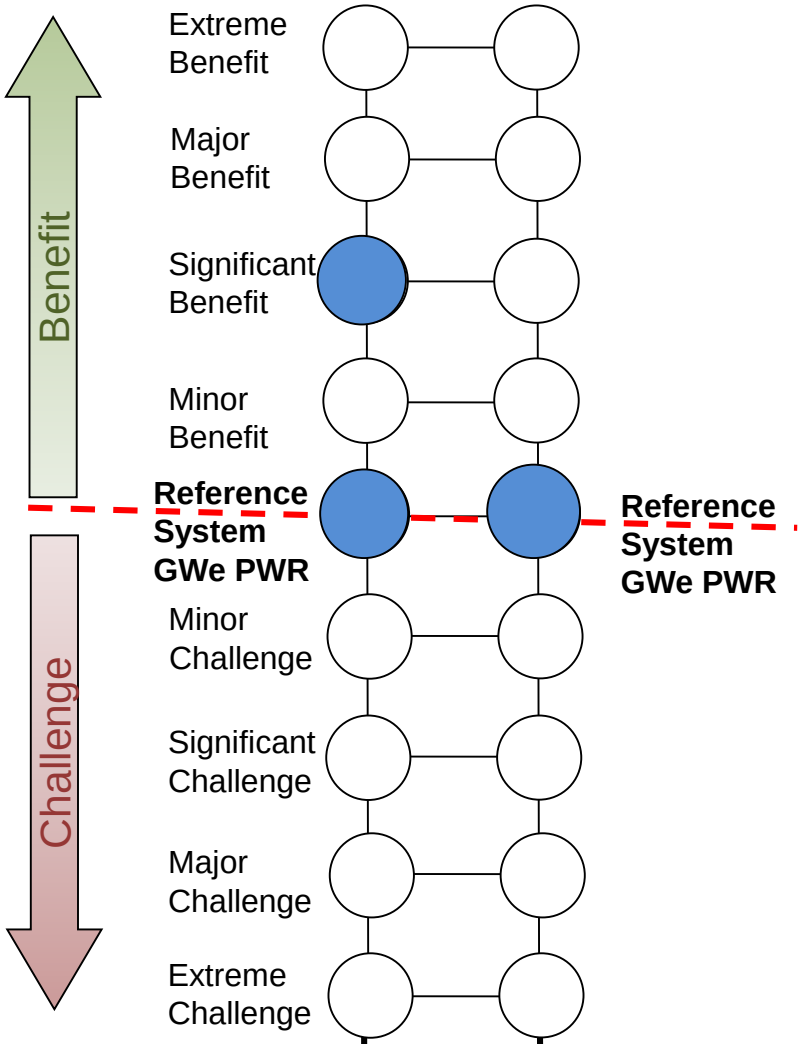
3c. Siting

Reactor systems can be commercially available, competitive, and reliable but all require sites with adequate access to cooling water, power transmission. This Strategic Attribute therefore examines the relative technical suitability of siting reactors and fuel cycle plants across the range of total generation capacity which may be required.

3c Siting - references

Insert

3c. Siting



3c.2 Siting – associated fuel cycle plants

3c.1 Siting - number and size of reactors c/f likely site availability

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Description

3c.1 Siting – number and size of reactors c/f likely site availability

The technical suitability of potential sites will be larger for small capacity installations of SMRs but equivalent to GWe-sized reactors when sited in larger groupings. However, generally lower reactor height will lead to reduced visual impact for SMR designs.

Assessed as 'Significant Benefit' (dispersed siting) to 'Reference' (GWe-sized groupings)

Metrics

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Description

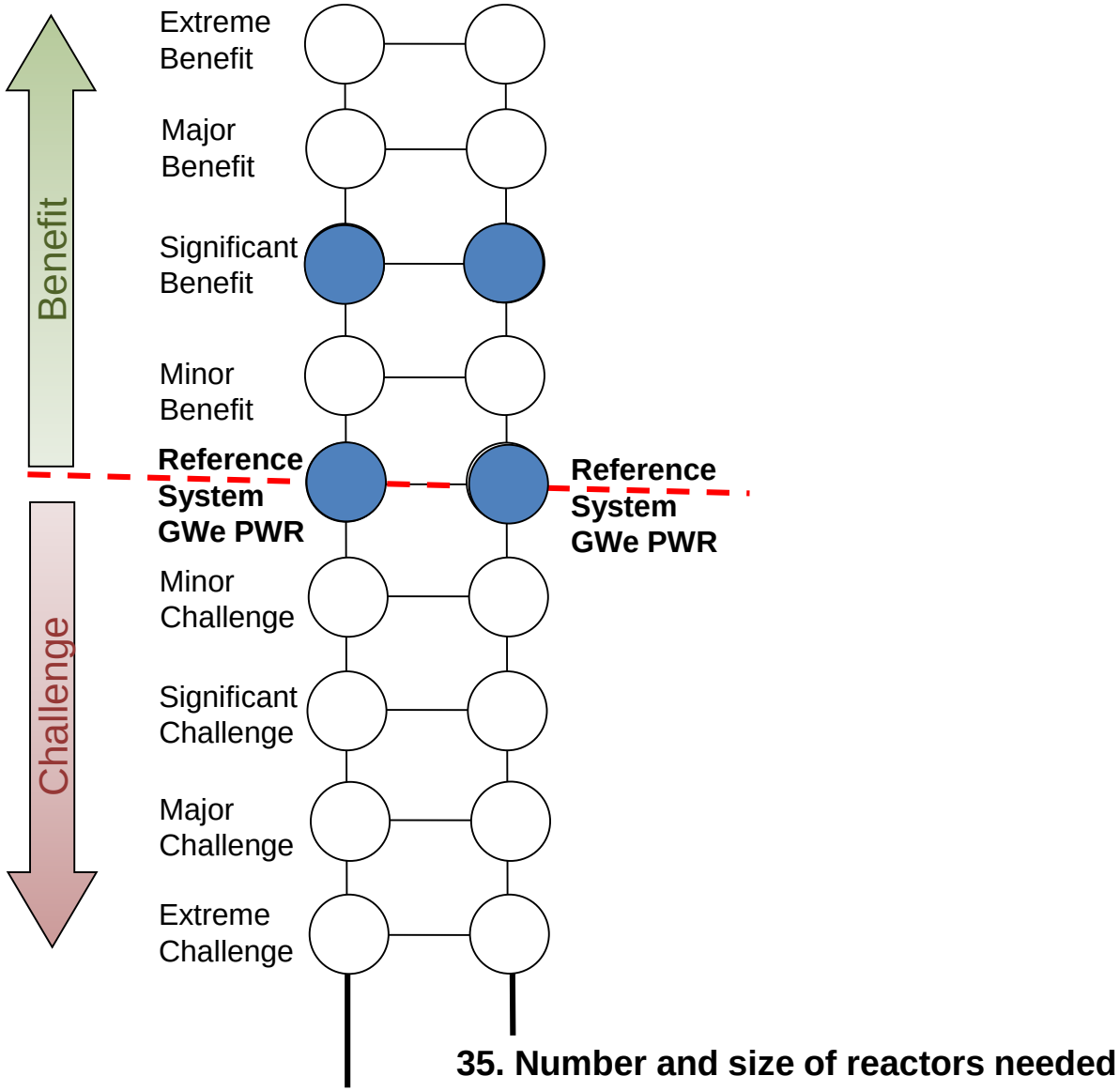
3c.1 Siting – number and size of reactors

3c.1 is intended to measure of how flexible reactor siting would be. It may be possible for small reactors to be sited at locations that would be unsuitable for large reactors on account of reduced land area required and reduced cooling water requirement. It may be possible for a reactor system which, in the event of Design Basis accidents, does not require evacuation outside the site boundary, to be sited more closely to dense concentrations of population.

3c.1 Siting – number and size of reactors - references

Insert

3c.1 Siting - number and size of reactors c/f likely site availability



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32. Flexibility of location

Significant improvement for small power station outputs. Less so for large outputs (>0.5 GWye). Potential benefits for small modular LWRs with respect to cooling water availability, ultimate heat sink (for decay heat), grid connections and avoidance of off-site evacuation zone and transmission infrastructure compatibility.

Small modular LWRs may offer increased scope for development on alternative locations, such as former coal fired power stations or other former industrial sites.

Assessed as 'Significant Benefit' (dispersed siting) to 'Reference' (GWe-sized groupings)

32. Flexibility of location

Reactors will have varying siting demands depending on their output and any dependence of co-siting with, for example, fuel cycle plants. Small reactors will make smaller demands on cooling water and grid connections, but will require more sites to reach the same installed output.

32. Flexibility of location - references

Insert

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35. Number and size of reactors needed

The size of the SMR modules will directly affect the number of reactors per GWe installed.

Assessed as 'Significant Benefit' (dispersed siting) to 'Reference' (GWe-sized groupings)

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Description

References

35. Number and size of reactors needed

The size of individual reactors will directly affect the number of reactors needed per GWe installed. The effects on numbers of sites and on economics are examined elsewhere,

35. Number and size of reactors needed - references

Insert

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3c.2 Siting – associated fuel cycle plants

Essentially same as large scale PWRs.

Assessed as 'Reference'

Metric - 36. Fuel cycle plants

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Description

References

3c.2 Siting – associated fuel cycle plants

3c.2 covers the need of closed reactor systems for reprocessing, waste processing and fuel refabrication plants. Many outline schemes assume co-location of reactor and fuel cycle plants – but, in nuclear scenarios with large contributions from closed systems, this carries the consequence of either (a) very large generation capacity at one site or (b) multiple sites and fuel cycle plants.

3c.2 Siting – associated fuel cycle plants - references

Insert

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36. Fuel cycle plants

Essentially same as large scale PWRs

Assessed as 'Reference'

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Description

References

36. Fuel cycle plants

The fuel cycle plants needed for the various reactor system options are potentially very different.

36. Fuel cycle plants - references

Insert

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4a. Access to international programmes

Strong potential for international collaboration, as demonstrated by the IRIS consortium. UK engagement in small modular PWR design, modelling and testing would be a fertile area for maintaining and developing expertise. It would help provide a positive focus for UK nuclear R&D.

Assessed as 'Significant Benefit'

Metric - 4a.1 Re-engagement in international programmes

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Description

References

4a. Access to international programmes

This Strategic Attribute assesses whether access to (or indeed the formation of) international programmes could aid the eventual deployment of a reactor system. The single Attribute assesses the information on the credibility of the route and on its possible timescale for deployment.

4a. Access to international programmes - references

Insert

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4a.1 Re-engagement in international programmes

Strong potential for international collaboration, as demonstrated by the IRIS consortium. UK engagement in small modular PWR design, modelling and testing would be a fertile area for maintaining and developing expertise. It would help provide a positive focus for UK nuclear R&D.

Assessed as 'Significant Benefit'

4a.1 Re-engagement in international programmes

This Attribute assesses whether access to (or indeed the formation of) international programmes could aid the eventual deployment of a reactor system. The single Attribute assesses the information on the credibility of the route and on its possible timescale for deployment.

4a.1 Re-engagement in international programmes - references

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4b. Time and Cost to Deployment

Summary

The defined Generic SMR (PWR with forced circulation) is judged to be at TRL5 and is estimated to have an estimated 10 year minimum 'time to licensing complete' (2025+) - specifically 5 years to prepare for GDA and 5 years for GDA. Allowing a FOAK build time of 5 years gives an 'earliest on the bars' date from 2030.

This represents a Significant Challenge when compared to the GWE-sized Gen III+ LWR designs currently undergoing (or in the case of EPR having passed) GDA and either building or operational in other parts of the world

Assessed as 'Significant Challenge'

Attributes
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Description
References

4b. Time and Cost to Deployment

This Strategic Attribute takes in information from the assessment of Strategic Attributes 1a, 1b, 1c and from Attribute 4a above, to assess the overall timescale on which the system could be deployed. This will be placed in the context of the relative economics of the system and its match to the market, which are examined under High Level Discriminator 2 – Competitiveness. The Technology Readiness level will be an assessment, with the grounds for that assessment given, while the Deployment Time should be a time in years, with the reasons and uncertainties stated.

In determining the timescale, funding for R&D activities will be assumed to be available as required, and regulatory effort will also be assumed to be available. Funding for reactor build will also be assumed to be available as required. The estimated time to deployment will be the time from the GFA to the time of power production by the first UK reactor

4b. Time and Cost to Deployment - references

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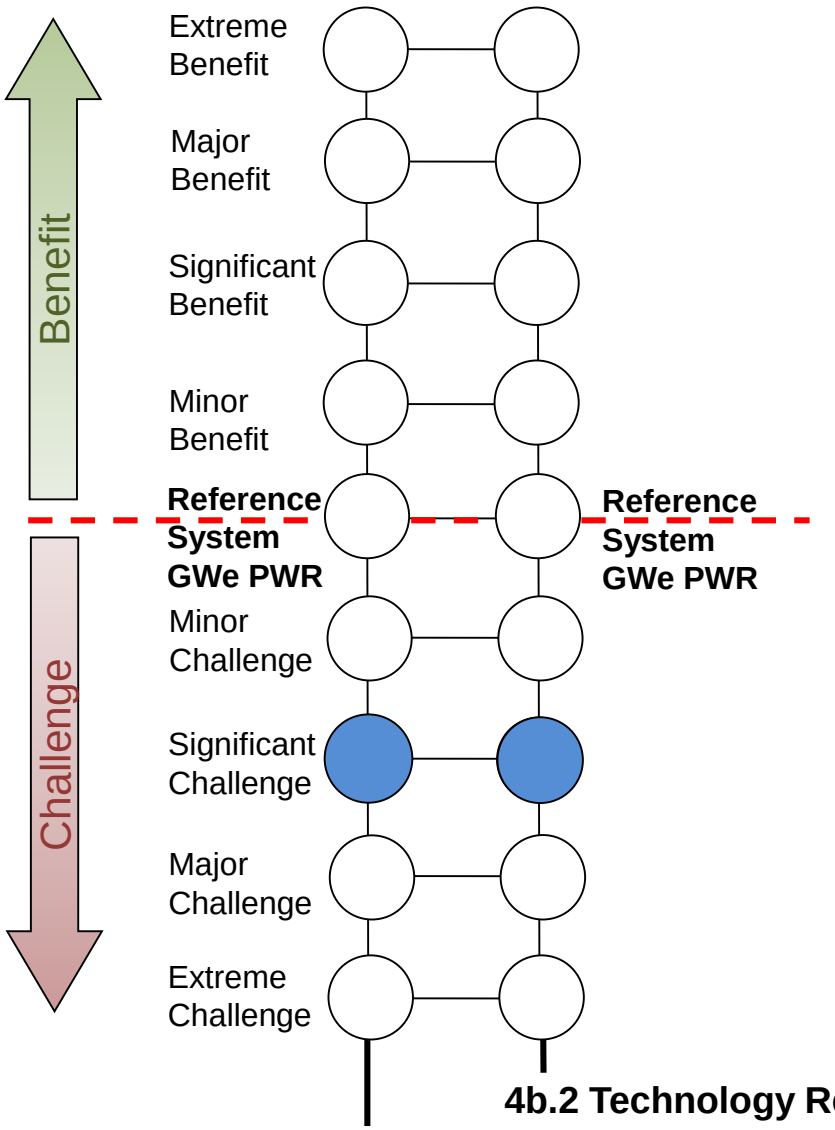
4b. Time and Cost to Deployment



4b.2 Technology Readiness level

4b.1 Commercial availability. Deployment time, plus feed from 1 and 2a

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Description

4b.1 Commercial availability – Deployment Time

Deployment in the UK will involve completing the development and testing of a design to the extent that it can apply for GDA, going through the GDA process, and then building the reactor on a selected UK site. Current designs are judged to be at least five years from being ready for GDA. The GDA process itself has been seen to last around 5 years, so a build time of 5 years after approval would give reactors operational around 2030.

Assessed as 'Significant Challenge'

Metrics

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Description

References

4b.1 Commercial availability – Deployment Time

4b.1 (Deployment time) is the earliest time until the first unit could become operational. It builds on the assessment under in Strategic Attributes 1a, 1b, 1c and 2, and the effect of any international programmes available from 4a.1.

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4b.1 Commercial availability – Deployment Time - references

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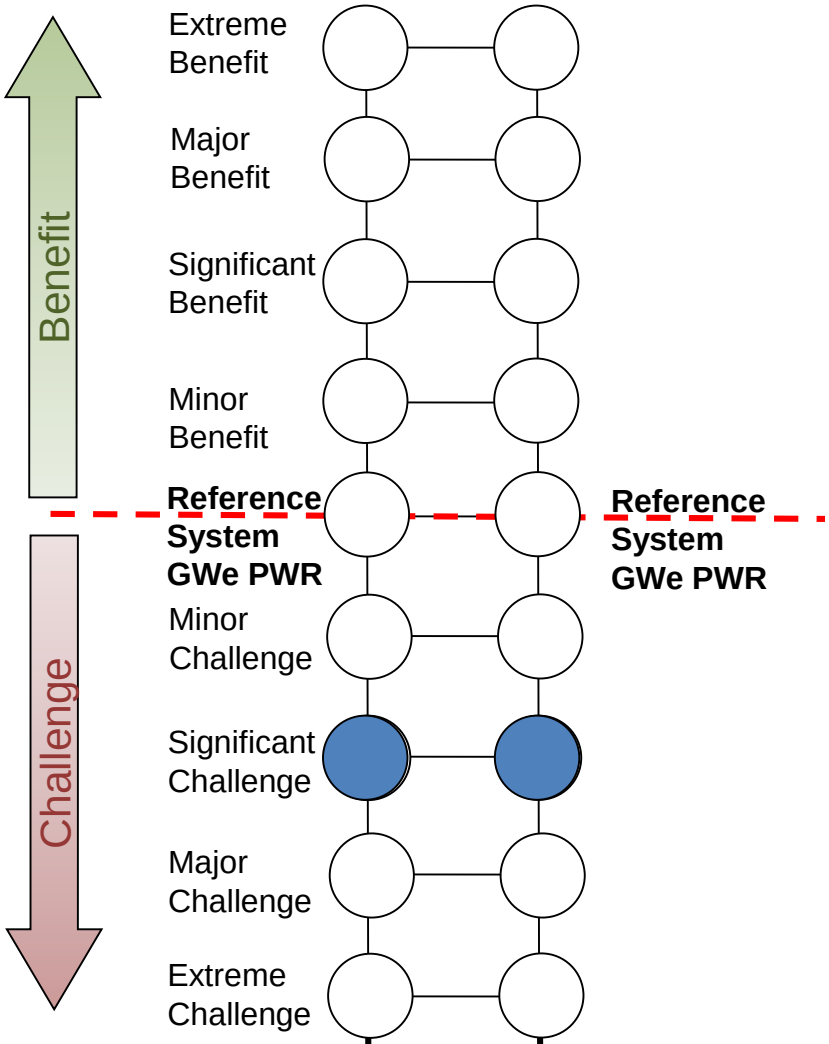
4b.1 Commercial availability



30. Timescales for deployment

25. Development costs

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25. Development costs

Significant and potentially comparable with those of large scale plants. Beyond reach for reactor vendors without help from governments and/or consortia.

Assessed as 'Significant Challenge'

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Description

References

25. Development costs

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.

25. Development costs - references

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30. Timescales to deployment

Estimated minimum 10 years to complete licensing for most mature designs. See 1a.2 Timescale required to demonstrate that SAPs can be satisfied.

Allowing a FOAK build time of 5 years would give a current timescale for a reactor ‘on the bars’ of 2030.

Assessed as ‘Significant Challenge’

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Description

References

30. Timescales to deployment

The timescale at which any new system could be deployed would be of high relevance to strategic planning in the UK.

In determining the timescale, funding for R&D activities will be assumed to be available as required, and regulatory effort will also be assumed to be available. Funding for reactor build will also be assumed to be available as required. The estimated time to deployment will be the time from the GFA to the time of power production by the first UK reactor

30. Timescales to deployment - references

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4b.2 Technology Readiness Level

No SMR designs yet to progress beyond TRL 5 (Demonstration of a basic system). This determines the minimum timescale to deployment. The timescales for progressing from TRL 5 to TRL 9 increase progressively.

Assessed as 'Significant Challenge'

Metric - 31 Technology Readiness Level

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Description

References

4b.2 Technology Readiness Level

4b.1. and 4b.2 combine to give a likely timescale for deployment in the UK. For reactor systems which are already commercially available, this is determined by the lead time for pre-licensing in the UK, the lead time for site approval and the construction time. For systems which are not yet commercially available, an additional lead time would be required for the system to be developed to commercial readiness, with the lead time being longest for systems which are at an early stage of R&D.

This assessment will give an idea of the likely deployment time in the UK. This needs to be compared with the timescales indicated in the Strategic Attributes 1a, 1b and 1c, to come to a consolidated overall view.

4b.2 Technology Readiness Level - references

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31. Technology Readiness Level

No SMR designs yet to progress beyond TRL 7 (the basic system was demonstrated in the Otto-Hahn, a 1968 ship using an integral small PWR). This determines the minimum timescale to deployment. The timescales for progressing from TRL 7 to TRL 9 increase progressively.

Assessed as 'Significant Challenge'

31. Technology Reference Level

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

31. Technology Readiness Level - - references

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4c. Meet and enable UK supply chain

Summary

The Generic SMR presents increased opportunity for UK involvement in the supply chain, but the ability of the UK to realise this potential will be challenging.

The deployment of more mature SMR technology would seem to offer limited potential for UK supply chain involvement, with the UK largely restricted to manufacturing components to a given design/specification.

By contrast, less mature designs may offer increased potential for UK supply chain, with the possibility of UK design expertise being input to develop component designs from the beginning and higher value.

Assessed as 'Significant Benefit'

Attribute - 4c.1 Supply chain opportunities

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Description

References

4c. Meet and enable UK supply chain

Summary

This Strategic Attribute examines the possibility of opportunities for the UK supply chain, providing an additional incentive for UK involvement in any particular reactor system.

4c. Meet and enable UK supply chain - references

Insert here

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4c.2 Supply chain opportunities

The Generic SMR presents increased opportunity for UK involvement in the supply chain, but the ability of the UK to realise this potential will be challenging.

The deployment of more mature SMR technology would seem to offer limited potential for UK supply chain involvement, with the UK largely restricted to manufacturing components to a given design/specification.

By contrast, less mature designs may offer increased potential for UK supply chain, with the possibility of UK design expertise being input to develop component designs from the beginning and higher value.

Assessed as 'Significant Benefit'

4c.2 Supply chain opportunities

This Attribute should attempt to assess the level of UK supply chain involvement that could accompany the development and deployment of a given system

4c.2 Supply chain opportunities - references

Insert

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5a Meets Energy Requirements - load follow capability

SM-PWRs have a number of attributes which are favourable with respect to load following. SM-PWRs generally have low power densities (relative to large PWRs) which is likely to result in less restrictive power manoeuvrability limits in SM-PWRs in comparison with large PWRs. Furthermore, some SM-PWRs operate without soluble boron, which is normally used to aid reactivity control in large PWRs; by operating without soluble boron, limits associated with the rate at which soluble boron can be removed from the coolant are eliminated and improvements in power manoeuvrability can be obtained. Finally, large PWRs can be susceptible to variations in fission product inventories complicating reactivity control; this can result in restrictions during power manoeuvres. For SM-PWRs with sufficiently short fuel rods (<~2.5 m) this problem can be removed.

Nuclear reactors in the UK do not currently load follow. However, nuclear plants that can load follow may become important in future scenarios involving strong nuclear growth, high intermittent renewable generation and/or dispersed nuclear siting. Market mechanisms will be needed accommodate load follow operation, otherwise nuclear utilities will suffer significant loss of revenue. The market mechanisms would recognise that providing a load follow capability helps support the grid system.

Assessed as 'Significant Benefit'

Attribute - 5a.1 Flexibility – load follow capability

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Description

References

5a Meets Energy Requirements - load follow capability

This Strategic Attribute assesses the ability of systems to respond to particular features of a future energy market. For example, if the percentage of nuclear electricity on the grid is high, and coupled with a significant randomly variable output from renewables, then nuclear systems may be required to load follow. Some systems are much more amenable to this than others.

4c.2 Supply chain opportunities - references

Insert

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5a.1 Flexibility – load follow capability

SM-PWRs have a number of attributes which are favourable with respect to load following. SM-PWRs generally have low power densities (relative to large PWRs) which is likely to result in less restrictive power manoeuvrability limits in SM-PWRs in comparison with large PWRs. Furthermore, some SM-PWRs operate without soluble boron, which is normally used to aid reactivity control in large PWRs; by operating without soluble boron, limits associated with the rate at which soluble boron can be removed from the coolant are eliminated and improvements in power manoeuvrability can be obtained. Finally, large PWRs can be susceptible to variations in fission product inventories complicating reactivity control; this can result in restrictions during power manoeuvres. For SM-PWRs with sufficiently short fuel rods (<~2.5 m) this problem can be removed.

Nuclear reactors in the UK do not currently load follow. However, nuclear plants that can load follow may become important in future scenarios involving strong nuclear growth, high intermittent renewable generation and/or dispersed nuclear siting. Market mechanisms will be needed accommodate load follow operation, otherwise nuclear utilities will suffer significant loss of revenue. The market mechanisms would recognise that providing a load follow capability helps support the grid system.

Assessed as 'Significant Benefit'

Metric – 28. Load follow capability

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Description

References

5a.1 Flexibility – load follow capability

5a.1 measures the ability of the reactor system to operate in non-baseload or load-follow mode. This is the ability of the reactor to increase or decrease output either in response to short term grid demands or in pre-planned load scheduling. If the total installed capacity of nuclear stations in the UK is only a small or modest fraction of the grid capacity, there is unlikely to be a major requirement for load-follow capability. However, if the nuclear capacity grows sufficiently, with only limited electricity storage capacity, there may come a point at which load-follow will be required, as is the case currently in France. Many current reactors are able to load-follow, but with limitations. Future reactor systems may be able to operate in load-follow mode without such restrictions, hence their ability to load follow will be compared, both from one system to another, and with the current LWR reference systems.

5a.1 Flexibility – load follow capability - references

Insert

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28. Load follow capability

Potential to improve load-follow response for PWRs without soluble boron control system. Lower specific rating allows more flexibility for reactor trimming with control rod insertion. Potential reduction in grid connection charges for more flexible response capability. Better fit to small grid systems. Not applicable to current UK market, but may become applicable in future scenarios involving strong nuclear growth and/or dispersed nuclear siting

Market mechanisms will be needed accommodate load follow operation, otherwise nuclear utilities will suffer significant loss of revenue. The market mechanisms would recognise that providing a load-follow capability helps support the grid system.

Assessed as 'Significant Benefit'

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Description

References

28. Load follow capability

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.

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28. Load follow capability - references

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Description

5b. Meets energy requirements – Process Heat

The Generic SMR as defined is capable of supplying only low grade heat. This would have limited application when deployed in GWe-sized groupings, but may need to be revisited for district energy supply if dispersed siting is contemplated.

Assessed as 'Reference'

Attribute - 5b.1 Industrial process heat – potential to drive thermal processes

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Description

References

5b. Meets energy requirements – Process Heat

This Strategic Attribute assesses the ability of systems to respond to particular features of a future energy market. For example If sectors such as transport are to be decarbonised, for example by use of hydrogen as an energy vector, then the ability of a reactor system to provide high grade heat (rather than electricity) to power chemical processes could be a significant advantage.

5b. Meets energy requirements – Process Heat - references

Insert

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Description

5b.1 Industrial process heat – potential to drive thermal processes

Not relevant to current UK market, but potential for future market to develop. Not relevant to PWRs, which are unable to provide high temperature heat..

Assessed as 'Reference'

Metrics

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Description

References

5b. 1 Industrial process heat – potential to drive thermal processes

5b.1 indicates whether the system has the potential to drive thermal processes, such as combined heat and power (CHP), hydrogen production, synthetic fuel production and as a heat source for other industrial processes to displace carbon emitting fossil fuel heating. For thermal applications, a high operating temperature is beneficial, which leads to a simple description based on three levels of temperature:

- LOW TEMPERATURE – Low operating temperatures similar to those of current Light Water Reactors (LWRs) ~300-320°C.
- MEDIUM TEMPERATURE – Medium operating temperatures in range 320-600°C beyond the range accessible with LWRs.
- HIGH TEMPERATURE – High operating temperatures >600°C.

5b. 1 Industrial process heat – potential to drive thermal processes - references

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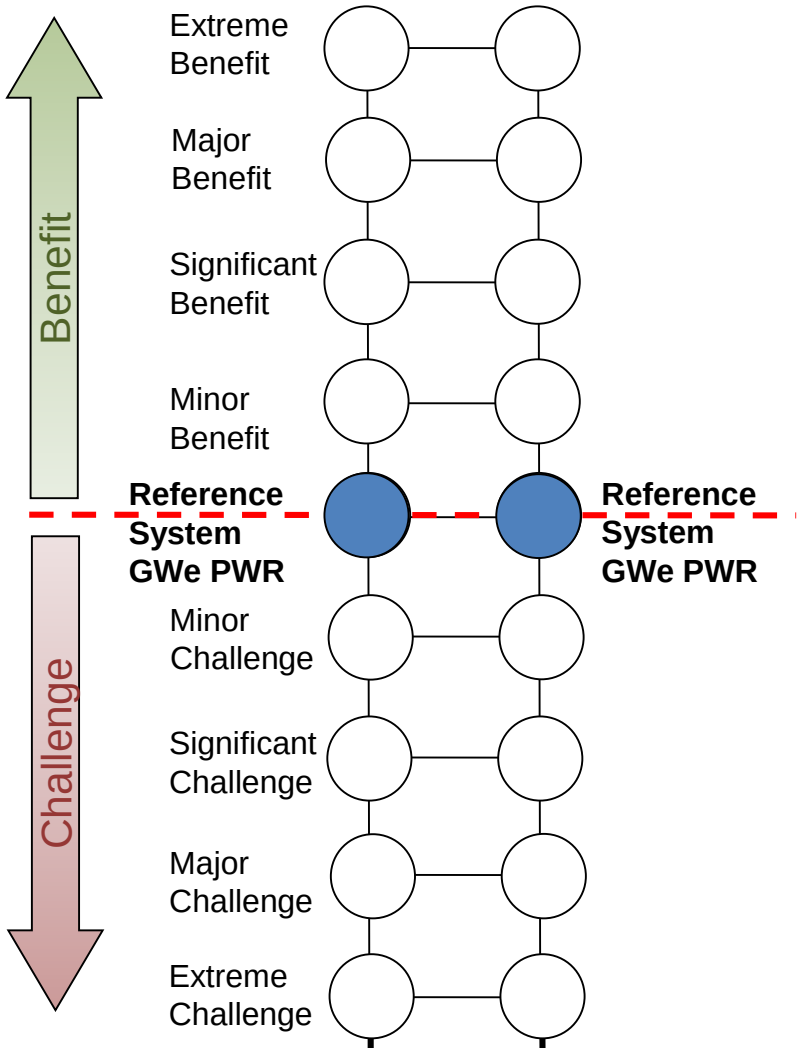
Description

5b.1 Industrial process heat – potential to drive thermal processes



42. Primary purpose

40. Potential to drive thermal processes

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Description

40. Potential to drive thermal processes

Not relevant to current UK market, but potential for future market to develop. Not relevant to PWRs, which are unable to provide high temperature heat.

Assessed as 'Reference'

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Description

References

40. Potential to drive thermal processes

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 systems (eg GFR, MSR and VHTR) have very primary circuit operating temperatures compatible with high temperature process heat applications.

40. Potential to drive thermal processes - references

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42. Primary purpose

Not relevant to current UK market, but potential for future market to develop. Widespread adoption of electric cars may change grid demand.

Assessed as 'Reference'

42. Primary purpose

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.

42. Primary purpose - references

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NATIONAL NUCLEAR LABORATORY

The Generic Feasibility Assessment:
An Essential Ingredient in Nuclear Policy making

Assessment Matrix with Descriptions

Subject System: **SM High Temperature Gas-Cooled Reactor**

Reference System: **Generic SM-PWR**

Template: **14**

Date of Assessment: **15th March 2016.** Modified to generalise references to Regulators. 20th December 2017

Assessment

IDM
integrated decision management

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Dalton Nuclear Institute

Work in Progress

NATIONAL NUCLEAR LABORATORY

Reference and Subject Systems

Reference System:

Small Modular PWR (SM-PWR)

Subject System:

A Generic High Temperature Reactor (HTGR) with a thermal output of around 100 MWth. The TRISO fuel kernel is UO_2 or UCO. Differences between a Generic Pebble-Bed HTGR and a Generic Prismatic HTGR are highlighted. The energy conversion system is a steam (Rankine) cycle.

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Version Development

2015.08.08 Initial GFA of Generic SMR based on 2014 assessment inserted into updated format Template 12

2015.12.08 Aiden Peakman & Kevin Hesketh

2015.12.13 Gregg Butler – spread of Fuel Security assessments OK – prismatic versus pebble bed. 2015.12.23 Order difference corrected around slides 85 – 90 (no problem with navigation)

2016.01.03 Needs estimated on-line date

2016.01.08 Aiden Peakman – Modifications to account for peer review comments and discussions between Aiden Peakman, Kevin Hesketh and Gregg Butler on 2016.01.08

2016.02.08 Minor connection glitches removed – slides 62-82

2016.02.24 Checked/mods accepted for Draft Report

2016.03.15 Update Process heat (slides 249, 252)

2017.12.20 Modified to generalise references to Regulators

References

This Generic Feasibility Assessment draws upon extensive work by NNL on nuclear energy technology assessment, IAEA, OECD/NEA, USDOE and other international literature. Individual references have not been included in the current draft GFA. It is anticipated that as more information becomes available relating to specific Attributes or Metrics, this might either further validate or modify the GFA. This additional information can then be referenced in the appropriate places in the GFA Template.

IDM
integrated decision management

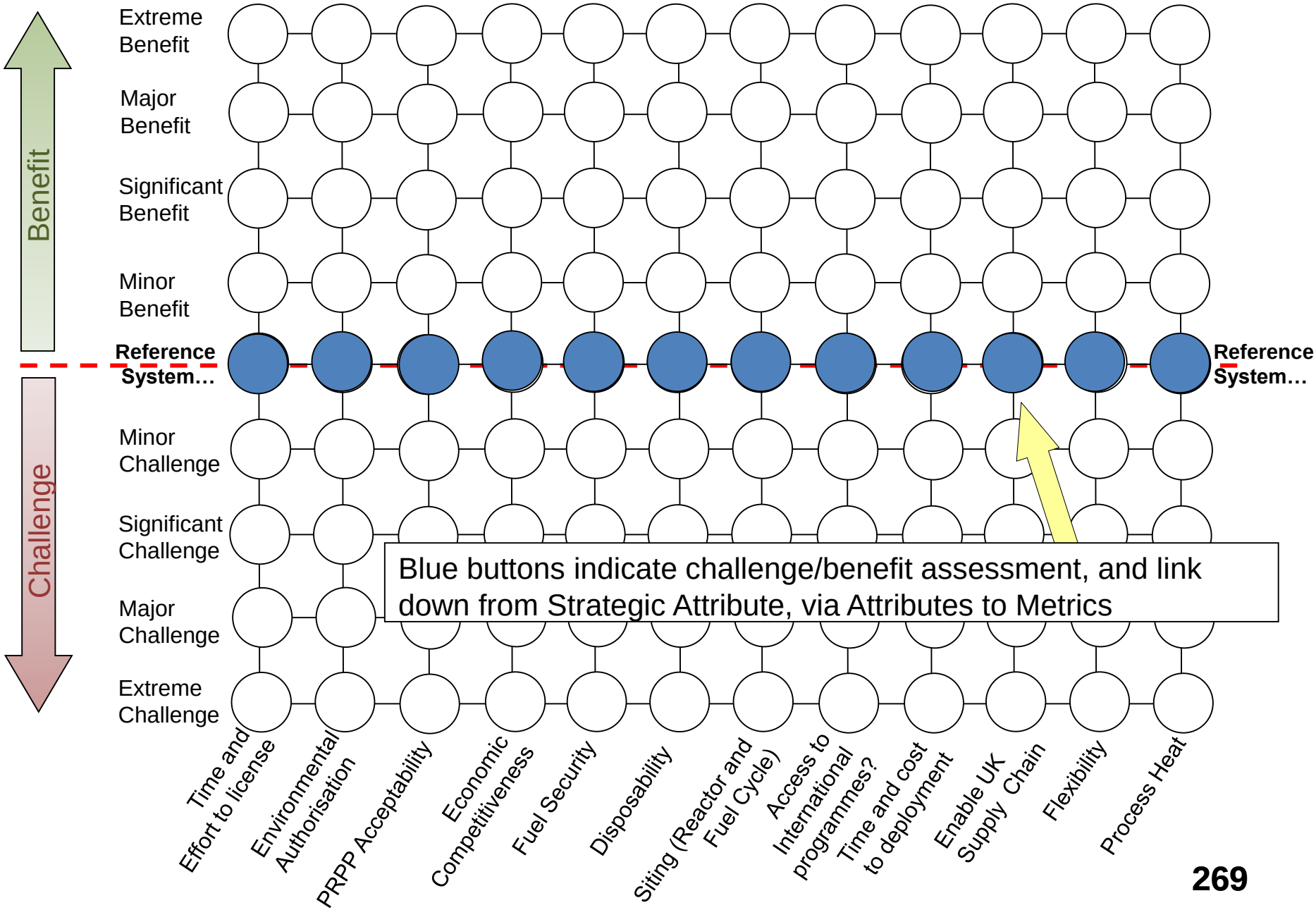
What is Generic Feasibility Assessment?

- GFA was developed for DECC to provide a high level strategic evaluation of nuclear reactor and fuel cycle systems
- It operates by making comparisons between the 'Subject System' and a Reference System, initially 'once-through LWR' as envisaged for new nuclear build in the UK
- The analysis uses 12 Strategic Attributes, using public domain information and informed professional judgement to assess the relative degree of benefit or challenge offered by the Candidate System.

What is Generic Feasibility Assessment?

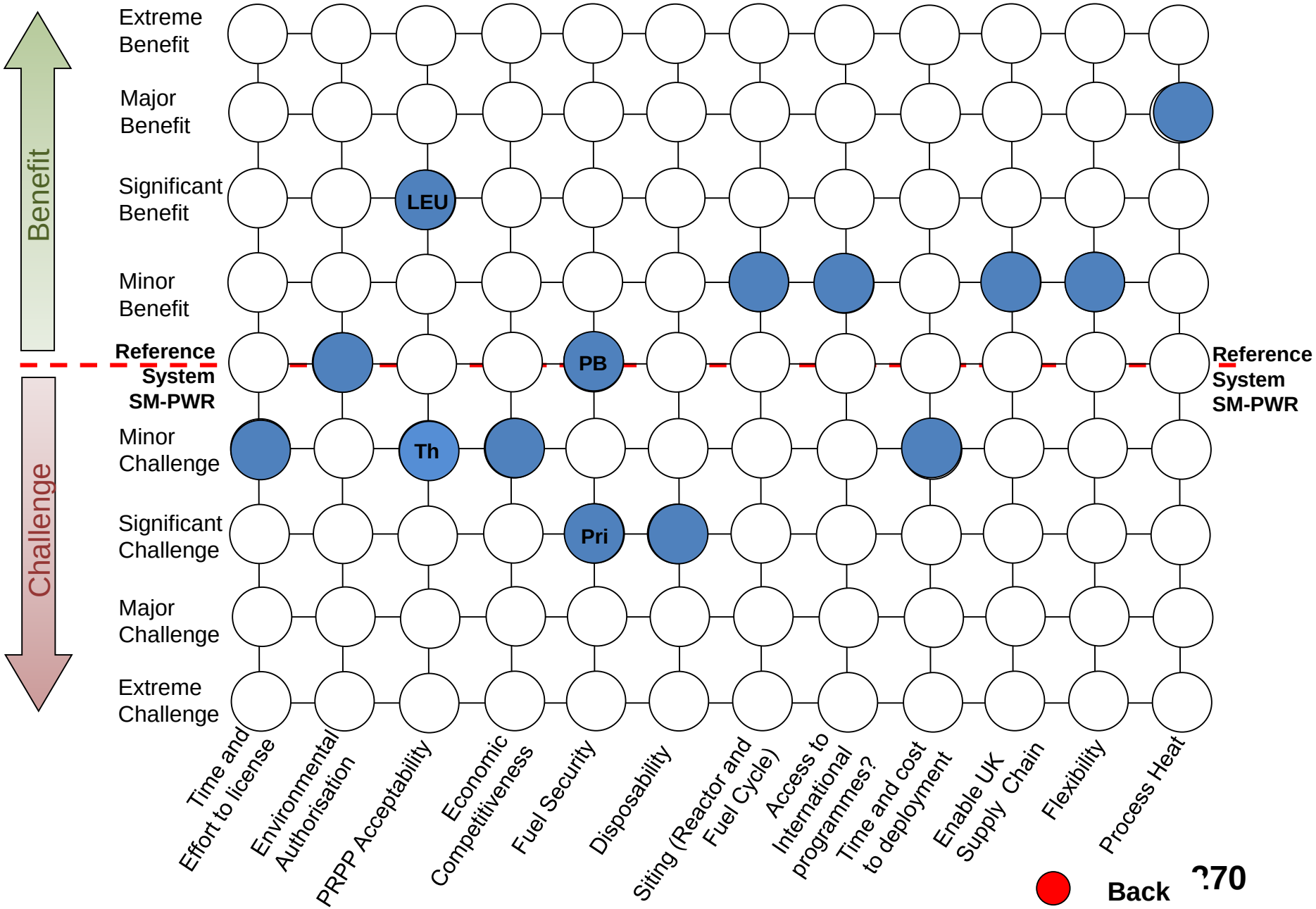
- GFA presents a high level, accessible visual representation of benefits and challenges, while allowing more detailed interrogation of the underpinning rationale and data
- As all information is public domain, any additional evidence can, and will, lead to modification of the assessment: GFA assessments are always 'Work in Progress'
- A full description of how GFA was derived and developed is available at: www.dalton.manchester.ac.uk/gfa
- This Visualisation provides a guide to how GFA is built up, the definitions of Strategic Attributes, Attributes and Metrics, and demonstrates how the information and logic tree can be navigated.

GFA Assessment Subject System: SM-HTGR Reference System: Generic SM-PWR – *Work in Progress*



Blue buttons indicate challenge/benefit assessment, and link down from Strategic Attribute, via Attributes to Metrics

GFA Assessment Subject System: SM-HTGR Reference System: Generic SM-PWR – *Work in Progress*



1a. Time and Effort to License

Summary

The overall assessment is that SM-HTGR will require slightly more effort than the SM-PWR Reference System to progress through licensing due to uncertainties surrounding material performance of the chosen graphite grade, uncertainties in the amount of graphite dust that could be released in a major fault and barriers to obtaining large quantities of TRISO based fuel from a commercial supplier.

Assessed as 'Minor Challenge'

Attributes

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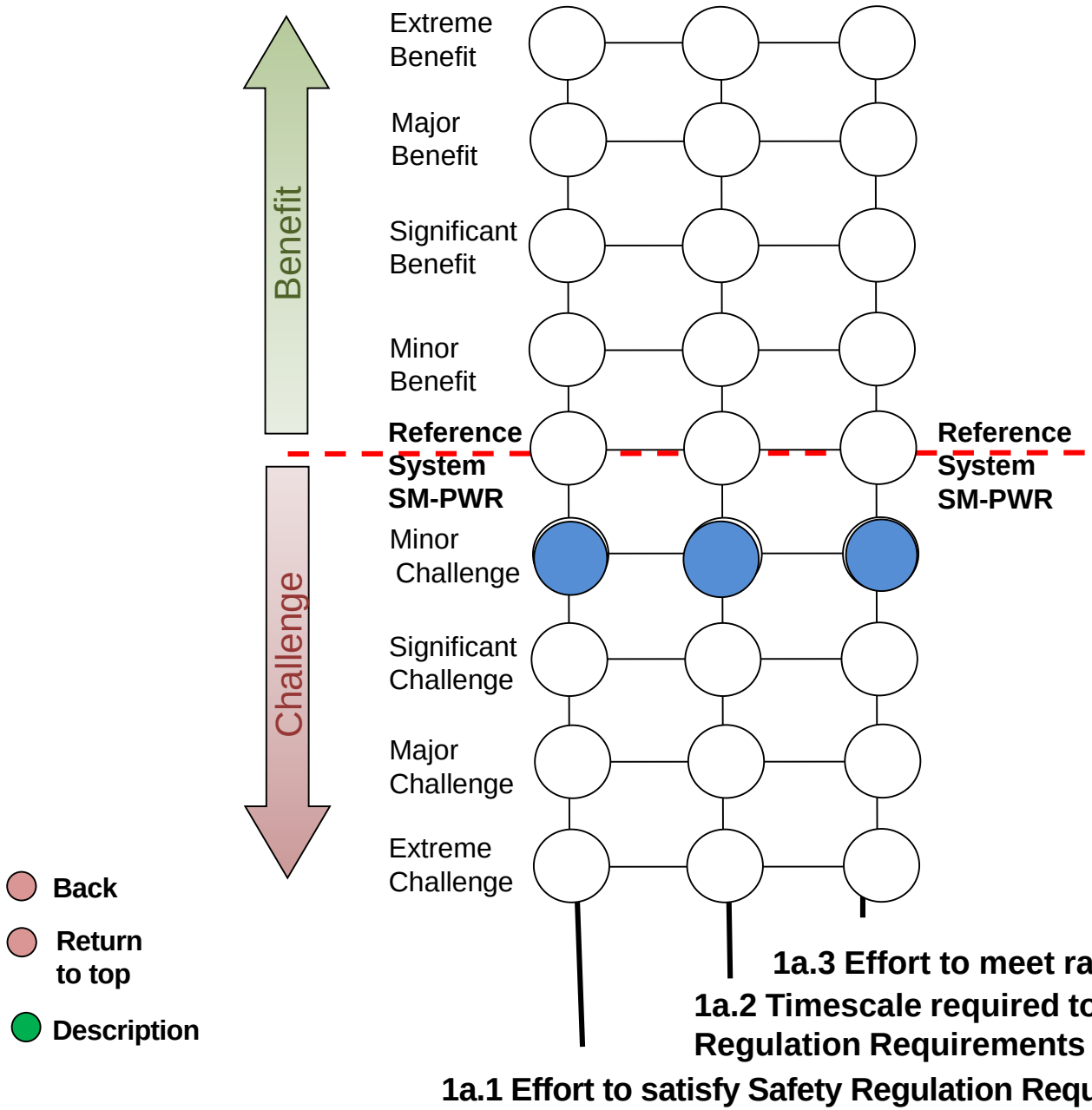
Description

1a. Time and Effort to License



1a. Time and Effort to License

Nuclear facilities in the UK are required to comply with the requirements set down by the appropriate regulatory bodies. Safety and licensing requirements are the responsibility of the Office of Nuclear Regulation (ONR), which also sets the radiological protection requirements for occupational exposure and members of the public.

Any reactor system to be deployed in the UK must be demonstrated to be safe, and to do so the reactor system must adhere to the fundamental safety principles as laid down by the licensing regulator. ONR has defined a series of Safety Assessment Principles known by the acronym 'SAPs'. These SAPs are seen as the top level goals which any system for deployment in the UK must be able to meet. The SAPs framework provides ONR with a set of guidelines by which ONR inspectors can make consistent judgements on nuclear safety assessment.

The top level safety criterion can be posed as: ***How much time and effort will be involved to allow the reactor system to meet the various UK safety regulatory requirements?***

From this top level criterion, the following attributes are obtained:

- ***Nuclear safety and regulation. What challenges must be met to enable the reactor system to meet well developed*** **Safety Regulation Requirements** ***(Button 1a.1)and on what timescale can such compliance be demonstrated? (Button 1a.2)***
- ***Radiological regulation. What challenges must be met to enable the reactor system to comply with the radiological dose limits defined by regulators for workers and members of the public? (Button 1a.3)***

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1a.1 Effort to satisfy Safety Regulation Requirement

Summary

SM-HTGR will face similar licensing issues to SM-PWR, especially if multiple units are deployed in close proximity. There are the added complexities surrounding unfamiliarity of HTGR systems with the regulator and uncertainties surrounding graphite material (particularly graphite in the fixed structures) performance under HTGR conditions, the integrity of the fuel compacts in pebble reactor designs and possibility of water or steam ingress from a steam generator failure. However, SM-HTGRs exhibit some very favourable safety performance characteristics.

Assessed as 'Minor Challenge'

Metrics

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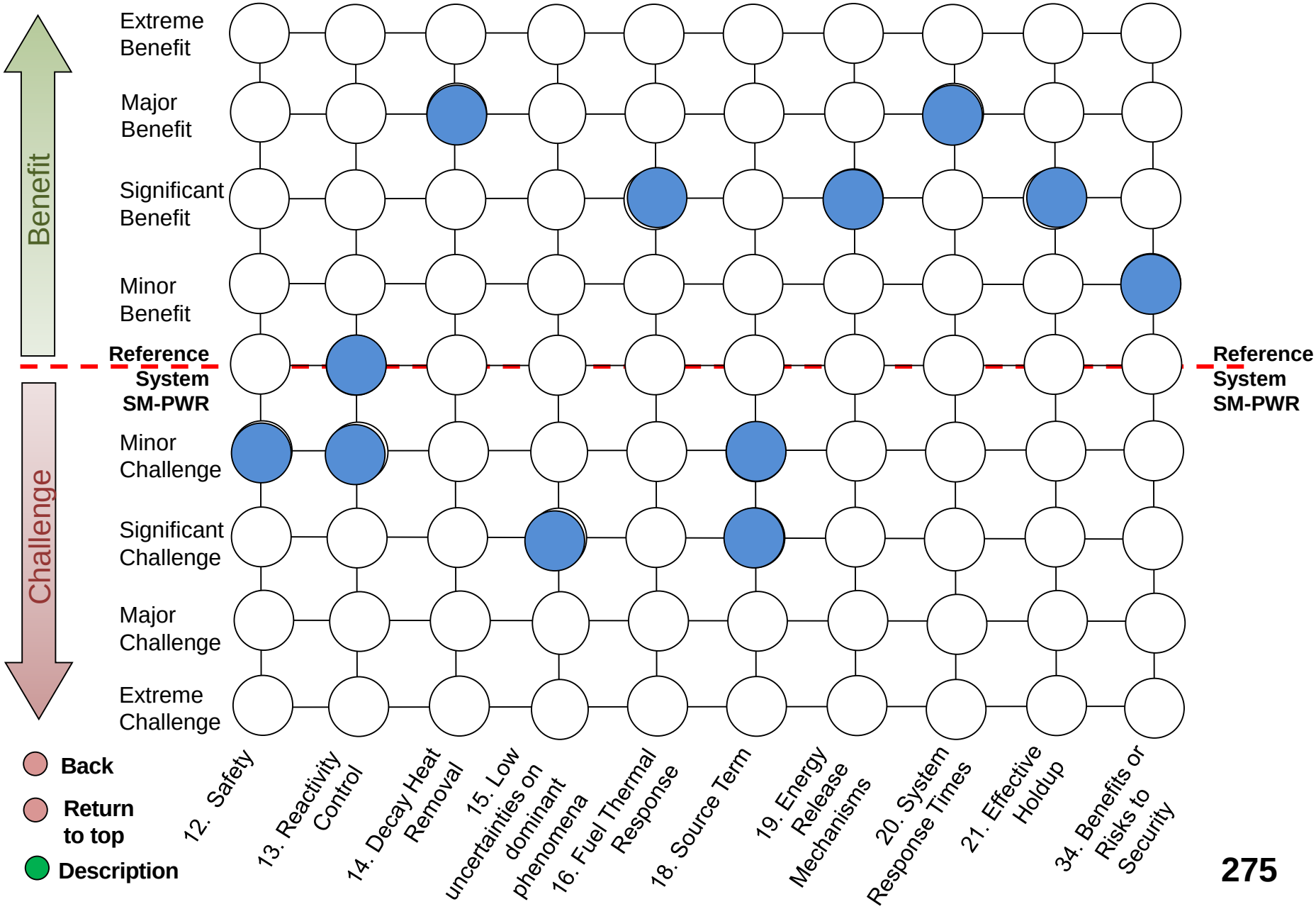
Description

References

1a.1 Effort to satisfy Safety Regulation Requirements



1a.1 Effort to satisfy Safety Regulation Requirements

1a.1 assesses the challenge faced by a reactor system in meeting the goals defined by the Safety Regulation Requirements. Levels of challenge would be expected to increase as the system examined moves further away from current experience, for example:

- Systems which are already deployed commercially or whose designs are already licensed in other countries.
- Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.
- Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.
- Systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

Assessments will assume that regulatory effort is available when and as required

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12. Safety

SM-HTGRs exhibit favourable safety characteristics thanks to the unique properties of TRISO fuel and the low fuel fraction in a large graphite mass. However, there are certain attributes of HTGRs that will likely require significant work such as demonstrating that the graphite grade employed will operate within design limits, the possibility of fuel compact fracture or dust creation (particularly in pebble bed reactors), and the danger of water ingress in a steam generator failure. Furthermore, it must be demonstrated that the probability of a fault leading to large scale graphite oxidation is highly unlikely.

There are also safety issues related to fuel manufacture, with significantly (~10%) enriched fuel. The TRISO particle manufacture uses fluidised bed CVD (Chemical Vapour Deposition) involving the pyrolysis of flammable hydrocarbons (including propane). Suitable safety measures will need to be established to prevent explosions from volatile hydrocarbon-air mixtures

Assessed as 'Minor Challenge'

12. Safety

Any new reactor system deployed in the UK would need to meet very stringent safety standards. Some of the systems considered will rely on passive safety and this might distinguish them from other systems that rely on conventional active safety systems.

12. Safety - references

Insert here

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13. Reactivity Control

Thermal reactors, such as HTGRs, generally exhibit favourable reactivity control properties thanks to relatively slow reactor kinetics and higher rod worths relative to fast spectrum systems. Furthermore, diverse and redundant reactivity control mechanisms are readily achievable through the use of control rods and injecting absorbing materials into the reactor (e.g. boron balls). However, HTGRs typically operate to higher burnups than PWRs and therefore it can become more challenging to compensate for the large excess reactivity at the beginning of life. Excess reactivity control is mainly an issue with prismatic cores as pebble-bed systems utilise online refuelling which minimises excess reactivity throughout core life. Therefore small modular prismatic cores are designated a minor challenge, with small modular pebble-bed systems deemed to have similar reactivity control systems to SM-PWRs.

Assessed as 'Minor Challenge' in prismatic cores and as 'Reference' in pebble-bed cores.

13. Reactivity Control

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. Shutdown means that the reactor must be demonstrated to be sub-critical (k-eff < 0.95), taking account of calculation uncertainties and one stuck control/shutdown rod with the reactor cooled to ambient temperature.

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.

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13. Reactivity Control - references

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14. Decay Heat Removal

SM-HTGRs have some inherent advantages and challenges in decay heat removal. On one hand the lower power density and the large thermal mass, together with essentially zero fission product release until the core temperature exceeds 1600°C, makes the system resilient. On the other hand the low thermal mass of the coolant makes it necessary to be able to cool the core by a combination of conduction and radiation in the case of a depressurisation accident. If the primary circuit is intact convection can be used but it is less effective than in LWRs. These concerns limit the size and shape of HTGR cores, in order to increase the surface area to volume ratio for radial conduction cooling.

Assessed as 'Major Benefit'

14. Decay Heat Removal

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. SM-HTGRs are in principle capable of achieving indefinite decay heat removal even in the event the helium inventory is reduced.

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.

14. Decay Heat Removal - references

Insert

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15. Low uncertainties on dominant phenomena

Many of the technologies behind SM-HTGRs are well demonstrated, but a number of issues were found during operation. The fuel integrity is very dependent on the quality of the fuel manufacture. Both prismatic and pebble bed designs need to account for graphite degradation by oxidation and radiation damage, particularly in the fixed graphite structures. Experience with pebble bed cores have shown some examples of pebbles getting stuck in the core and causing blockages, fractures of pebbles and accumulation of dust from friction between pebbles. There have also been examples of steam generator failure allowing moisture get into the core. Depending on the fuel design there may be reactivity issues if the core were to be flooded. All of these issues and others will need attention in the safety case.

Assessed as 'Significant Challenge'

15. Low uncertainties on dominant phenomena

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 and might be expected to require more protracted R&D including physical model development, validation and verification.

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. .

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15. Low uncertainties on dominant phenomena - references

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16. Fuel Thermal Response

The large thermal inertia of SM-HTGR systems and the use of an all-ceramic fuel results in significant improvements over SM-PWR fuel's thermal response.

Assessed as 'Significant Benefit'

16. Fuel Thermal Response

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.

16. Fuel Thermal Response - references

Insert

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18. Source Term

TRISO particles are known to retain hazardous fission products up to very high temperatures for sustained periods of time. However, release of fission products from TRISO particles can occur from particles with defects (i.e. poor quality manufacture), fracture of particles as a result of fracture of a fuel compact, migration of the fuel kernel thought the particle walls in a temperature gradient (amoeba effect), prolonged oxidation of fuel compacts by contact with air or steam at high temperatures or temperatures over 1600°C.

Activated graphite dust represents a C-14 hazard in the event sufficient quantities are ejected from the core. Graphite dust production is expected to be more pronounced in pebble-bed systems.
Factoring in the excellent fission product retention capabilities of TRISO fuel, provided manufacturing quality is high and accidents are within the design basis, it is judged that SM-HTGR source term characteristics represent minor and significant challenges for prismatic and pebble-bed cores respectively.

Assessed as 'Minor Challenge' for prismatic cores and 'Significant Challenge' for pebble-bed cores

18. Source Term

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.

18. Source Term - references

Insert

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19. Energy Release Mechanisms

SM-HTGRs exhibit improved Energy Release Mechanism (ERM) performance relative to SM-PWRs as SM-HTGRs are designed to operate at high temperatures without exothermic reactions. However, sustained graphite oxidation, whilst likely very difficult to achieve, is an exothermic ERM that is of concern, i.e. air or steam ingress into a hot core.

Assessed as 'Significant Benefit'

19. Energy Release Mechanisms

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.

19. Energy Release Mechanisms - references

Insert

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20. System response times

The large thermal inertia of SM-HTGR systems and the use of an all-ceramic fuel capable of operating at very high temperatures for prolonged periods of time results in major improvements over SM-PWR systems' response times. Well designed SM-HTGRs are capable of achieving indefinite decay heat removal under a variety of accident scenarios.

Assessed as 'Major Benefit'

20. System response times

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.

20. System response times - references

Insert

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21. Effective Holdup

SM-HTGR fuel, at burnups up to ~ 100 GWd/tHM, has been repeatedly demonstrated to retain hazardous fission products even at very high temperatures for sustained time periods, except where the fuel fabrication quality is poor. However, activated graphite dust may be released in the event the primary circuit is breached, which presents a C-14 hazard.

Assessed as 'Significant Benefit'

21. Effective Holdup

Effective hold-up refers to mechanisms in the design of a plant for containing radioactive material following an accident condition. The hold-up of volatile fission product will impact the containment design will affect whether there is a requirement for off-site evacuation procedures to be in place.

21. Effective Holdup - references

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34. Benefits or challenges for security

The once-through cycle in PWRs exhibits favourable security characteristics as the inventory of spent fuel is relatively easy to track, no separated weapons usable materials are produced and the high radioactivity of spent fuel is a further barrier in itself. SM-HTGRs further improve on these favourable characteristics by utilising a highly robust and dilute fuel form. Pebble-bed systems exhibit some unfavourable security properties as the large inventory of spherical elements is inherently difficult to track. However, the mass of uranium in each pebble is very low (~6 g) and the difficulty in extracting uranium makes the impact of obtaining pebbles by sub-national groups of limited concern.

Assessed as 'Minor Benefit'

34. Benefits or challenges for security

Inherent Proliferation Resistance and Proliferation Protection PRPP is an area which needs to be assessed for new reactor systems according with best practice set out by IAEA INPRO and GIF. The threats considered are diversion of fissile material by a state and acquisition of radioactive materials by an illegal sub-national group. Both threats are considered by OCNS as part of defining the security and safeguards requirements and these requirements are not affected in inherent PRPP. Inherent PRPP is simply to be regarded as a fall-back protective feature that would apply in the hypothetical case of a nuclear system falling outside national controls.

34. Benefits or challenges for security - references

Insert

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1a.2 Timescale required to demonstrate that Safety Regulation Requirements can be satisfied

In the UK the Generic Design Approval (GDA) process is new and only EPR has been through it in its entirety. The process for EPR took almost 6 years, but the experience gained should allow future LWRs to gain approval within 4 years or so. ONR already had expertise in PWR safety assessment and this must have been helpful for the GDA. For HTGRs with outlet temperatures of ~800°C there is currently no expertise within ONR; however ONR has substantial experience with gas-cooled, graphite moderated systems, thanks to the long term UK deployment of Advanced Gas-cooled Reactors (AGRs) with outlet temperatures of 650°C. The similarities between AGRs and HTGR systems and the up-to-date experience on TRISO fuel performance should help reduce the burden on licensing HTGRs relative to other Emerging SMR Technologies. Nevertheless, there are uncertainties surrounding a number of phenomena including material performance for the selected graphite grade and the quantity of contaminated dust that could be released in the event of a primary circuit breach. Hence, the timescale required for deployment are likely to be longer than the reference system.

Assessed as 'Minor Challenge'

1a.2 Timescale required to demonstrate that Safety Regulation Requirements can be satisfied

1a.2 assesses how long it might reasonably be expected to take to demonstrate that the system can satisfy stringent Safety Regulation Requirements. Levels of challenge would be expected to increase as the system examined moves further away from current experience, for example:

- Systems which are already deployed commercially or whose designs are already licensed in other countries.
- Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.
- Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.
- Systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

Assessments will assume that regulatory effort is available when and as required

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1a.2 Timescale required to demonstrate that SAPs can be satisfied - references

Insert

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1a.3 Effort to meet radiological regulations

TRISO fuel is a mature, well-demonstrated technology, with both Uranium oxycarbide (UCO) and UO_2 fuel undergoing recent irradiation test programmes. TRISO fuel that has been appropriately fabricated and qualified can retain hazardous fission products at high temperatures (1600°C) for prolonged periods of time (~10^2 hours). This will require very high standards of particle manufacture and quality control. However, whilst TRISO fuel exhibits very favourable radiological release properties there are significant uncertainties surrounding the quantity of activated graphite dust that could be released in the event the primary circuit is breached. Furthermore, prolonged graphite oxidation could, in the unlikely event of a major fault, contribute to fission product release.

Assessed as 'Minor Challenge'

Metric - 11. Worker Exposures

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Description

References

1a.3 Effort to meet radiological regulations

1a.3 assesses the difficulty likely to be experienced in meeting the worker radiological protection requirements defined by regulators, noting that this includes the reactor and its fuel cycle. Levels of challenge would be expected to increase as the system examined moves further away from current experience, for example:

- Systems which are already deployed commercially or whose designs are already licensed in other countries.
- Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.
- Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.
- Systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

Assessments will assume that regulatory effort is available when and as required

1a.3 Effort to meet radiological regulations - references

Insert

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11. Worker Exposures

During normal operation worker dose rates should be no worse than SM-PWRs. However, due to uncertainties, such as activation of graphite dust, it is judged that further analyses will be required to ensure that in off-normal situations worker dose rates no worse than those in SM-PWRs.

Assessed as 'Minor Challenge'

11. Worker Exposures

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.

11. Worker Exposures - references

Insert

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1b. Time and Effort for Environmental Permitting

Summary

No worse than SM-PWRs, but details of environmental impacts will be design specific, and will vary with the number of units on a site, and the site location, particularly if a distributed network of SMRs is envisaged

Assessed as 'Reference'

Attribute – 1b.1 Effort to meet environmental regulations

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Description

References

1b. Time and Effort for Environmental Permitting

Nuclear facilities in the UK are required to comply with the requirements set down by the appropriate regulatory bodies. Environmental regulations are the responsibility of the Environment Agencies (EA, NRW, SEPA) and are implemented through the granting of site aerial and liquid Discharge Authorisations. The Environment Agencies are also responsible for the authorisation of solid waste disposal.

1b. Time and Effort for Environmental Permitting - References

Insert

1b.1 Effort to meet environmental regulations

SM-HTGRs are likely to be capable of meeting environmental regulations. In terms of discharges to the environment and doses to members of the public, they are likely to be no worse than SM-PWRs.

Assessed as 'Reference'

Metric – 06 Environmental Impact

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Description

References

1b.1 Effort to meet environmental regulations

1b.1 assesses the challenge faced by a reactor system in meeting the environmental impact requirements defined by the regulators, noting that this includes the reactor and its fuel cycle. This parameter is assumed to refer to routine operational environmental discharges. Levels of challenge would be expected to increase as the system examined moves further away from current experience, for example:

- Systems which are already deployed commercially or whose designs are already licensed in other countries.
- Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.
- Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.
- Systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

Assessments will assume that regulatory effort is available when and as required

1b.1 Effort to meet environmental regulations - references

Insert

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06. Environmental Impact

SM-HTGRs are likely to be capable of meeting environmental regulations. In terms of discharges to the environment and doses to members of the public, they are likely to exhibit similar performance to SM-PWRs.

Assessed as 'Reference'

06. Environmental Impact

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, using closed fuel cycles, would score more highly in this respect, but only if the facilities needed produced little or no radioactive emissions.

06. Environmental Impact - references

Insert

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1c. Proliferation Resistance and Physical Protection (PRPP) Acceptability

Summary

SM-HTGRs operated with a once-through cycle, using LEU fuel, but at a significantly higher enrichment to the SM-PWRs, avoid the production of weapons usable materials. SM-HTGRs further improve PRPP due to the highly robust nature of HTGR fuel and very low uranium concentrations in fuel elements (for instance each pebble, in a pebble bed reactor, contains only ~6 g of uranium). However, if thorium based fuels (thorium mixed with HEU or Pu) are used some of these benefits are lost.

Assessed as 'Significant Benefit' for LEU systems and 'Minor Challenge' for thorium systems

Attributes

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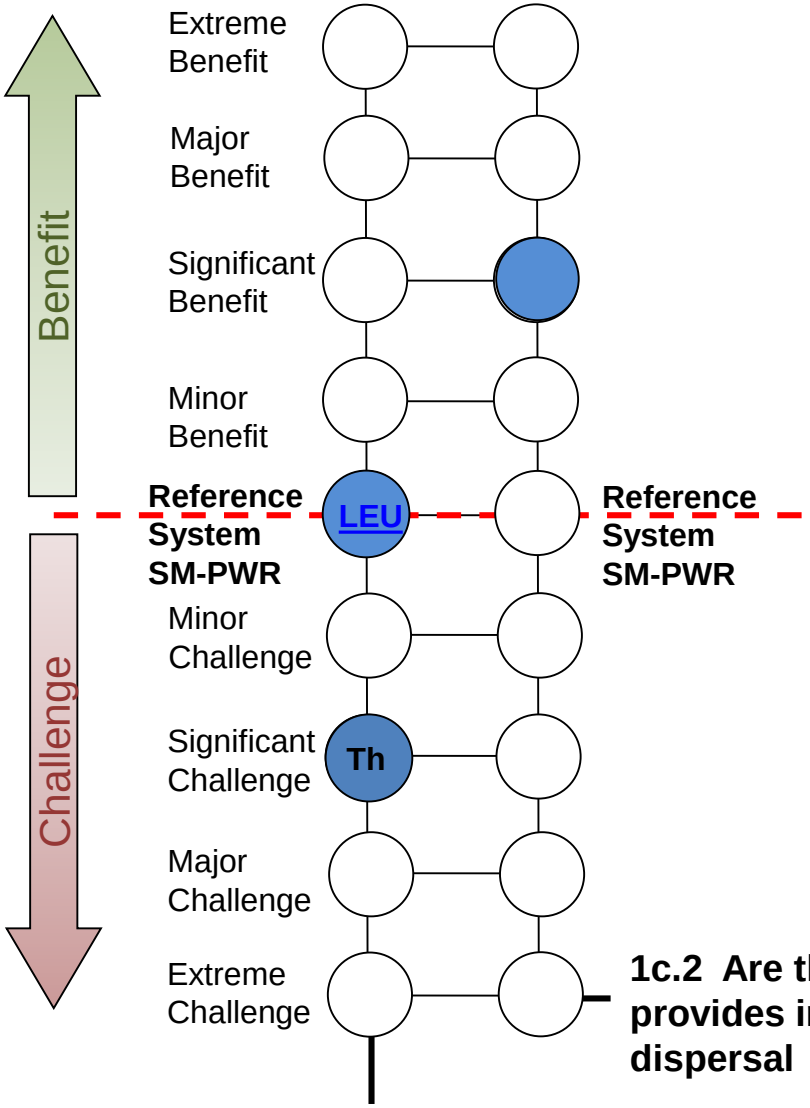
Description

1c. Proliferation Resistance and Physical Protection (PRPP) Acceptability



1c.2 Are the nuclear materials in a form that provides inherent self-protection against theft or dispersal

1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage

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1c. Proliferation Resistance and Physical Protection (PRPP) Acceptability

Any new system deployed in the UK will be required to satisfy the Nuclear Industries Security Regulations 2003. This is a system which responds to the nuclear processes being carried out and the amount and form of nuclear materials being used, and ensures that a system is in place which will “prevent the theft or sabotage of nuclear material or the sabotage of nuclear facilities”. The Office of Civil Nuclear Security (OCNS) is the responsible regulator.

UK situation is that, while systems may not accord with the ideals of PRPP, yet there are systems, monitored and enforced by OCNS, which ensure risks of theft or sabotage are maintained at acceptably low levels. Thus while it is highly relevant to monitor the PRPP characteristics of nuclear reactor systems, the value of this Attribute in the UK context is predominantly to be judged by policy makers. The assessment will, however, give an indication of the challenges to be met in order to generate an approved Security Plan for the candidate system.

The top level PRPP criterion can be posed as: *“Are the nuclear materials produced in the fuel cycle difficult to access?”*

Back

1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage

Most SM-HTGR~~s~~ designs operate on a once-through cycle using LEU fuel. However, some SM-HTGR designs utilise the thorium fuel cycle. This presents some difficult problems as thorium is not fissile. In the past this was achieved by adding HEU (highly enriched uranium) to the thorium, but his is no longer an option, so any thorium containing core will have to also contain a higher fraction of uranium based fuel with enrichment below 20%, possibly plutonium. If the driver and breeder fuel is separate then the breeder fuel will contain a chemically separable weapons grade fissile material in the form of U-233. Associated radioactivity will make this difficult to handle but it does represent a similar proliferation risk to LEU uranium open cycles.

Assessed as 'Reference' for LEU systems and Significant Challenge for thorium systems'

Metrics

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Description

References

1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage

This attribute accounts for the physical forms of fissile materials in the fuel cycle. The levels of challenge will vary between:

Fuel cycles in which high grade fissile materials are present at any stage, for example high enriched uranium (HEU) or plutonium, which will be considered to present considerable PRPP challenges. Examples would include a fuel cycle based on HEU fuel or the separation of pure plutonium for recycle (as in conventional PUREX reprocessing).

A LWR fuel cycle with low enriched uranium (LEU) and a once-through fuel cycle will present a lower level of PRPP challenge.

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1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage - references

Insert

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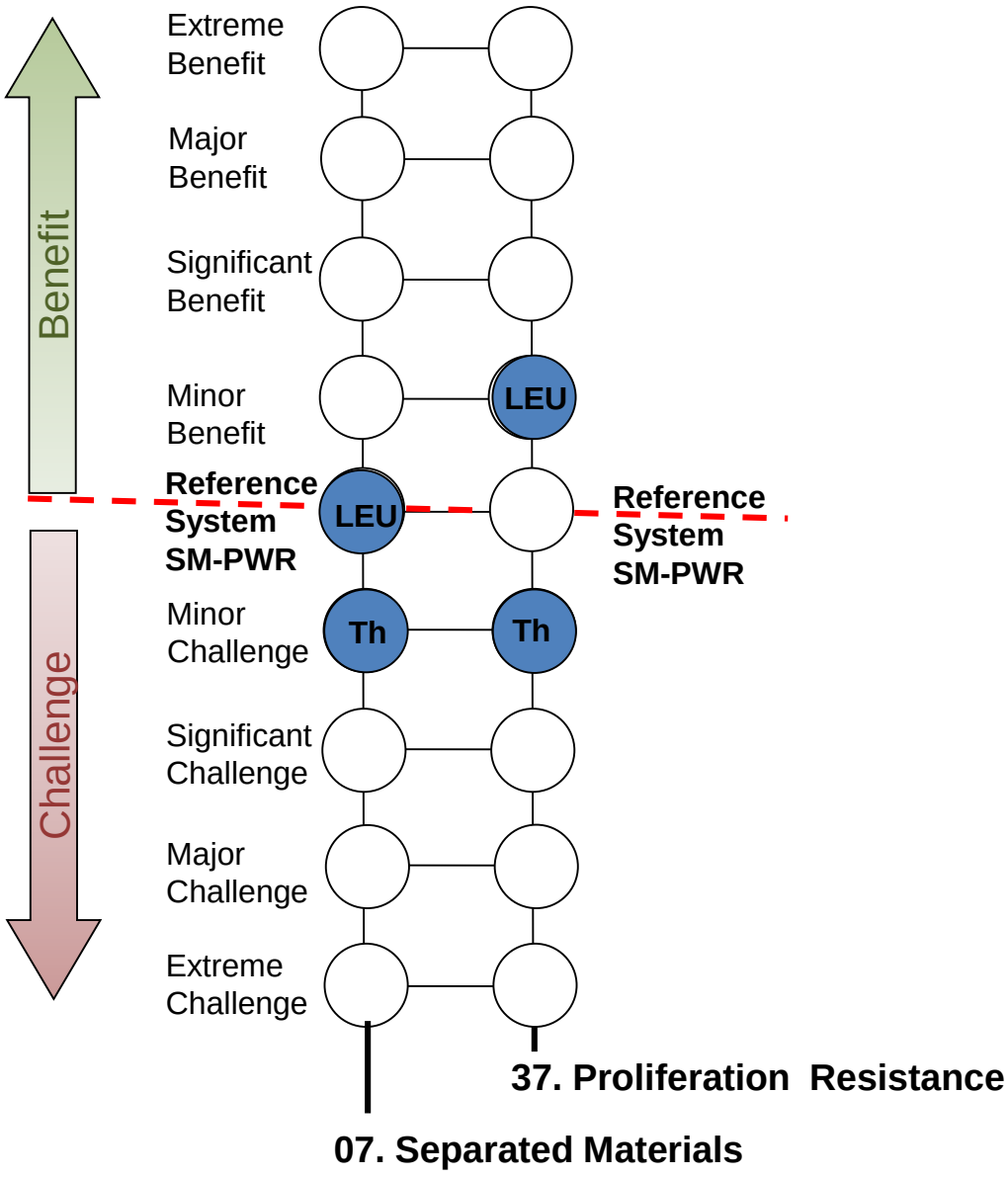
1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage



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07. Separated Materials

SM-HTGRs operated with a once-through cycle, using LEU fuel, but at a significantly higher enrichment to the SM-PWRs, avoids the production of weapons usable materials. SM-HTGRs further improve PRPP due to the highly robust nature of HTGR fuel and very low uranium concentrations in fuel elements (for instance each pebble in a pebble bed reactor, contains only ~6 g of uranium). However, if thorium based fuels (thorium mixed with HEU or Pu) are used some of these benefits are lost.

Assessed as 'Reference' for LEU fuel and 'Minor Challenge' for a thorium cycle

07. Separated Materials

One of the PRPP goals of advanced systems is that they 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.

07. Separated Materials - references

Insert

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37. Proliferation Resistance

SM-HTGRs operated with a once-through cycle, using LEU fuel, but at a significantly higher enrichment to the SM-PWRs, avoids the production of weapons usable materials. SM-HTGRs further improve PRPP due to the highly robust nature of HTGR fuel and very low uranium concentrations in fuel elements (for instance each pebble, in a pebble bed reactor, contains only ~6 g of uranium). However, the introduction of thorium cycles will need careful management as there is an increased proliferation risk through the use of higher enriched or plutonium drivers fuels and the production of U-233 in thorium blanket material.

Assessed as 'Minor Benefit' for LEU systems and 'Minor Challenge' for thorium systems

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Description

References

37. Proliferation Resistance

There is increasing interest in international reactor systems development to be able to demonstrate increased proliferation resistance by design, and different reactor systems may be considerably differentiated by inherent proliferation resistance. 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. SM-HTGR fuel is very difficult to reprocess on a large scale.

37. Proliferation Resistance – references

Insert

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1c.2 Are the nuclear materials in the fuel cycle in a form which provides inherent self-protection against theft or dispersal

The highly robust nature of HTGR fuel and very low uranium concentrations in fuel elements (for instance each pebble, in a pebble bed reactor, contains only ~6 g of uranium) act as significant barriers to theft and/or dispersal.

Assessed as 'Significant Benefit'

Metrics

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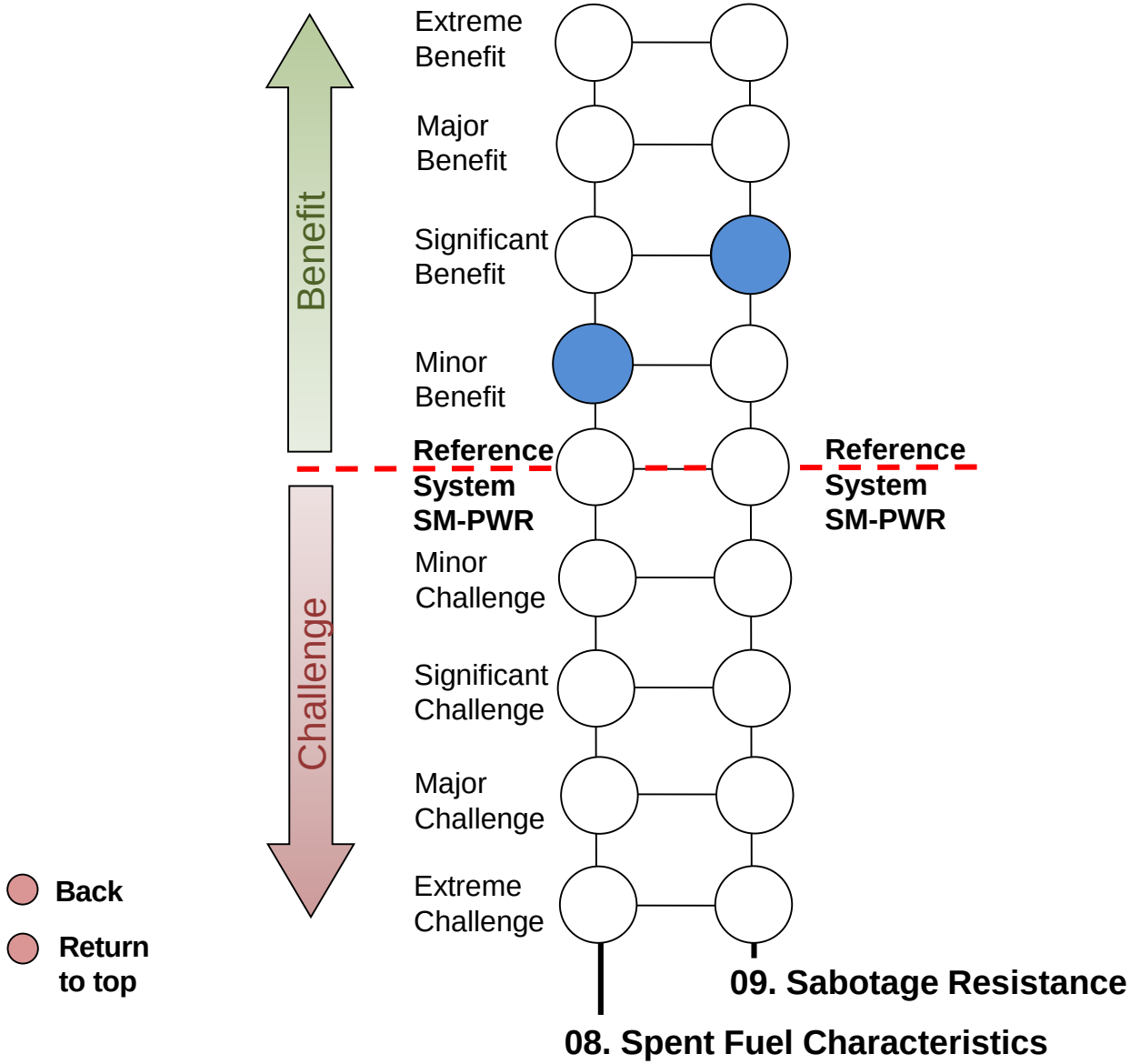
Description

References

1c.2 Are the nuclear materials in the fuel cycle in a form which provides inherent self-protection against theft or dispersal



1c.2 Are the nuclear materials in the fuel cycle in a form which provides inherent self-protection against theft or dispersal

1c.2 (Inherent PRPP). This attribute tests whether nuclear material is inherently protected by physical or chemical form, or by a strong self-protective radiation field. It is also intended to test whether the material is in a form that could be readily dispersed. Illustrations of levels of challenge are:

- a once-through fuel cycle with uranium oxide fuel in which there are multiple inherent barriers to accessing fissile material.
- fuel cycles which involve the production at some stage of unirradiated HEU fuel or plutonium oxide powder which present no inherent barriers.

1c.2 Are the nuclear materials in the fuel cycle in a form which provides inherent self-protection against theft or dispersal - references

Insert

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08. Spent fuel characteristics

SM-HTGRs utilise LEU fuel that operates to very high burnups. The characteristics of the spent fuel are therefore beneficial with respect to proliferation resistance. The introduction of thorium cycles will result in lower proliferation resistance.

Assessed as 'Minor Benefit'

08. Spent fuel characteristics

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. The spent fuel from SM-HTGRs is very difficult to reprocess compared to SM-PWR fuel and also SM-HTGRs typically operate to high burnups. High burnups degrade the isotopic composition of fissile material and also increases the difficulty in handling the waste form.

08. Spent fuel characteristics - references

Insert

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Return to top

09. Sabotage resistance

A detailed design assessment of the vulnerability of SM-HTGR to sabotage/missile attack will need to be made. Nevertheless, there are significant benefits to utilising a very robust fuel form that is both mechanically robust and is capable of retaining hazardous fission products even at very high temperatures for prolonged periods of time.

Assessed as 'Significant Benefit'

09. Sabotage resistance

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 but in some of the systems, for example small modular PWRs, the nuclear island is largely sited underground and therefore exceptionally well protected.

09. Sabotage resistance - references

Insert

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2a. Economic Competitiveness

Summary

SM-HTGRs will not only have to overcome scaling laws that favour large plants (perhaps by relying on new compensating mechanisms, such as cost savings from factory replication, lower risk financing and more favourable grid connection charges) but SM-HTGR core's are also quite large for a given power output and utilise a more complex, and therefore expensive, fuel form. SM-HTGRs will have to demonstrate that their safety performance advantages and/or the benefits associated with process heat can overcome these economic penalties.

Assessed as 'Minor Challenge'

Attributes

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Description

2a. Economic Competitiveness

The electrical generation cost is one of the principal criteria against which a nuclear system will be assessed – without a demonstrably economically competitive system, utilities are unlikely to invest.

The top level economics Attribute can be posed as: *Will the reactor system be economically competitive in the electricity generation market or in possible future heat generation markets?*

From this Strategic Attribute, the following Criteria are obtained:

Overnight construction cost. The cost of building and financing the nuclear system, usually expressed as £/MWe.

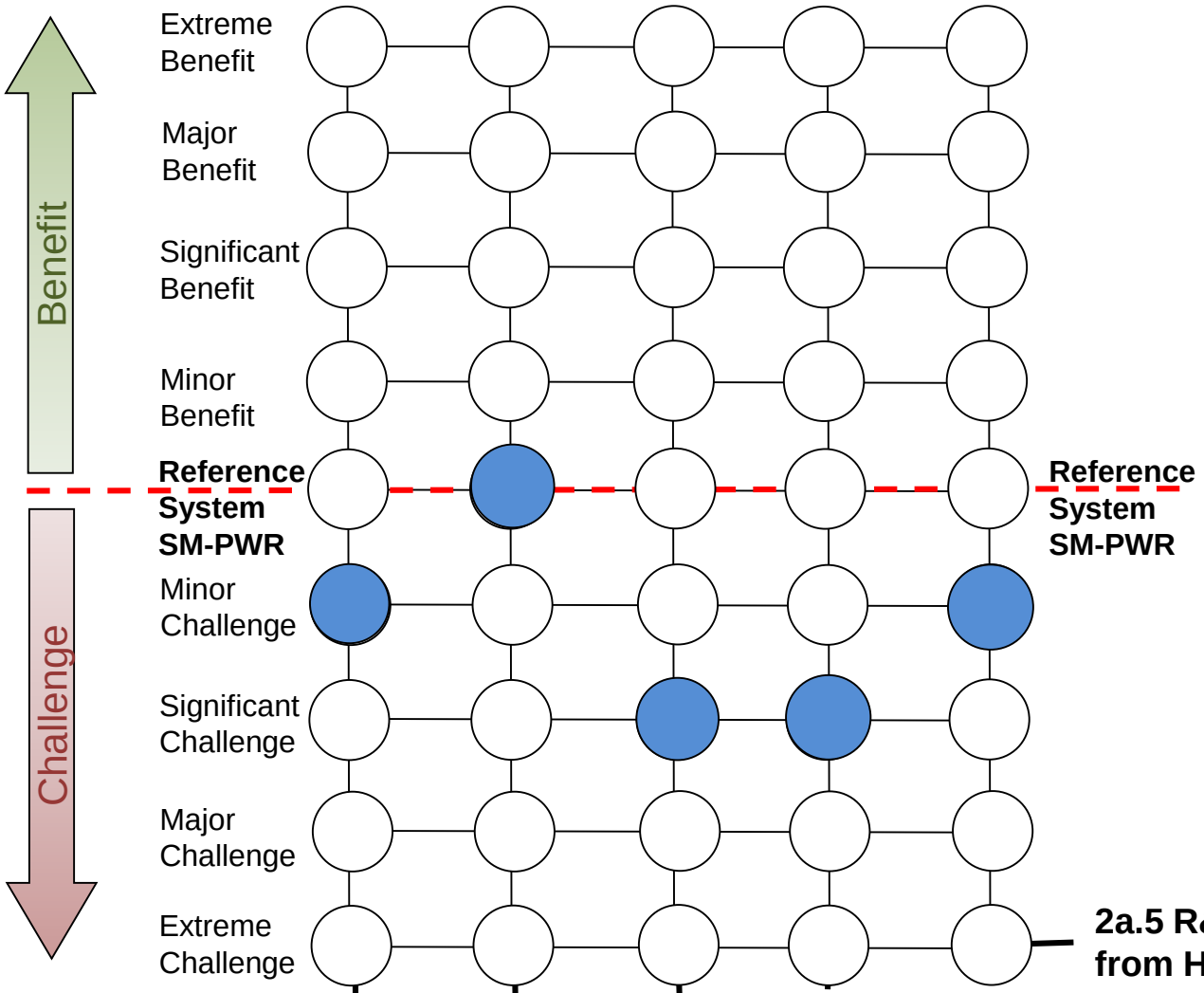
Operating and maintenance cost: This is the cost of operating and maintenance (O&M), taken to include staffing costs, operating costs (excluding fuel), the cost of routine maintenance and other related costs, usually expressed as a levelised cost in £/MWh.

Fuel cycle cost: This criterion is intended to capture the cost of operating the fuel cycle, both procuring new fuel and all the back-end costs associated with spent fuel management or reprocessing/recycle, usually expressed as a levelised cost in £/MWh.

Decommissioning cost: This is the actual cost of decommissioning *without* applying financial discounting, expressed as £/MWe.

R&D cost: This is the cost of the research and development programme needed to bring a system to commercial readiness. This will generally be an infeed into this attribute from High Level Discriminator 1 – Regulatory Challenges and Timescales.

2a. Economic Competitiveness



2a.5 R&D cost – feed from HLD1

2a.4 Decommissioning cost

2a.3 Fuel cycle cost – front and back end combined

2a.2 Operating and Maintenance cost

2a.1 Overnight construction cost

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Description

2a1. Overnight construction cost

For SMR systems generally there is an economy of scale penalty (for which there is a consensus), but with potential for savings from replication, factory build and increased modularisation. There is also the Potential for first module to finance later modules but note need for common infrastructure to be in place for the first module.

The relatively large size of HTGR cores and the more complex fuel form are likely to detrimentally increase overnight construction costs compared with SM-PWRs. However, there may be benefits related to a simpler safety system that can offset, to some extent, these economic penalties.

Assessed as 'Minor Challenge'

Metrics

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Description

References

2a.1 Overnight construction cost

2a.1 (Overnight construction cost). The cost of building and financing the nuclear system, usually expressed as £/MWe. This attribute is the cost of construction and of financing construction, usually taken as the overnight construction cost with all financing costs discounted to the date at which the plant becomes operational. Included in this context, is the construction cost of any fuel cycle plants needed for fuel reprocessing, recycle or waste management. Illustrations of levels of challenge are:

- Plants with a high degree of modularisation and short construction times.
- Plants with a limited degree of modularisation and moderate construction times. This might apply to current large PWRs operating a once-through fuel cycle, for example.
- Complex plants with long and difficult construction demands. This might apply to systems involving extensive reprocessing and recycle.

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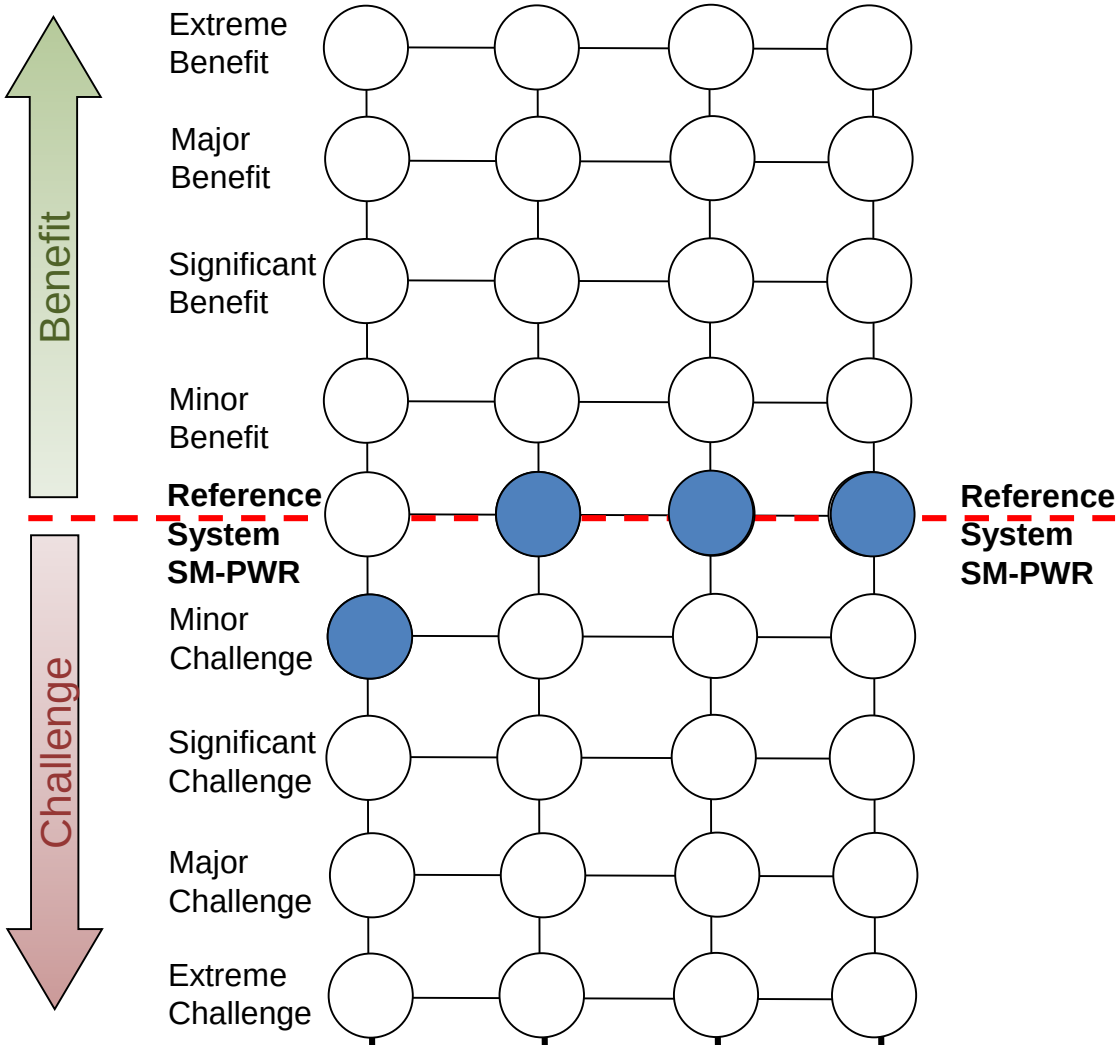
2a.1 Overnight construction cost



34. Ease of Construction

29. Scaleability

24. Construction Duration

22. Overnight construction cost

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Description

22. Overnight construction cost

For SMR systems generally there is an economy of scale penalty (for which there is a consensus), but with potential for savings from replication, factory build and increased modularisation. There is also the Potential for first module to finance later modules but note need for common infrastructure to be in place for the first module.

The relatively large size of HTGR cores (due to their low power density) and the more complex fuel form are likely to detrimentally increase overnight construction costs compared with SM-PWRs. However, there may be benefits related to a simpler safety system that can offset, to some extent, these economic penalties.

Assessed as 'Minor Challenge'

22 Overnight construction cost

22 (Overnight construction cost). The cost of building and financing the nuclear system, usually expressed as £/MWe. This attribute is the cost of construction and of financing construction, usually taken as the overnight construction cost with all financing costs discounted to the date at which the plant becomes operational. Included in this context, is the construction cost of any fuel cycle plants needed for fuel reprocessing, recycle or waste management. Illustrations of levels of challenge are:

- Plants with a high degree of modularisation and short construction times.
- Plants with a limited degree of modularisation and moderate construction times. This might apply to current large PWRs operating a once-through fuel cycle, for example.
- Complex plants with long and difficult construction demands. This might apply to systems involving extensive reprocessing and recycle.

22. Overnight construction costs - references

None of the SM-HTGR designs currently being developed have reached the stage where there is a detailed breakdown of construction costs.

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24. Construction duration

Short construction times reduces finance cost and risk with theoretically lower £/kWe. SM-HTGRs designs currently being developed are not yet at the stage where short construction times are demonstrated. The goal of achieving short construction times can be considered no more than an aspiration at present. SM-HTGRs shares this position with the SM-PWR Reference System.

Assessed as 'Reference'

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Description

References

24. Construction duration

The duration of plant construction has already been discussed under Item 22 (overnight construction cost) and the same assessment applies.

24. Construction duration - references

Insert here

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29. Scaleability

Better fit for grid management. SM-HTGR is regarded equivalent to the SM-PWR Reference System in this respect.

Assessed as 'Reference'

29. Scaleability

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.

29. Scaleability - references

Insert

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34. Ease of Construction

Potential for SM-HTGR to reduce finance costs through lower risk in exactly the same way as the SM-PWR Reference System.

Assessed as 'Reference'

34. Ease of Construction

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.

34. Ease of Construction - references

Insert here

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2a.2 Operating and maintenance cost

Economy of scale penalty potentially offset by reduced maintenance requirements .
Minimum manning level agreed with regulator a potential issue.
Grid connection cited as an area where SMRs can be beneficial, but not demonstrated. SM-HTGR equivalent to SM-PWR Reference System.

Assessed as 'Reference'

Metrics

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Description

References

2a.2 Operating and maintenance cost

This Attribute covers the cost of operating and maintenance, taken to include staffing costs, operating costs (excluding fuel), the cost of routine maintenance and other related costs. Illustrations of levels of O&M costs are:

- Plants such as LWRs with long operating lives and no requirement for mid-life refurbishment of major plant items
- Plants with a requirement for through-life replacement of major components
- Complex plants with difficult operational requirements

2a.2 Operating and maintenance cost - references

Insert here

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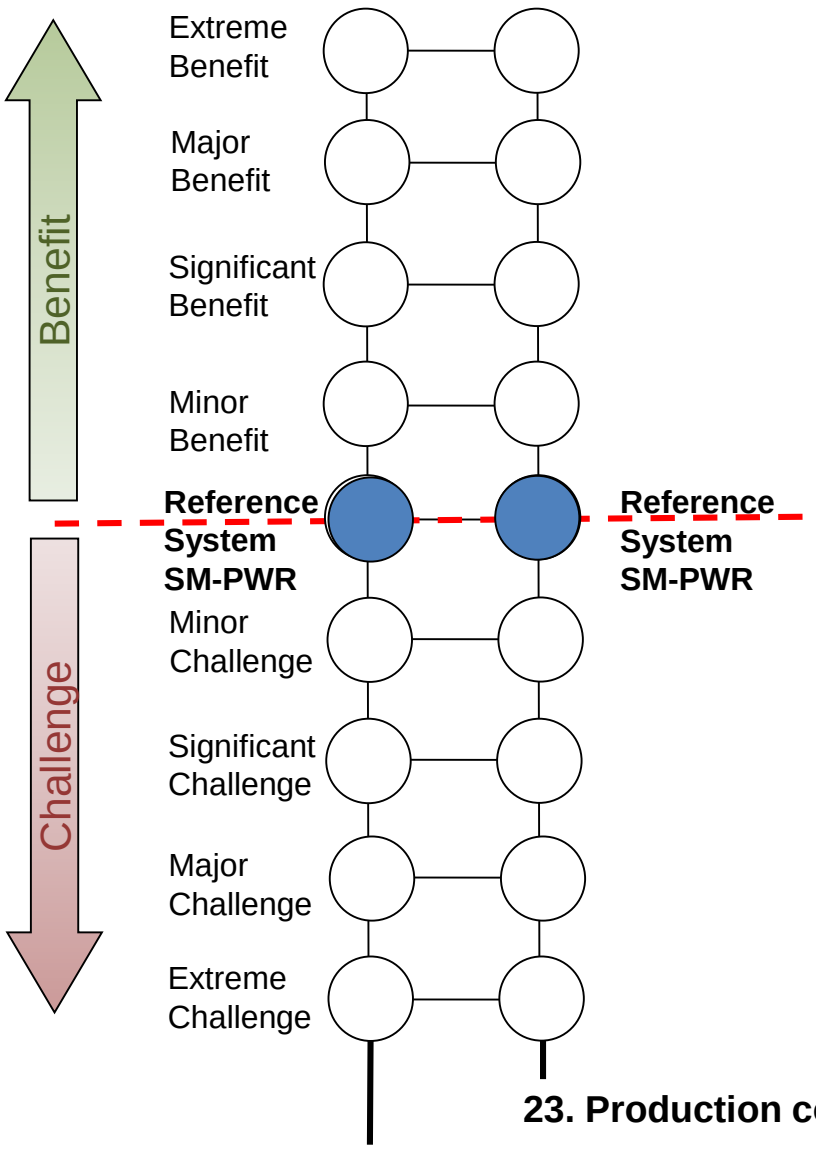
2a.2 Operating and maintenance cost



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10. Reliability

Potential reduction in grid connection charge due to smaller loss of capacity from a single unit. But risk of loss of capacity of entire power station from common factors (eg loss of grid connection) unaffected. SM-HTGR is equivalent to the SM-PWR Reference System in this respect.

Assessed as 'Reference'

10. Reliability

This is the forced outage rate, which should be very low. It is an operational safety and reliability issue, but it is also important for economics. Best operational practice at modern PWRs 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.

10. Reliability - references

Insert

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23. Production costs (O&M)

Economy of scale penalty potentially offset by reduced maintenance requirements .
Minimum manning level agreed with regulator a potential issue.
Grid connection cited as an area where SMRs can be beneficial, but not demonstrated.
SM-HTGR equivalent to SM-PWR Reference System.

Assessed as 'Reference'

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Description

References

23. Production costs (O&M)

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. There is no distinction here between SM-HTGR and the SM-PWR Reference System.

23. Production costs (O&M) - references

Insert here

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2a.3 Fuel cycle costs (front and back-end combined)

The more complex and therefore expensive fuel form, in addition to the large spent fuel waste volumes are likely to significantly increase fuel cycle costs relative to SM-PWRs.

Assessed as 'Significant Challenge'

2a.3 Fuel cycle costs (front and back-end combined)

2a.3 (Fuel cycle cost). This attribute is intended to capture the cost of operating the fuel cycle, both procuring new fuel and all the back-end costs associated with spent fuel management or reprocessing/recycle. Illustrations of varying levels of challenge with choice of fuel cycle are:

- the once-through LWR fuel cycle
- the closed LWR fuel, cycle (i.e. thermal recycle)
- a fast reactor system with recycle, especially if there was recycle of minor actinides.

2a.3 Fuel cycle costs (front and back-end combined) - references

Insert

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2a.4 Decommissioning costs

41. Decommissioning costs

Large quantities of irradiated graphite and spent fuel volumes will result in higher decommissioning costs relative to SM-PWRs.

Assessed as 'Significant Challenge'

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Description

References

2a.4 Decommissioning costs

41. Decommissioning costs

2a.4 (Decommissioning cost). This attribute is intended to represent the actual cost of decommissioning without applying financial discounting. The decommissioning cost represents a significant risk element in financial analysis, even though the discounted cost is usually very low. Levels of challenge are illustrated by:

- A nuclear system with small, modular components compatible with disposal as self-contained units.
- Current LWRs where, after defueling, there are only medium active components that need to be decommissioned in the core.
- Systems with graphite moderation, such as the UK's legacy gas cooled reactors, due to the need to deal with large masses of material.

2a.4 Decommissioning costs - references

41. Decommissioning costs

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2a.5 R&D cost

Many of the technologies behind SM-HTGRs are well-demonstrated. However, HTGR technology is less mature than PWR technology.

Assessed as 'Minor Challenge'

Metrics

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Description

References

2a.5 R&D cost

This Attribute covers the cost of the research and development programme needed to bring a system to commercial readiness. Illustrations of levels of R&D cost are:

- Those associated with an existing system or a minor development of an existing system
- Those associated with the evolution of a current system
- Those associated with novel systems involving significant innovations and long and extensive R&D

2a.5 R&D cost - references

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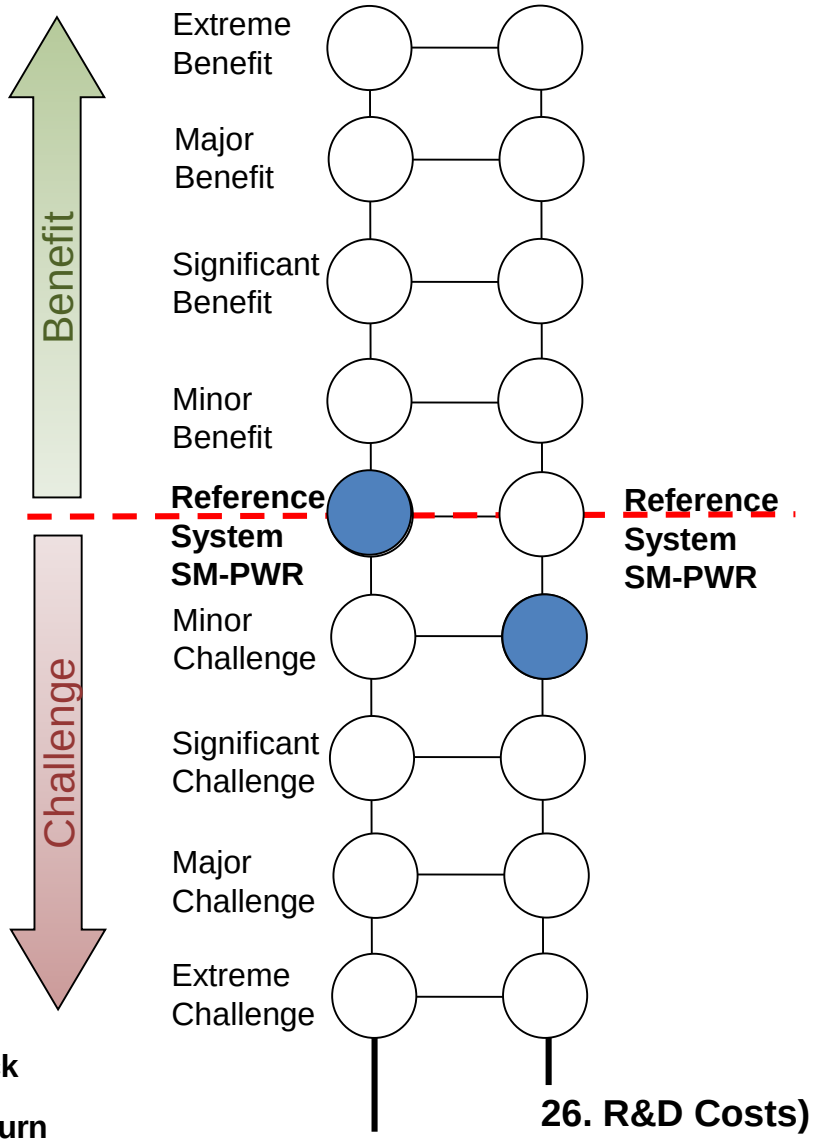
2a.5 R&D cost



26. R&D Costs)

17. Integral experiment scaleability

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17. Integral experiment scaleability

A number of HTGR systems have operated with varying degrees of success. Generally, the smaller HTGRs (<~100 MWth) have operated successfully, especially when factoring many of the smaller HTGRs that have operated tended to be prototypes. Furthermore, there is recent experience operating small HTGRs due research programmes undertaken in Japan and China.

Assessed as 'Reference'

17. Integral experiment scaleability

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.

17. Integral experiment scaleability - references

Insert

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26. R&D costs

Many of the technologies behind SM-HTGRs are well demonstrated. However, HTGR technology is less mature than PWR technology. In addition there is an need to develop an internationally funded and up-to-date design code for high temperature structural components.

Assessed as 'Minor Challenge'

26. R&D costs

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. However, if the UK was to buy into technology that was not being developed elsewhere, the UK could incur the R&D costs and risks.

26. R&D costs - references

Insert

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3a. Fuel Security

Summary

SM-HTGRs typically operate with uranium fuel and utilise LEU. Given the current availability of uranium, there is no reason to suspect fuel security issues will arise during SM-HTGR's operational lives. The energy produced per unit of uranium feed for pebble-bed SM-HTGRs is comparable to SM-PWRs. However, prismatic cores have higher uranium feed requirements as they utilise fuel less efficiently than pebble-bed cores, which leads to the alternative assessment as 'Significant Challenge'.

Assessed as 'Reference' for pebble-bed cores and 'Significant Challenge' for prismatic cores

Attributes

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Description

References

3a. Fuel Security

Summary

This Strategic Attribute assesses whether fissile materials are available to start up a reactor system, and whether the supplies are sufficient and secure enough to fuel the reactor(s) over their projected lifetime

3a. Fuel Security - references

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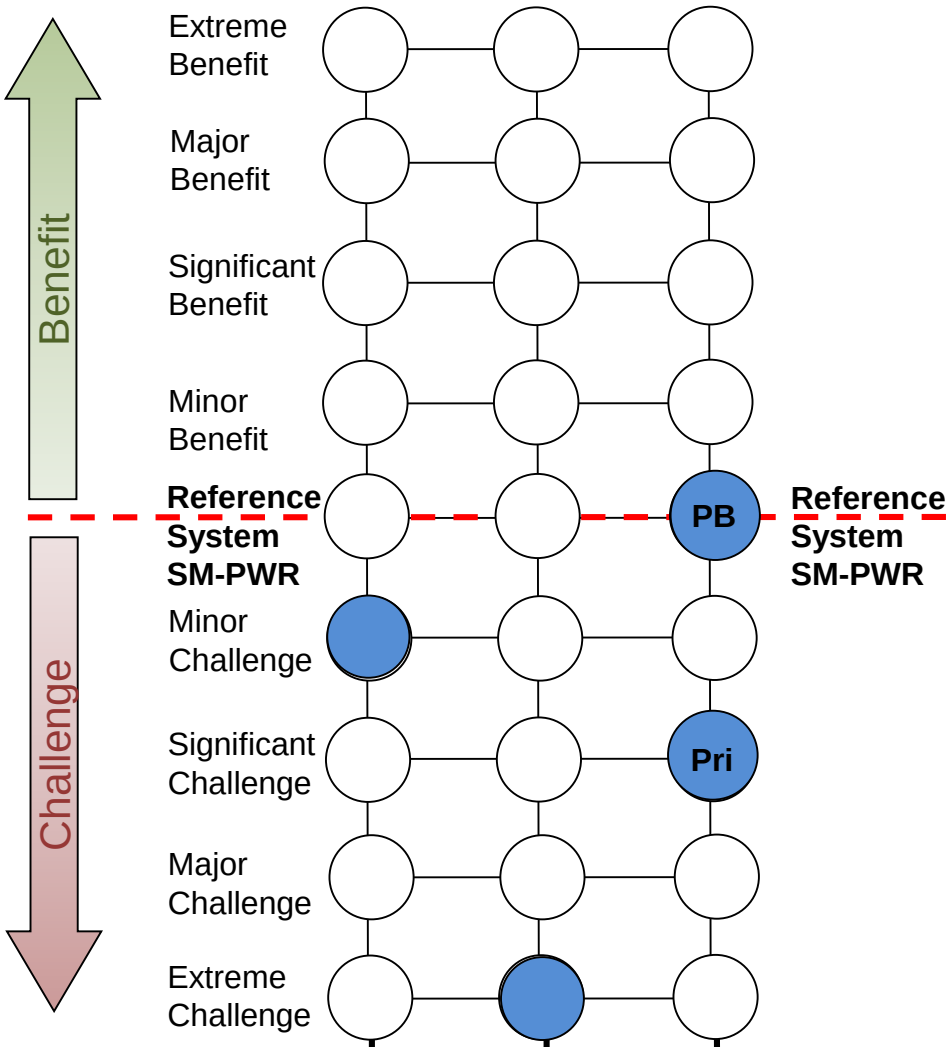
3a. Fuel Security



3a.3 Uranium dependence

3a.2 Spent fuel characteristics – compatible with existing reprocessing technology?

3a.1 Ability to deploy – fissile material availability

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Description

3a.1 Ability to deploy – fissile material availability

The production of low enriched uranium is well established. However, the absence of commercial suppliers of large quantities of HTGR fuel and potential issues surrounding procuring fuel enriched beyond 5 wt.% may postpone deployment in the near-term. If the UK decides to adopt HTGR technology then it will be necessary to establish fuel production at the same time.

Assessed as 'Minor Challenge'

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Description

References

3a.1 Ability to deploy – fissile material availability

3a.1 (Fissile material availability) applies specifically to closed fuel cycle systems which may have limitations on the rate at which new reactors could be deployed because of the need to acquire and/or build up the necessary fissile material. The levels of challenge vary between open and closed fuel cycle systems:

OPEN - this designates an open fuel cycle in which reactors are fuelled by LEU, which as natural uranium or LEU is available on the world market. In this instance the deployment rate would not be restricted, provided that world market supplies are sufficient and sufficient reactor build capacity was available.

CLOSED – this designates a closed fuel cycle which will eventually operate virtually independently of uranium availability, but which may be subject to constraints on the initial rate of deployment depending on the availability of fissile material. Limitations to closed cycle deployment can be calculated for any assumed future nuclear generation scenario.

3a.1 Ability to deploy – fissile material availability - references

Insert

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3a.2 Spent fuel characteristics – compatible with existing reprocessing technology?

No. The robustness of SM-HTGR fuel makes getting access to the uranium residing at the centre of the TRISO particle very difficult via a commercial process that can operate at large scale.

Assessed as 'Extreme Challenge'

3a.2 Spent fuel characteristics – compatible with existing reprocessing technology?

3a.2 (Spent fuel characteristics).
Spent fuel characteristics: Is the spent fuel of a form that is compatible with established reprocessing methods, or are there features that would preclude its reprocessing using current reprocessing methods? This Attribute tests whether or not the spent fuel form is compatible with established reprocessing technologies and gives a measure of the accessibility of the contained fissile material and hence the ability to affect any closed cycle deployment limitations in 3a.1.

Conventional spent oxide or metallic fuel, irrespective of whether the main fissile material is uranium or plutonium, are compatible with existing reprocessing technologies.

Unconventional fuels, such as fuels based on thorium matrix or coated particle TRISO fuels (used in high temperature gas reactors) are incompatible with established reprocessing methods. Fuel which is not straightforward to reprocess represents an intrinsic barrier to accessing fissile material.

3a.2 Spent fuel characteristics – compatible with existing reprocessing technology?

References

Insert

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3a.3 Uranium dependence

The energy output per unit of uranium feed for pebble-bed cores is similar to SM-PWR systems.

Prismatic cores require higher enriched fuel than pebble-bed cores whilst achieving comparable burnups. Therefore prismatic cores produce less energy per unit of uranium feed than pebble-bed systems and hence their uranium dependence is higher.

SM-HTGRs typically utilise LEU fuel and operate with a once-through cycle. However, SM-HTGRs utilise fuel enriched to higher levels which increases uranium dependence. Pebble-bed HTGR systems will have some benefits over prismatic HTGRs as pebble-bed systems operate with lower enrichments.

Assessed as 'Reference' for pebble-bed cores and 'Significant Challenge' for prismatic cores

Metrics

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Description

References

3a.3 Uranium dependence

The uranium usage Attribute poses the questions: "*Will there be sufficient uranium available on the world market to meet the requirements of the reactor system over its operational lifetime?"* and therefore *"Is the system more or less dependent on uranium ore availability/supply on the world market?*"

3a.3 therefore categorises the dependence of the nuclear system on uranium obtained from the world market. Illustrations of levels of uranium usage are:

LWRs have a specific uranium requirement of approximately 200 tU/GWye. CANDU reactors have a lower specific uranium requirement of approximately 160 tU/GWye.

Systems with high conversion ratios or with partial recycle of fissile materials are less dependent on uranium ore, defined as specific uranium requirements in the range 20 to 160 tU/GWye.

The lower range is set arbitrarily to 20 tU/GWye to allow for systems with high conversion ratios that are not quite self-sustained. Systems which have full recycle of fissile materials and operate a breeding cycle totally independent of external uranium supplies.

3a.3 Uranium dependence - References

Insert

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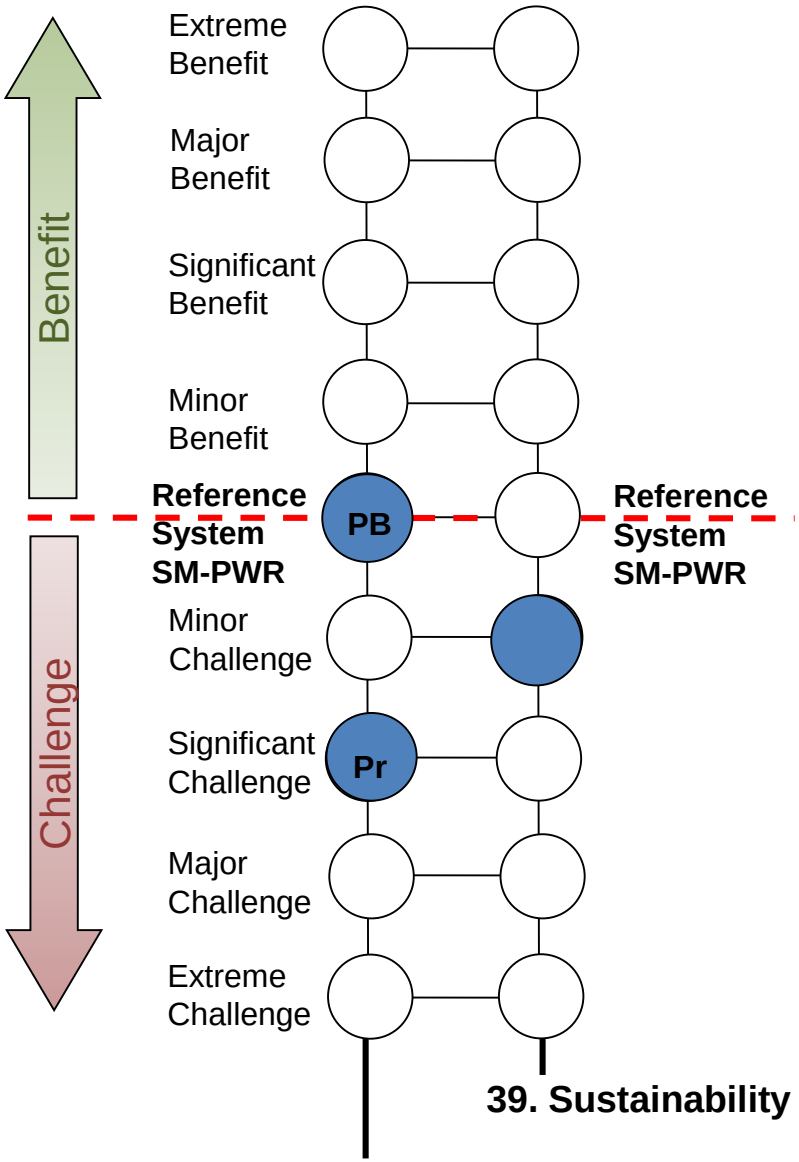
3a.3 Uranium dependence



References

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Return to top
Description

01. Fuel utilisation

PWR systems typically achieve burnups around 45 GWd/tHM and require enrichments of around 4.5 wt.%. For every unit of product at 4.5 wt.%, the amount of uranium feed is 9 units. Therefore the energy produced per unit feed is ~5. For pebble-bed cores that achieve burnups around 80 GWd/tHM with an enrichment of around 8 wt.%, and requiring 17 units of feed for every unit of product, the energy output per unit feed is also ~5. Prismatic cores typically operate up to around 100 GWd/tHM but require enrichments of around 15 wt.%. For every unit of product at 15 wt%, the amount of uranium feed required is 32 units. Hence the energy output per unit feed is ~ 3.

Assessed as 'Reference' for pebble-bed cores and 'Significant Challenge' for prismatic cores

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Description

References

01. Fuel utilisation

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.

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.

01. Fuel utilisation - references

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39. Sustainability

SM-HTGR operate on a once-through cycle like SM-PWRs. However, unlike SM-PWR spent fuel recovery of fissile material from spent fuel is extremely challenging.

Assessed as 'Minor Challenge'

39. Sustainability

Sustainability is potentially a broad area encompassing the uranium ore requirement, environmental impact, waste arisings and others.

39. Sustainability - references

Insert

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3b. Waste storage and disposability

Summary

The ability of TRISO particles to effectively retain fission products is a favourable characteristic for direct disposal. However, there are significant uncertainties surrounding the necessary preconditioning processes for irradiated graphite and limited experience with disposing of TRISO fuel. Moreover, the low power density of HTGR cores results in large volumes of waste that requires storage and eventual disposal relative to SM-PWR spent fuel.

Assessed as 'Significant Challenge'

Attributes

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Description

References

3b. Waste storage and disposability

Summary

All nuclear reactors generate nuclear waste that needs to be managed as part of the fuel cycle. The management and disposability of nuclear waste is one of the key long term considerations for the nuclear power industry. The current solution sought for long term disposability is to encapsulate waste into solid forms which are then protectively packaged and placed into a geological disposal facility (GDF). It is therefore required that any spent fuel, high level or intermediate level waste arising must be suitable for encapsulation and safe long term disposal in a GDF.

The waste management Strategic Attribute can be posed as: *Can the waste arisings from reactor systems be managed and eventually disposed of in a safe manner that is compatible with the acceptance criteria for existing or anticipated waste treatment plants and disposal facilities?*

From this top level Strategic Attribute, the following attributes are obtained:

Compatibility of waste forms: The masses and volumes of waste forms for disposal.

Suitability for disposal in GDF: Waste incorporation rate, long term decay heat and radiotoxicity.

3b. Waste storage and disposability - References

Insert

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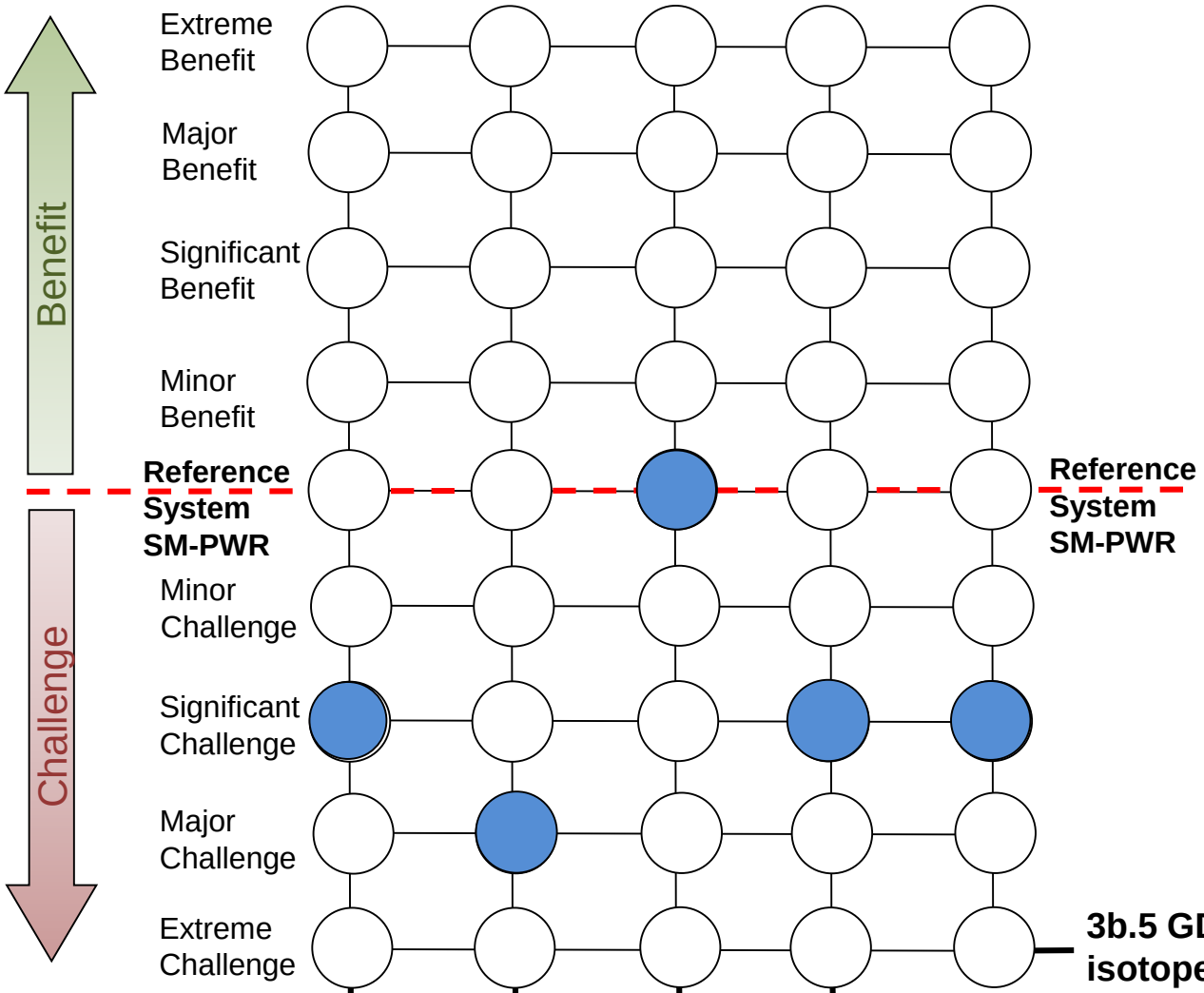
3b. Waste storage and disposability



3b.5 GDF disposal impact – isotopes driving safety case

3b.4 GDF disposal impact – long term radiotoxicity

3b.3 GDF disposal impact – long term decay heat

3b.2 GDF disposal impact – waste incorporation rate

3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology?

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3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology?

The number of waste forms is limited for SM-HTGR systems if direct disposal is pursued and there is little in the way of preconditioning. However, there are significant uncertainties regarding the suitability for direct disposal of irradiated graphite because of the presence of C-14 and Cl-36 radionuclides. These nuclides exhibit long half lives, high mobility in GDF environment and high bio-compatibility characteristics.

Assessed as 'Significant Challenge'

3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology?

3b.1 (Number and type of waste forms). This attribute accounts for the number of different waste forms produced. It is intended to take account of waste forms that are incompatible with existing or expected future waste packaging and disposal facilities. Any incompatible waste forms produced will require the construction and operation of new facilities to deal with them, and this will be noted..

01/39. Essentially same as large scale LWRs for batch refuelling. Significant penalty for single-batch refuelling.

3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology? References

Insert

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Return to top

3b.2 GDF disposal impact – waste incorporation rate

SM-HTGR spent fuel suffers from relatively low power densities resulting in large volumes of HLW.

Assessed as 'Major Challenge'

Metric - 33. Waste arisings – volumes of HLW, ILW, LLW

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Description

References

3b.2 GDF disposal impact – waste incorporation rate

3b.2 (Waste Incorporation rate). Waste packages for disposal in the GDF mass may consist of spent fuel assemblies or immobilised high level waste forms (such as glass blocks) depending upon the fuel cycle. For the disposal of spent fuel assemblies, disposal canisters would normally be designed to accommodate uranium fuel assemblies with a relatively low long term decay heat output. Other types of fuel assemblies, for example MOX assemblies, would have a higher long term decay heat output and the disposal canister might be able to accommodate fewer of them, giving a low incorporation rate. Immobilised high level waste from reprocessing of low burnup fuels contains relatively low amounts of transuranics contributing to heat and neutron output and therefore can give a high incorporation rate. High burnup fuels are characterised by high transuranic content, with high heat and neutron outputs that may results in reduced incorporation rates. Illustrations of levels of waste incorporation rate are:

HIGH – Applies to reactor systems producing waste forms with relatively low heat and neutron outputs compatible with current waste forms.

LOW – Applies to reactor systems producing waste forms with relatively high heat and neutron outputs that are incompatible with current waste forms.

3b.2 GDF disposal impact – waste incorporation rate - references

Insert

33. Waste arisings – volumes of HLW, ILW, LLW

Low power density of SM-HTGR results in significantly larger high level waste volumes. ILW may be slightly worse depending on the extent of irradiated graphite deemed ILW (some irradiated graphite will contain fuel and therefore will be HLW). LLW is expected to be broadly similar to SM-PWRs.

Assessed as 'Major Challenge'

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Description

References

33. Waste arisings – volumes of HLW, ILW, LLW

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.

33. Waste arisings – volumes of HLW, ILW, LLW - references

Insert

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3b.3 GDF disposal impact – long term decay heat

On a per TWh basis the long term decay heat from spent SM-HTGR fuel will be comparable to SM-PWR spent fuel. This is because both systems rely on LEU fuel and utilise a thermal spectrum. Hence, the build up of minor actinides and fission products in both spent fuel types will be approximately the same.

Assessed as 'Reference'

Metrics

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Description

References

3b.3 GDF disposal impact – long term decay heat

This is a measure of the long term decay heat of spent fuel or high level waste in interim storage pending disposal and in the GDF. Decay heat is important, because it determines how long spent fuel or immobilised high level waste will need to be held in interim storage prior to final disposal. Also, decay heat loading is the principal determinant of repository footprint. Spent uranium fuel or immobilised high level waste derived from uranium fuels sets the baseline for low long term decay heat. Spent fuel containing higher inventories of transuranics (such as MOX fuels) or immobilised high level waste originating from such fuels will have elevated decay heat output. Immobilised high level waste from fast spectrum systems with recycle of transuranics and from thorium systems would be expected to have a low inventory of transuranics and therefore low decay heat.
Illustrations of levels of long term decay heat are:

LOW – Applies to reactor systems producing waste forms with relatively low long term decay heat output consistent with long, but manageable interim storage times.

HIGH – Applies to reactor systems producing waste forms with relatively high long term decay heat output that would lead to unfeasibly long interim storage times.

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3b.3 GDF disposal impact – long term decay heat - references

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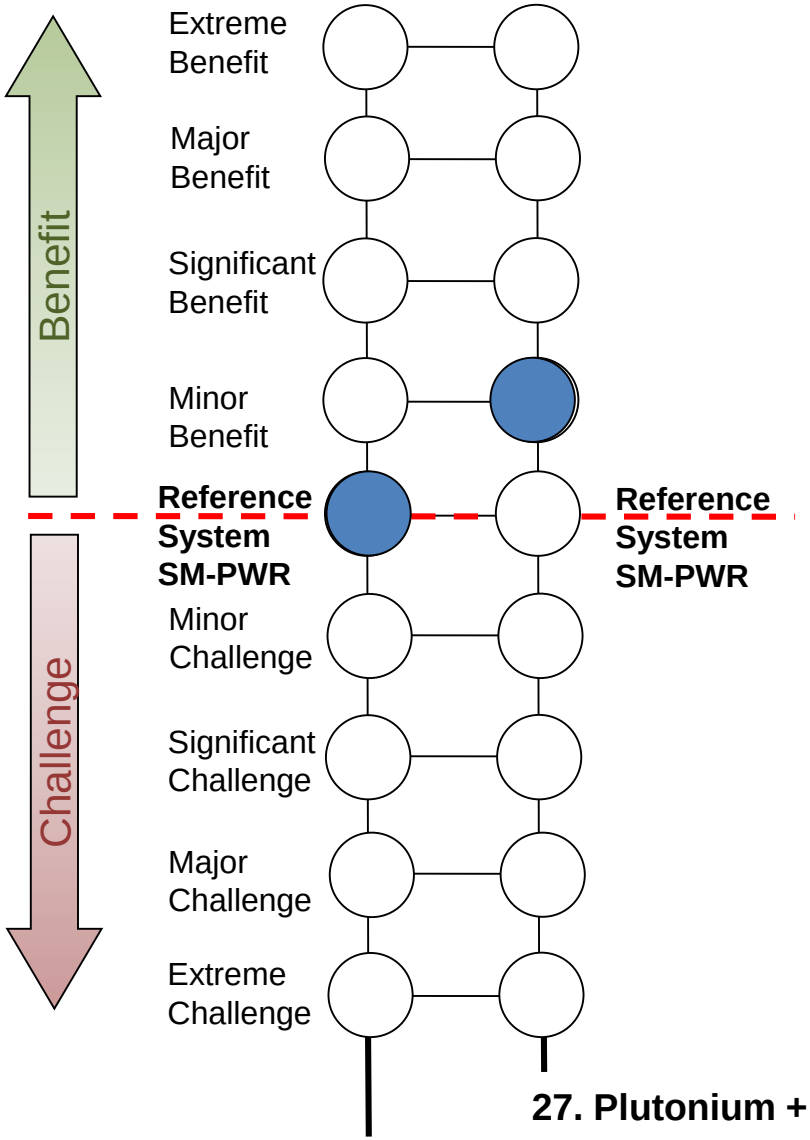
3b.3 GDF disposal impact – long term decay heat



27. Plutonium + minor actinide management

04. Long term heat output

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04. Long term heat output

On a per TWh basis the long term decay heat from spent SM-HTGR fuel will be comparable to SM-PWR spent fuel. This is because both systems rely on LEU fuel and utilise a thermal spectrum. Hence, the build up of minor actinides and fission products in both spent fuel types will be approximately the same.

Assessed as 'Reference'

04. Long term heat output

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.

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

04. Long term heat output - references

Insert

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27. Plutonium and minor actinide management

Thermal spectrum reactors have a limited ability to transmute minor actinides. However, there are potential benefits with destroying plutonium in SM-HTGRs relative to SM-PWRs as HTGRs are more tolerant to higher plutonium loadings.

Assessed as 'Minor Benefit'

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Description

References

27. Plutonium and minor actinide management

Most systems are capable in principle of recycling plutonium and some would also be capable of destroying minor actinides (principally neptunium and americium). This ability to manage plutonium and minor actinides is assessed in this attribute.

27. Plutonium and minor actinide management - references

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3b.4 GDF Disposal Impact – Long Term Radiotoxicity

Radiotoxicity is dominated by burnup (which will be significantly higher in SM-HTGRs) and fuel type (which with UO_2 or UCO will be comparable to SM-PWRs). However, there is the added complications associated with the production of problematic C-14 and Cl-36 from irradiated graphite.

Assessed as 'Significant Challenge'

Metrics

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Description

References

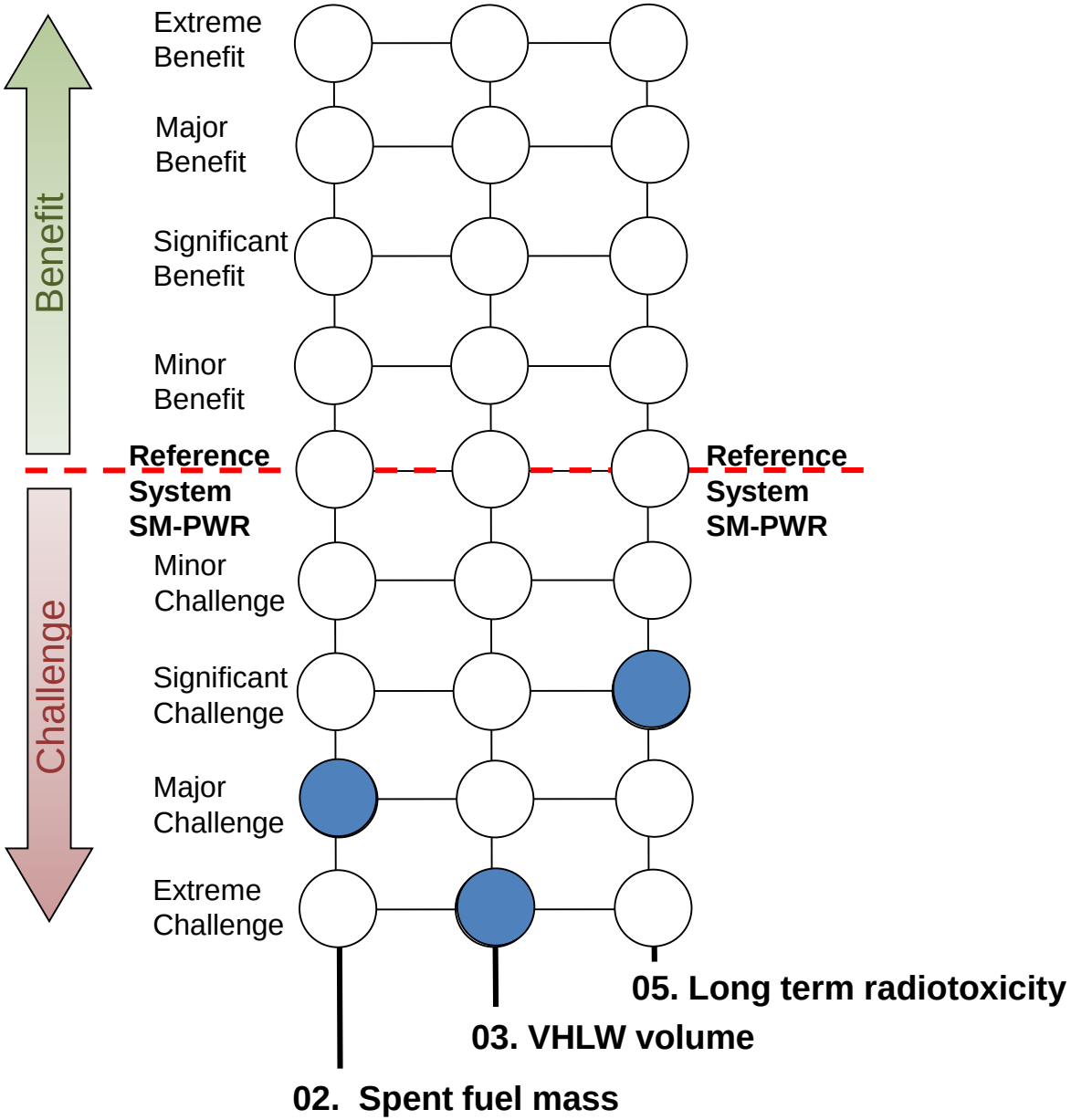
3b.4 GDF Disposal Impact – Long Term Radiotoxicity

For cooling times up to approximately 500 years, it is the fission products that determine the radiotoxicity of spent fuel or immobilised high level waste and only marginal differences are expected between different systems. Beyond 500 years, where there are transuranics present in the spent fuel or immobilised high level waste, it is these that dominate radiotoxicity for up to 10^5 years. Low radiotoxicity on a timeframe of the order of 500 years is sometimes regarded as a desirable attribute of a fuel cycle because it might be feasible to argue that engineering barriers might retain their effectiveness up to that point. Spent uranium or MOX fuel assemblies and immobilised high level waste from uranium or MOX fuels will have high inventories of transuranics and therefore high long term radiotoxicity. Recycling transuranics in fast reactors can reduce the inventory in repository, possibly leading to low long term radiotoxicity. Fuel cycles based on the Th-232/U-233 fuel cycle have low transuranic inventories which give an intermediate level of radiotoxicity for spent thorium assemblies (in the once-through thorium cycle) and a lower level for immobilised waste from a closed Th-232/U-233 fuel cycle. Th-232/U-233 generally have higher radiotoxicities after 1E5 years.

3b.4 GDF Disposal Impact – Long Term Radiotoxicity - references

Insert

3b.4 GDF disposal impact – long term radiotoxicity



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02. Spent fuel mass

Spent fuel mass from SM-HTGRs will be much higher than SM-PWRs.

Assessed as 'Major Challenge'

02. Spent fuel mass

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).

For the recycle options the spent fuel arising is important only in that it determines the throughput and capacity of reprocessing plants,

02. Spent fuel mass - references

Insert

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03. VHLW volume

Volume of high level waste from SM-HTGRs will be far higher than SM-PWRs due to the much lower power density associated with SM-HTGRs.

Assessed as 'Extreme Challenge'

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Description

References

03. VHLW volume

This is the volume of high activity (heat generating) waste, expressed in m3 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.

03. VHLW volume - references

Insert

05. Long term radiotoxicity

Radiotoxicity is dominated by burnup (which will be significantly higher in SM-HTGRs) and fuel type (which with UO_2 or UCO will be comparable to SM-PWRs). However, there is the added complications associated with the production of problematic C-14 and Cl-36 from irradiated graphite.

Assessed as 'Significant Challenge'

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Description

References

05. Long term radiotoxicity

The radiotoxicity is a measure of the hazard potential of radioactive material. Radiotoxicity can be measured as the potential dose from the waste in Sieverts (Sv) per Gwye, or by Toxic Potential, which measures the dilution required to allow dissolved waste to meet dose standards if used for drinking.

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 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.

05. Long term radiotoxicity - references

Insert

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3b.5 GDF disposal impact – isotopes driving safety case

Significant complications surrounding the production of C-14 and Cl-36 which are problematic radionuclides due to their long half lives, mobility and bio-compatibility.

Assessed as 'Significant Challenge'

3b.5 GDF disposal impact – isotopes driving safety case

As GDF safety cases are generally driven by long-lived mobile fission and activation products rather than by radiotoxicity per se, this attribute assesses any material differences in mobile isotope yields on a per GWye basis.

3b.5 GDF disposal impact – isotopes driving safety case - references

Insert

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3c. Siting

Summary

SM-PWRs already offer significant benefits attached to lower demands on cooling water and grid connections if the aim is to deploy a dispersed network. SM-HTGRs are able to replicate the benefits attached to SM-PWRs in addition to being able to offer process heat to a greater number of industrial customers.

Most SM-HTGR concepts tend to operate at the lower end of SMR system thermal outputs (less than or approximately equal to 100 MWth) and the concepts do not envisage deploying dozens of units at one site to achieve the equivalent electrical output from a single large PWR.

Assessed as 'Minor Benefit'

Attributes

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Description

References

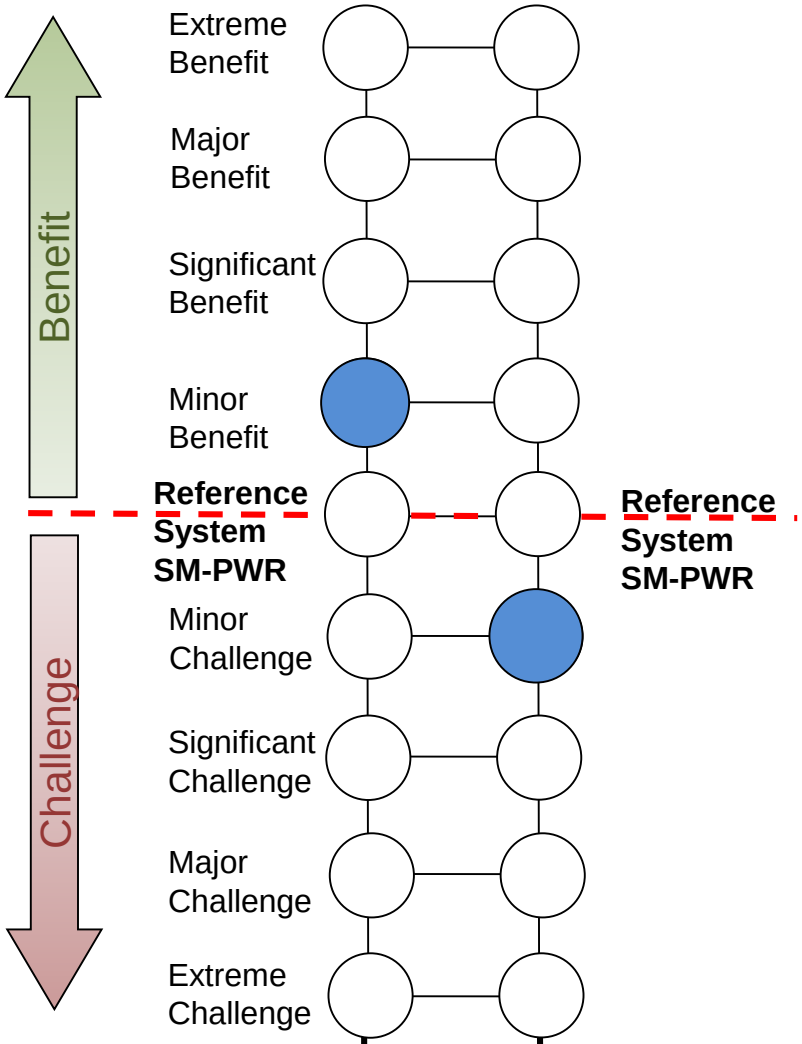
3c. Siting

Reactor systems can be commercially available, competitive, and reliable but all require sites with adequate access to cooling water, power transmission. This Strategic Attribute therefore examines the relative technical suitability of siting reactors and fuel cycle plants across the range of total generation capacity which may be required.

3c Siting - references

Insert

3c. Siting



3c.2 Siting – associated fuel cycle plants

3c.1 Siting - number and size of reactors c/f likely site availability

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Description

3c.1 Siting – number and size of reactors c/f likely site availability

SM-PWRs already offer significant benefits attached to lower demands on cooling water and grid connections if the aim is to deploy a dispersed network. SM-HTGRs are able to replicate these benefits attached to SM-PWRs in addition to being able to offer process heat to a number of industrial customers.

Assessed 'Minor Benefit'

Metrics

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Description

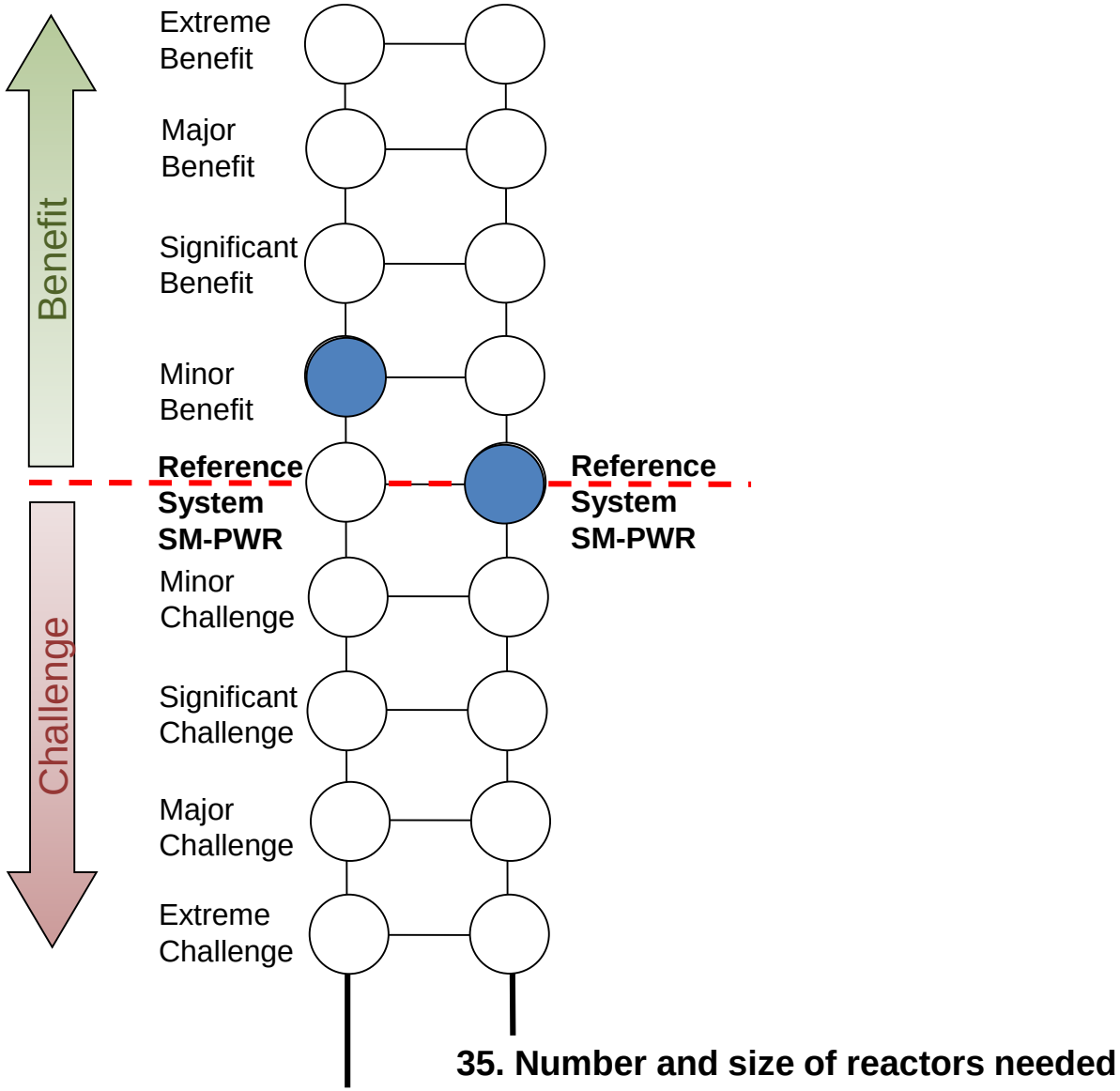
3c.1 Siting – number and size of reactors

3c.1 is intended to measure of how flexible reactor siting would be. It may be possible for small reactors to be sited at locations that would be unsuitable for large reactors on account of reduced land area required and reduced cooling water requirement. It may be possible for a reactor system which, in the event of Design Basis accidents, does not require evacuation outside the site boundary, to be sited more closely to dense concentrations of population.

3c.1 Siting – number and size of reactors - references

Insert

3c.1 Siting - number and size of reactors c/f likely site availability



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32. Flexibility of location

Comparable benefits to SM-PWRs but with the added flexibility of being able to provide process heat to a number of industries.

Assessed as 'Minor Benefit'

32. Flexibility of location

Reactors will have varying siting demands depending on their output and any dependence of co-siting with, for example, fuel cycle plants. Small reactors will make smaller demands on cooling water and grid connections, but will require more sites to reach the same installed output.

32. Flexibility of location - references

Insert

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35. Number and size of reactors needed

The size of the SMR modules will directly affect the number of reactors per GWe installed. Most SM-HTGR concepts tend to operate at the lower end of SMR system thermal outputs (less than or approximately equal to 100 MWth) and the concepts do not envisage deploying dozens of units at one site to achieve the equivalent output from a single large PWR.

Assessed as 'Reference'

35. Number and size of reactors needed

The size of individual reactors will directly affect the number of reactors needed per GWe installed. The effects on numbers of sites and on economics are examined elsewhere,

35. Number and size of reactors needed - references

Insert

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3c.2 Siting – associated fuel cycle plants

SM-PWR would have central facilities for manufacturing fuel (as SM-PWRs do) and spent fuel storage would be similar to SM-PWRs. However, SM-HTGRs would need to identify a commercial supplier capable of producing large quantities of TRISO based fuel.

Assessed as 'Minor Challenge'

Metric - 36. Fuel cycle plants

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Description

References

3c.2 Siting – associated fuel cycle plants

3c.2 covers the need of closed reactor systems for reprocessing, waste processing and fuel refabrication plants. Many outline schemes assume co-location of reactor and fuel cycle plants – but, in nuclear scenarios with large contributions from closed systems, this carries the consequence of either (a) very large generation capacity at one site or (b) multiple sites and fuel cycle plants.

3c.2 Siting – associated fuel cycle plants - references

Insert

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36. Fuel cycle plants

SM-HTGRs would need to identify a commercial supplier capable of producing large quantities of TRISO based fuel.

Assessed as 'Significant Challenge'

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Description

References

36. Fuel cycle plants

The fuel cycle plants needed for the various reactor system options are potentially very different.

36. Fuel cycle plants - references

Insert

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4a. Access to international programmes

SM-PWRs offers strong potential for international collaboration. HTGRs, being less mature, further expand the benefits attached to access to international programmes. UK engagement in design, modelling and testing would be a fertile area for maintaining and developing expertise. It would help provide a positive focus for UK nuclear R&D.

Assessed as 'Minor Benefit'

Metric - 4a.1 Re-engagement in international programmes

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Description

References

4a. Access to international programmes

This Strategic Attribute assesses whether access to (or indeed the formation of) international programmes could aid the eventual deployment of a reactor system. The single Attribute assesses the information on the credibility of the route and on its possible timescale for deployment.

4a. Access to international programmes - references

Insert

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4a.1 Re-engagement in international programmes

Strong potential for international collaboration. SM-HTGR would help provide a positive focus for UK nuclear R&D.

Assessed as 'Minor Benefit'

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Description

References

4a.1 Re-engagement in international programmes

This Attribute assesses whether access to (or indeed the formation of) international programmes could aid the eventual deployment of a reactor system. The single Attribute assesses the information on the credibility of the route and on its possible timescale for deployment.

4a.1 Re-engagement in international programmes - references

Insert

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4b. Time and Cost to Deployment

Summary

SM-HTGRs are less mature than SM-PWRs and will therefore take longer to deploy. However, many of the fundamental HTGR technologies are well-demonstrated and therefore time and cost to deployment is considered a minor challenge over SM-PWRs.

Assessed as 'Minor Challenge'

Attributes

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Description

References

4b. Time and Cost to Deployment

This Strategic Attribute takes in information from the assessment of Strategic Attributes 1a, 1b, 1c and from Attribute 4a above, to assess the overall timescale on which the system could be deployed. This will be placed in the context of the relative economics of the system and its match to the market, which are examined under High Level Discriminator 2 – Competitiveness. The Technology Readiness level will be an assessment, with the grounds for that assessment given, while the Deployment Time should be a time in years, with the reasons and uncertainties stated.

In determining the timescale, funding for R&D activities will be assumed to be available as required, and regulatory effort will also be assumed to be available. Funding for reactor build will also be assumed to be available as required. The estimated time to deployment will be the time from the GFA to the time of power production by the first UK reactor

4b. Time and Cost to Deployment - references

NNL 12415 – Manchester Report on TRL of Gen IV Systems

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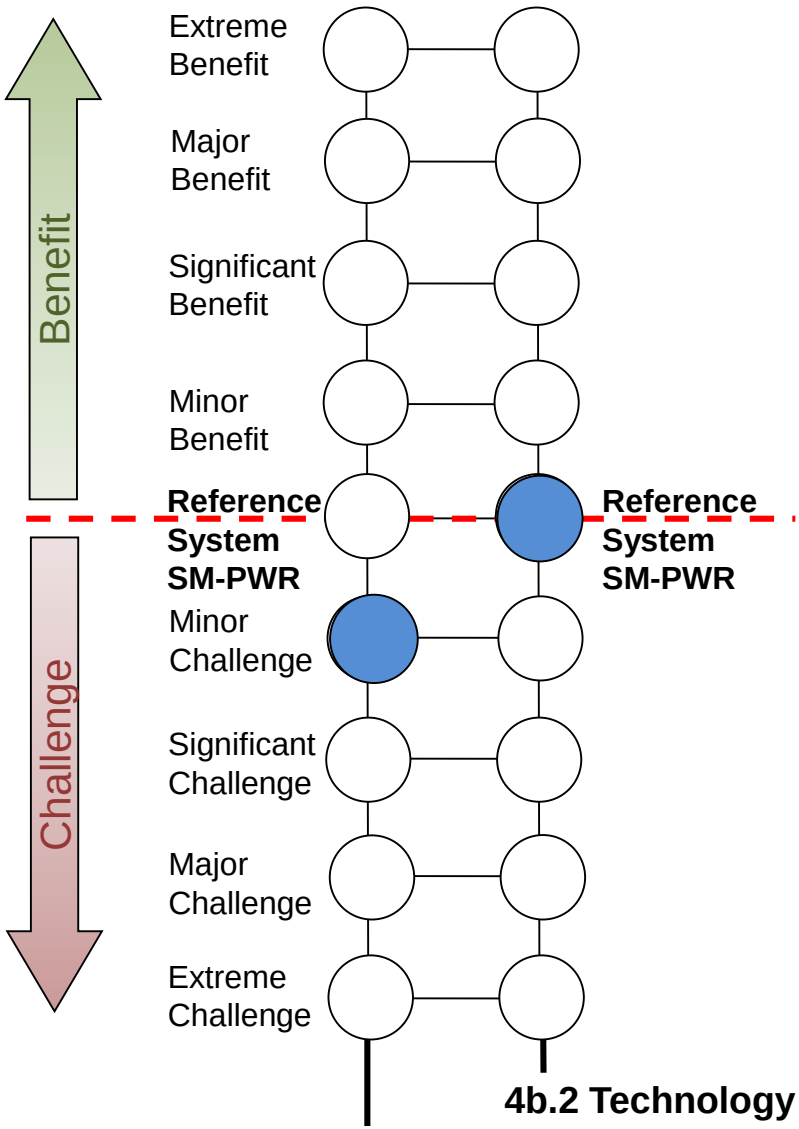
4b. Time and Cost to Deployment



4b.2 Technology Readiness level

4b.1 Commercial availability. Deployment time, plus feed from 1 and 2a

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Description

4b.1 Commercial availability – Deployment Time

HTGR technology is relatively mature with a number of small prototype HTGRs operated in recent years. Furthermore, significant R&D has been on going to qualify the performance of TRISO fuel, which HTGRs are dependent on to achieve many of their stated benefits. However, there are currently no commercial suppliers of TRISO fuel and any SM-HTGR project will need to ensure they have all of the material test data to prove that the specified graphite grade will operate within design limits. Furthermore, there may be issues (such as graphite oxidation and/or graphite dust production) that require experimentation/modelling to provide data to support licensing.

It is judged that over a 10 year period, with sufficient resources dedicated, the above issues could be addressed. This would give time for regulators to become more informed regarding HTGR technology. Then a standard 5 year GDA process and 5 year FOAK build is assumed. Hence, current designs of SM-HTGRs therefore are unlikely to achieve commercial deployment until at least around 2035.

Assessed as 'Minor Challenge'

4b.1 Commercial availability – Deployment Time

4b.1 (Deployment time) is the earliest time until the first unit could become operational. It builds on the assessment under in Strategic Attributes 1a, 1b, 1c and 2, and the effect of any international programmes available from 4a.1.

4b.1 Commercial availability – Deployment Time - references

Insert

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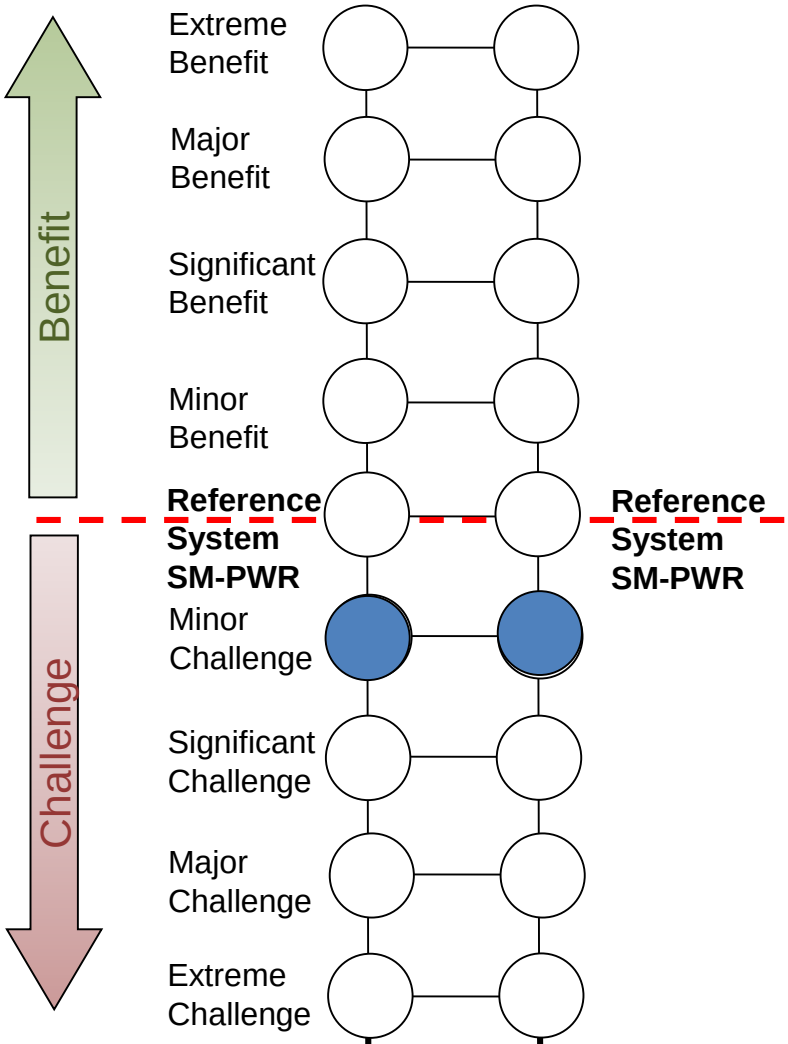
4b.1 Commercial availability



30. Timescales for deployment

25. Development costs

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25. Development costs

SM-HTGR designs will likely require more experimentation/modelling to support licensing relative to SM-PWRs.

Assessed as 'Minor Challenge'

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Description

References

25. Development costs

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.

25. Development costs - references

Insert

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30. Timescales to deployment

HTGR technology is relatively mature with a number of small prototype HTGRs operated in recent years. Furthermore, significant R&D has been on going to qualify the performance of TRISO fuel, which HTGRs are dependent on to achieve many of their stated benefits. However, there are currently no commercial suppliers of TRISO fuel and any SM-HTGR project will need to ensure they have all of the material test data to prove that the specified graphite grade will operate within design limits. Furthermore, there may be issues (such as graphite oxidation and/or graphite dust production) that require experimentation/modelling to provide data to support licensing.

It is judged that over a 10 year period, with sufficient resources dedicated, the above issues could be addressed. This would give time for regulators to become more informed regarding HTGR technology. Then a standard 5 year GDA process and 5 year FOAK build is assumed. Hence, current designs of SM-HTGRs therefore are unlikely to achieve commercial deployment until at least around 2035.

Assessed as 'Minor Challenge'

30. Timescales to deployment

The timescale at which any new system could be deployed would be of high relevance to strategic planning in the UK.

In determining the timescale, funding for R&D activities will be assumed to be available as required, and regulatory effort will also be assumed to be available. Funding for reactor build will also be assumed to be available as required. The estimated time to deployment will be the time from the GFA to the time of power production by the first UK reactor

30. Timescales to deployment - references

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4b.2 Technology Readiness Level

No SMR designs yet to progress beyond TRL 5 (Demonstration of a basic system). This determines the minimum timescale to deployment.

Assessed as 'Reference'

Metric - 31 Technology Readiness Level

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Description

References

4b.2 Technology Readiness Level

4b.1. and 4b.2 combine to give a likely timescale for deployment in the UK. For reactor systems which are already commercially available, this is determined by the lead time for pre-licensing in the UK, the lead time for site approval and the construction time. For systems which are not yet commercially available, an additional lead time would be required for the system to be developed to commercial readiness, with the lead time being longest for systems which are at an early stage of R&D.

This assessment will give an idea of the likely deployment time in the UK. This needs to be compared with the timescales indicated in the Strategic Attributes 1a, 1b and 1c, to come to a consolidated overall view.

4b.2 Technology Readiness Level - references

NNL 12415 – Manchester Report on TRL of Gen IV Systems

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31. Technology Readiness Level

SM-HTGR is assessed at TRL 5 (Demonstration of a basic system). This determines the minimum timescale to deployment.

Assessed as 'Reference'

31. Technology Reference Level

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

31. Technology Readiness Level - - references

NNL 12415 – Manchester Report on TRL of Gen IV Systems

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4c. Meet and enable UK supply chain

Summary

SM-HTGRs presents increased opportunity for UK involvement in the supply chain, but the ability of the UK to realise this potential will be challenging.

The deployment of more mature SMR technology would seem to offer limited potential for UK supply chain involvement, with the UK largely restricted to manufacturing components to a given design/specification.

By contrast, less mature designs may offer increased potential for UK supply chain, with the possibility of UK design expertise being input to develop component designs from the beginning and higher value.

Assessed as 'Minor Benefit'

Attribute - 4c.1 Supply chain opportunities

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Description

References

4c. Meet and enable UK supply chain

Summary

This Strategic Attribute examines the possibility of opportunities for the UK supply chain, providing an additional incentive for UK involvement in any particular reactor system.

4c. Meet and enable UK supply chain - references

Insert here

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4c.2 Supply chain opportunities

SM-HTGRs are less mature than SM-PWRs, which favours supply chain opportunities.

Assessed as 'Minor Benefit'

4c.2 Supply chain opportunities

This Attribute should attempt to assess the level of UK supply chain involvement that could accompany the development and deployment of a given system

4c.2 Supply chain opportunities - references

Insert

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5a Meets Energy Requirements - load follow capability

SMR-HTGRs as thermal reactors have the same limitation on power as the reference case because of Xe poisoning. However, SM-HTGRs have some advantage in that they are not susceptible to pellet clad interactions on power rises, which are most damaging after operation for lengthy periods at lower power. The TRISO fuel is very resilient to power changes and should be able to load follow within reactivity constraints.

Assessed as 'Minor Benefit'

Attribute - 5a.1 Flexibility – load follow capability

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Description

References

5a Meets Energy Requirements - load follow capability

This Strategic Attribute assesses the ability of systems to respond to particular features of a future energy market. For example, if the percentage of nuclear electricity on the grid is high, and coupled with a significant randomly variable output from renewables, then nuclear systems may be required to load follow. Some systems are much more amenable to this than others.

4c.2 Supply chain opportunities - references

Insert

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5a.1 Flexibility – load follow capability

SMR-HTGRs as thermal reactors have the same limitation on power as the reference case because of Xe poisoning. However, SM-HTGRs have some advantage in that they are not susceptible to pellet clad interactions on power rises, which are most damaging after operation for lengthy periods at lower power. The TRISO fuel is very resilient to power changes and should be able to load follow within reactivity constraints.

Assessed as 'Minor Benefit'

Metric – 28. Load follow capability

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Description

References

5a.1 Flexibility – load follow capability

5a.1 measures the ability of the reactor system to operate in non-baseload or load-follow mode. This is the ability of the reactor to increase or decrease output either in response to short term grid demands or in pre-planned load scheduling. If the total installed capacity of nuclear stations in the UK is only a small or modest fraction of the grid capacity, there is unlikely to be a major requirement for load-follow capability. However, if the nuclear capacity grows sufficiently, with only limited electricity storage capacity, there may come a point at which load-follow will be required, as is the case currently in France. Many current reactors are able to load-follow, but with limitations. Future reactor systems may be able to operate in load-follow mode without such restrictions, hence their ability to load follow will be compared, both from one system to another, and with the current LWR reference systems.

5a.1 Flexibility – load follow capability - references

Insert

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28. Load follow capability

SMR-HTGRs as thermal reactors have the same limitation on power as the reference case because of Xe poisoning. However, SM-HTGRs have some advantage in that they are not susceptible to pellet clad interactions on power rises, which are most damaging after operation for lengthy periods at lower power. The TRISO fuel is very resilient to power changes and should be able to load follow within reactivity constraints.

Assessed as 'Minor Benefit'

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Description

References

28. Load follow capability

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.

28. Load follow capability - references

Insert

5b. Meets energy requirements – Process Heat

As currently configured, SM-HTGR has a reactor outlet temperature of 800°C, which is adequate for some, but not all, industrial processes. However, there are a number of key industries (such as cement and steel) that require temperatures significantly above 800°C in their production processes, and the production of hydrogen using thermo-chemical processes ideally requires outlet temperatures around 1000°C. Current technology would involve temperature 'boosts', using heat pumps for example, to raise outlet temperatures.

HTGRs capable of producing hydrogen could have a role in future energy mixes that utilise hydrogen for industrial processes, for maintaining grid stability and/or helping to decarbonise transport.

Assessed as 'Major Benefit'

Attribute - 5b.1 Industrial process heat – potential to drive thermal processes

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Description

References

5b. Meets energy requirements – Process Heat

This Strategic Attribute assesses the ability of systems to respond to particular features of a future energy market. For example If sectors such as transport are to be decarbonised, for example by use of hydrogen as an energy vector, then the ability of a reactor system to provide high grade heat (rather than electricity) to power chemical processes could be a significant advantage.

5b. Meets energy requirements – Process Heat - references

Insert

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Description

5b.1 Industrial process heat – potential to drive thermal processes

As currently configured, SM-HTGR has a reactor outlet temperature of 800°C, which is adequate for some, but not all, industrial processes. However, there are a number of key industries (such as cement and steel) that require temperatures significantly above 800°C in their production processes, and the production of hydrogen using thermo-chemical processes ideally requires outlet temperatures around 1000°C. Current technology would involve temperature 'boosts', using heat pumps for example, to raise outlet temperatures.

HTGRs capable of producing hydrogen could have a role in future energy mixes that utilise hydrogen for industrial processes, for maintaining grid stability and/or helping to decarbonise transport.

Assessed as 'Major Benefit'

Metrics

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Description

References

5b. 1 Industrial process heat – potential to drive thermal processes

5b.1 indicates whether the system has the potential to drive thermal processes, such as combined heat and power (CHP), hydrogen production, synthetic fuel production and as a heat source for other industrial processes to displace carbon emitting fossil fuel heating. For thermal applications, a high operating temperature is beneficial, which leads to a simple description based on three levels of temperature:

- LOW TEMPERATURE – Low operating temperatures similar to those of current Light Water Reactors (LWRs) ~300-320°C.
- MEDIUM TEMPERATURE – Medium operating temperatures in range 320-600°C beyond the range accessible with LWRs.
- HIGH TEMPERATURE – High operating temperatures >600°C.

5b. 1 Industrial process heat – potential to drive thermal processes - references

Insert

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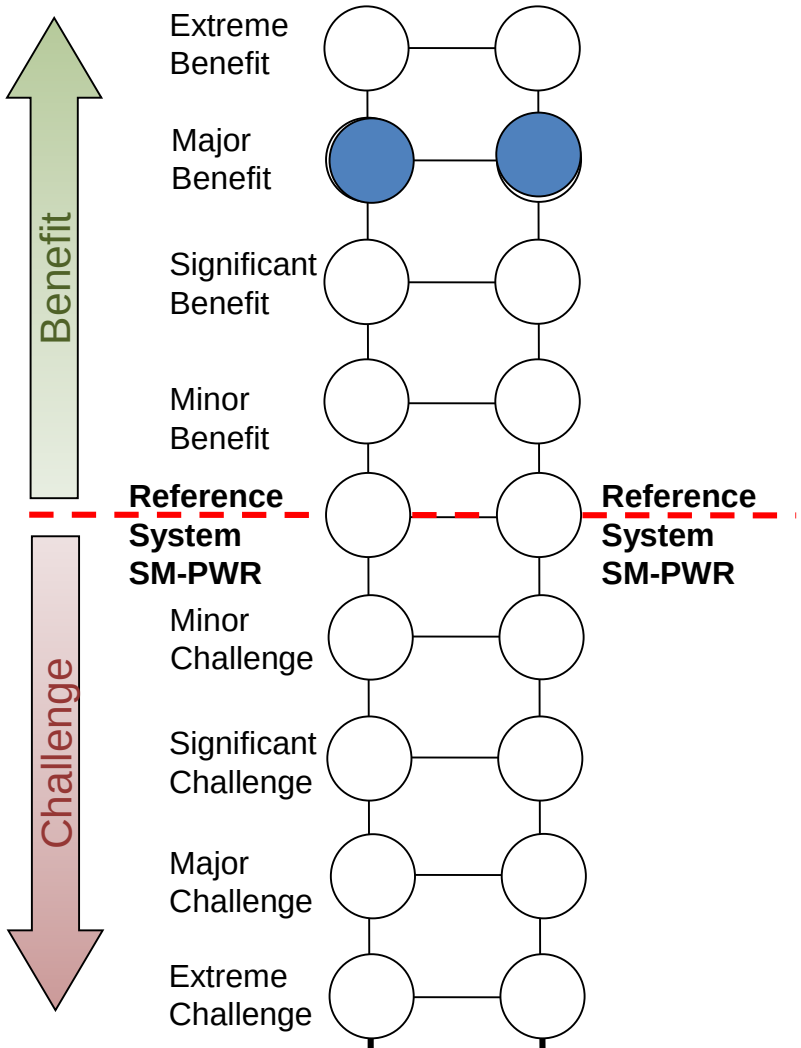
Description

5b.1 Industrial process heat – potential to drive thermal processes



42. Primary purpose

40. Potential to drive thermal processes

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Description

40. Potential to drive thermal processes

The SM-HTGR has a reactor outlet temperature of 800°C. There are a large number of industries that require process heat at temperatures up to 800°C. However, there are a number of key industries (such as cement and steel) that require temperatures significantly above 800°C in their production processes. Future HTGR designs are likely to be designed with significantly higher outlet temperatures for gas turbine cycles, these could also provide higher quality heat.

Recent interest in HTGRs has been focused on their ability to produce hydrogen using thermo-chemical processes. Hydrogen production ideally requires outlet temperatures around 1000 °C. However, many of the hoped for breakthroughs in hydrogen production have not materialised. Therefore the ability to provide process heat for hydrogen production is currently of limited interest.

Assessed as 'Major Benefit'

40. Potential to drive thermal processes

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 systems (eg LFR, MSR and VHTGR) may be able to achieve very high primary circuit operating temperatures compatible with high temperature process heat applications.

40. Potential to drive thermal processes - references

Insert

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42. Primary purpose

Many SM-HTGRs are designed primarily to provide industrial process heat.

Assessed as 'Major Benefit'

42. Primary purpose

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.

42. Primary purpose - references

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NATIONAL NUCLEAR LABORATORY

The Generic Feasibility Assessment:
An Essential Ingredient in Nuclear Policy making

Assessment Matrix with Descriptions

Subject System: **SM thermal MSR**

Reference System: **Generic SM-PWR**

Template: **13**

Date of Assessment: **24th February 2016.** Modified to generalise references to Regulators. 20th December 2017

Skip to Assessment

IDM
integrated decision management

Return to Start

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Reference and Subject Systems

Reference System:

Small Modular PWR (SM-PWR)

Subject System:

A Generic Small Modular Thermal Spectrum MSR (SM-MSThR) with an electric capacity of less than 300 MWe. It should be capable of being deployed in multiple units. It is novel technology which has been partially demonstrated at prototype level in the Oak Ridge Molten Salt Reactor Experiment (MSRE), but which will require long term development. The fuel cycle can be uranium-plutonium (P-Pu) or thorium-uranium (Th-U233). SM-MSThR is assumed to have only a basic reprocessing system, with removal of volatile gases and no separation of fissile materials.

IDM
integrated decision management

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Dalton Nuclear Institute

Work in Progress

NATIONAL NUCLEAR LABORATORY

Version Development

2015.08.08 Initial GFA of Generic SMR based on 2014 assessment inserted into updated format Template 12

2015.12.08 Kevin Hesketh & Aiden Peakman

2015.12.13 Gregg Butler – removal of spread of Fuel Security assessments

2016.01.11 Kevin Hesketh - modified to incorporate actions agreed at Workshop on 2015.12.11 and 5 Jan meeting

2016.02.08 Minor connection glitches removed – slides 62-82

2016.02.24 Checked/mods accepted for Draft Report

2017.12.20 Modified to generalise references to Regulators

References

This Generic Feasibility Assessment draws upon extensive work by NNL on nuclear energy technology assessment, IAEA, OECD/NEA, USDOE and other international literature. Individual references have not been included in the current draft GFA. It is anticipated that as more information becomes available relating to specific Attributes or Metrics, this might either further validate or modify the GFA. This additional information can then be referenced in the appropriate places in the GFA Template.

IDM
integrated decision management

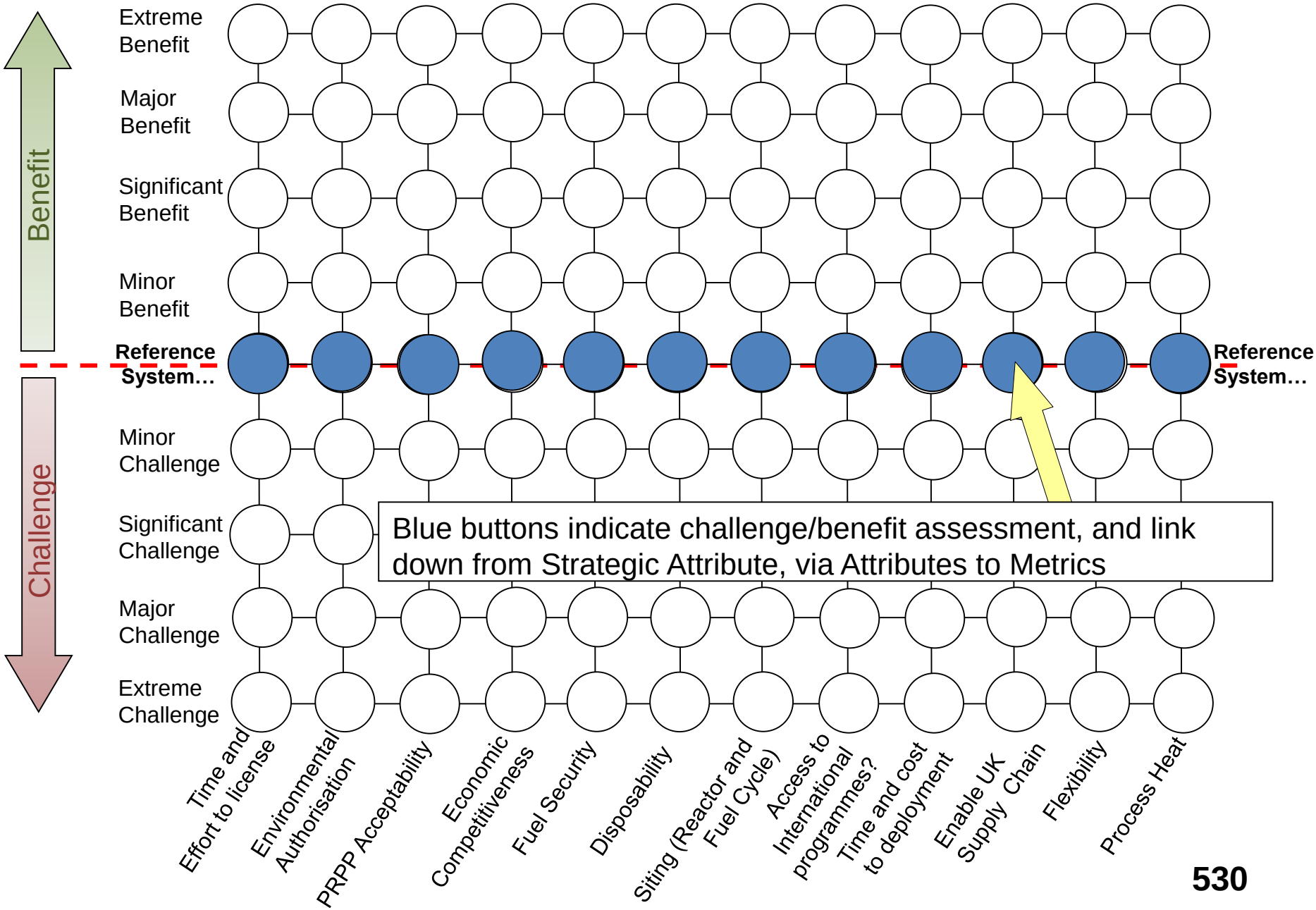
What is Generic Feasibility Assessment?

- GFA was developed for DECC to provide a high level strategic evaluation of nuclear reactor and fuel cycle systems
- It operates by making comparisons between the 'Subject System' and a Reference System, initially 'once-through LWR' as envisaged for new nuclear build in the UK
- The analysis uses 12 Strategic Attributes, using public domain information and informed professional judgement to assess the relative degree of benefit or challenge offered by the Candidate System.

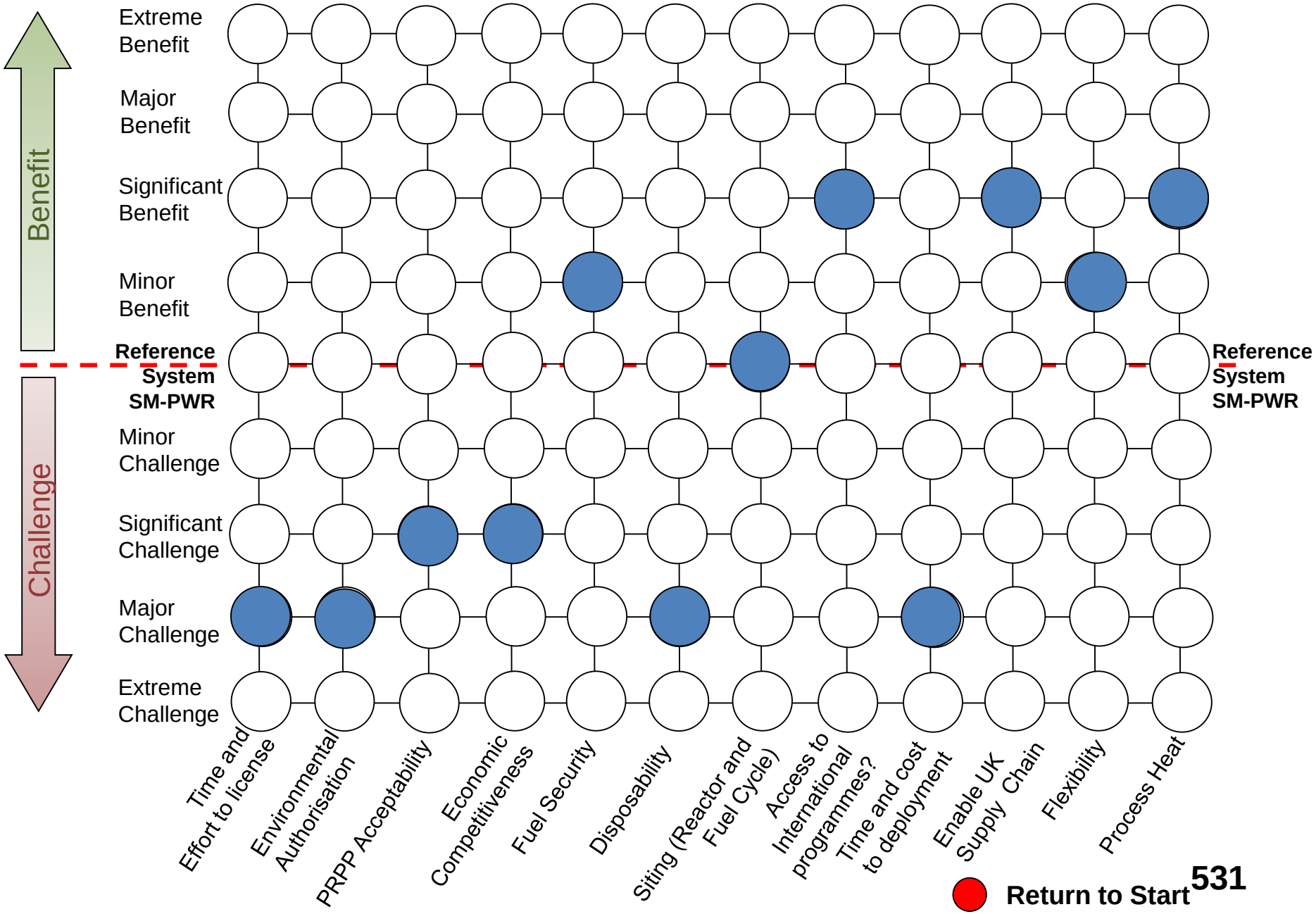
What is Generic Feasibility Assessment?

- GFA presents a high level, accessible visual representation of benefits and challenges, while allowing more detailed interrogation of the underpinning rationale and data
- As all information is public domain, any additional evidence can, and will, lead to modification of the assessment: GFA assessments are always 'Work in Progress'
- A full description of how GFA was derived and developed is available at: www.dalton.manchester.ac.uk/gfa
- This Visualisation provides a guide to how GFA is built up, the definitions of Strategic Attributes, Attributes and Metrics, and demonstrates how the information and logic tree can be navigated.

GFA Assessment Subject System: SM-MSThR Reference System: Generic SM-PWR – *Work in Progress*



GFA Assessment Subject System: SM-MSThR Reference System: Generic SM-PWR – *Work in Progress*



1a. Time and Effort to License

Summary

The overall assessment is that SM-MSThR will require considerably more design and development effort than the SM-PWR Reference System and the timescales for commercial readiness will be correspondingly longer.

Assessed as 'Major Challenge'

Attributes

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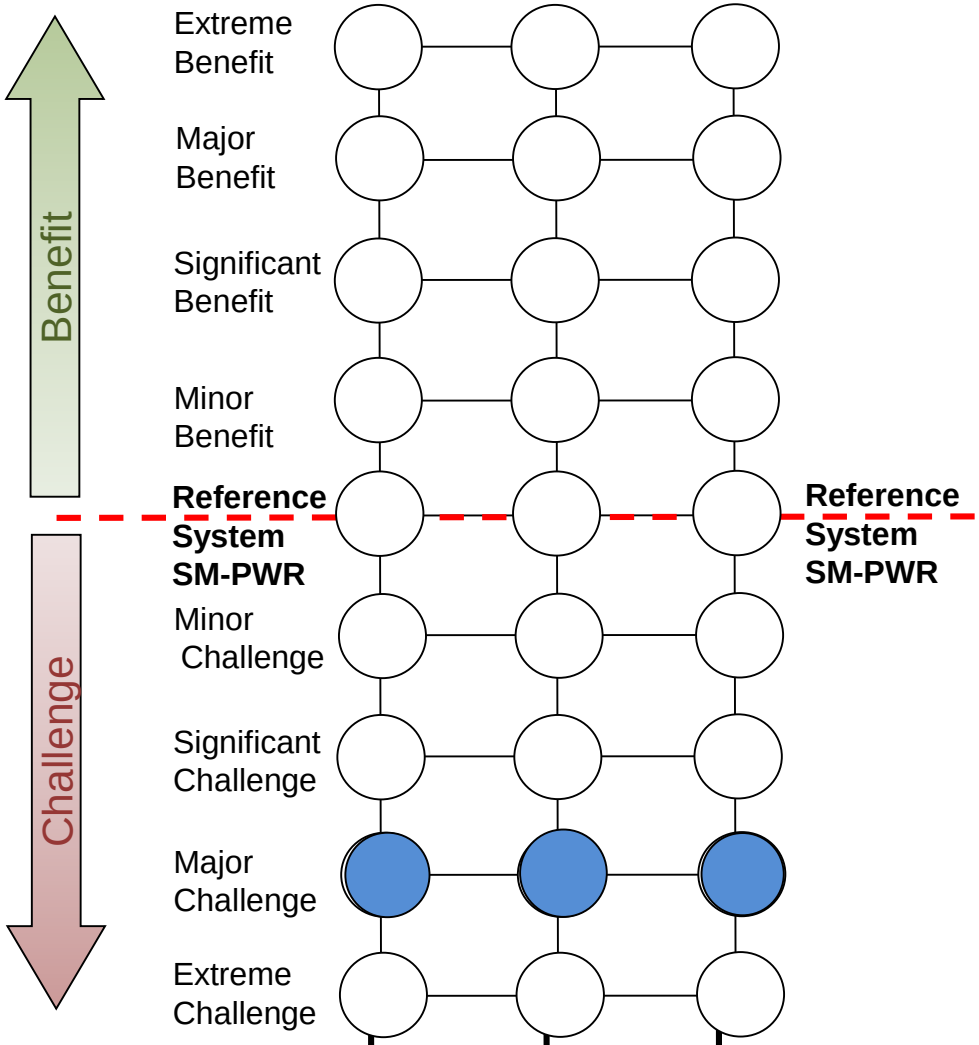
Description

1a. Time and Effort to License



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Description

1a.3 Effort to meet radiological regulations

1a.2 Timescale required to demonstrate that Safety Regulation Requirements can be satisfied

1a.1 Effort to satisfy Safety Regulation Requirements

1a. Time and Effort to License

Nuclear facilities in the UK are required to comply with the requirements set down by the appropriate regulatory bodies. Safety and licensing requirements are the responsibility of the Office of Nuclear Regulation (ONR), which also sets the radiological protection requirements for occupational exposure and members of the public.

Any reactor system to be deployed in the UK must be demonstrated to be safe, and to do so the reactor system must adhere to the fundamental safety principles as laid down by the licensing regulator. ONR has defined a series of Safety Assessment Principles known by the acronym 'SAPs'. These SAPs are seen as the top level goals which any system for deployment in the UK must be able to meet. The SAPs framework provides ONR with a set of guidelines by which ONR inspectors can make consistent judgements on nuclear safety assessment.

The top level safety criterion can be posed as: ***How much time and effort will be involved to allow the reactor system to meet the various UK safety regulatory requirements?***

From this top level criterion, the following attributes are obtained:

- ***Nuclear safety and regulation. What challenges must be met to enable the reactor system to meet well developed*** **Safety Regulation Requirements** ***(Button 1a.1)and on what timescale can such compliance be demonstrated? (Button 1a.2)***
- ***Radiological regulation. What challenges must be met to enable the reactor system to comply with the radiological dose limits defined by regulators for workers and members of the public? (Button 1a.3)***

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1a.1 Effort to satisfy Safety Regulation Requirements

Summary

SM-MSThR will require a long term design and development programme before it is ready licensing. Although the Oak Ridge Molten Salt Reactor Experiment (MSRE) demonstrated aspects of the technology, world experience is very limited and MSR remains at a low TRL.

Assessed as 'Major Challenge'

Metrics

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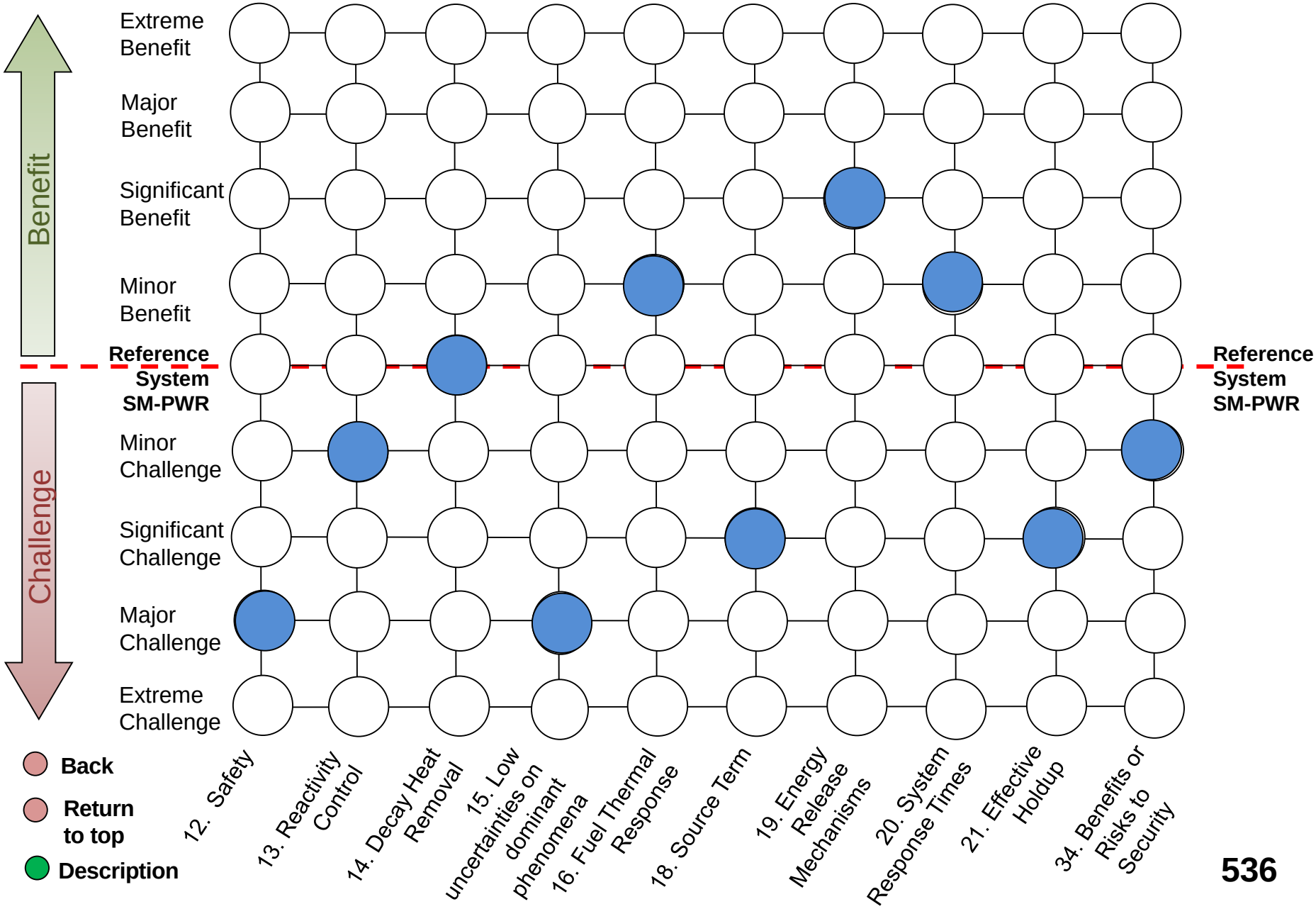
Description

References

1a.1 Effort to satisfy Safety Regulation Requirements



1a.1 Effort to satisfy Safety Regulation Requirements

1a.1 assesses the challenge faced by a reactor system in meeting the goals defined by the Safety Regulation Requirements. Levels of challenge would be expected to increase as the system examined moves further away from current experience, for example:

- Systems which are already deployed commercially or whose designs are already licensed in other countries.
- Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.
- Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.
- Systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

Assessments will assume that regulatory effort is available when and as required

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12. Safety

The approach to constructing a safety case for SM-MSThR will necessarily be very different to those for a conventional solid fuel reactor. This is dictated by the fact that in an MSR the normal operating condition is with the fuel melted and therefore some of the barriers to release of fission products, actinides and activation products in a solid fuel reactor no longer apply. Although MSR designs are typically characterised by strong negative temperature feedback coefficients, un-pressurised systems, tolerance of high temperatures, large thermal inertias and passive decay heat removal, these features per se may not necessarily make the safety case easy to demonstrate. There will need to be extensive experimental test data available that will substantiate all aspects of the safety case. At present this database does no exist and it is arguable whether the experience gained with MSRE will count for much beyond having demonstrated initial proof of concept.

Assessed as 'Major Challenge'

12. Safety

Any new reactor system deployed in the UK would need to meet very stringent safety standards. Some of the systems considered will rely on passive safety and this might distinguish them from other systems that rely on conventional active safety systems.

12. Safety - references

Insert here

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13. Reactivity Control

The strong negative temperature feedback coefficients that are typical of MSRs are generally considered a favourable feature (though positive moderator temperature coefficients have been reported for graphite MSRs). However, the Reference SM-PWR also is characterised by strong negative temperature coefficients for most of its operating cycle, so in this sense the two systems are more similar than they might at first appear to be. Strongly negative feedback coefficients do not eliminate the need for two independent reactor shutdown systems and indeed the positive reactivity insertion on cool-down to shutdown conditions is made worse by strong negative feedback. Cooldown faults are also adversely affected.

SM-MSThR will need a mechanism to control excess reactivity.

Demonstrating adequate reactivity control is assessed to be a Minor Challenge on account of the novelty of SM-MSThR.

Assessed as 'Minor Challenge'

13. Reactivity Control

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. Shutdown means that the reactor must be demonstrated to be sub-critical (k-eff < 0.95), taking account of calculation uncertainties and one stuck control/shutdown rod with the reactor cooled to ambient temperature.

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.

13. Reactivity Control - references

Insert

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14. Decay Heat Removal

The generic SM-MSThR is assumed to have passive decay heat removal, as does the Reference System. It is expected that a considerable amount of design and development effort, including test data will be needed to support the safety case for decay heat removal.

.

Assessed as 'Reference'

14. Decay Heat Removal

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. SM-MSThR would typically rely on passive decay heat removal, which is the same as the Reference System.

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.

14. Decay Heat Removal - references

Insert

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15. Low uncertainties on dominant phenomena

The safety behaviour of SM-MSThR is not demonstrated and therefore the dominant phenomena necessarily have large uncertainties.

Assessed as 'Major Challenge'

15. Low uncertainties on dominant phenomena

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.

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15. Low uncertainties on dominant phenomena - references

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16. Fuel Thermal Response

SM-MSThR would be expected to have a large thermal inertia on account of the mass and specific heat capacity of the molten salt, though possibly countered by a high power density. Compared with the Reference System, fuel thermal response times would be slower, which is beneficial.

Assessed as 'Minor Benefit'

16. Fuel Thermal Response

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.

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16. Fuel Thermal Response - references

Insert

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18. Source Term

The source term for an MSR is substantially different to that from a solid fuel reactor, since the fission products, actinides and fuel activation products are in the molten salt. The mobilities of the various radionuclide species in the molten salt under normal operating and fault conditions are uncertain and will need to be substantiated.

The source term for SM-MSThR will be lower than for conventional reactors if fission products are actively removed during operation, which may be a significant benefit. The equilibrium fission product inventory depends on the rate of fuel salt processing and the decontamination factors that are achievable. At present, fuel salt processing is at the conceptual design stage and it is too soon to know what is achievable. Different fission products may achieve different equilibrium levels, if the decontamination factors vary. This will certainly apply to gaseous fission products. There is a tendency to focus on the fission product equilibrium inventories in the core and this potentially overlooks the fact that the fission products will still be physically present at the reactor site and therefore there will retain their hazard potential.

The timescale and effort required to substantiate the Source Term leads to the assessment of Significant Challenge, despite there potentially being a significant performance benefit.

Assessed as 'Significant Challenge'

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Description

References

18. Source Term

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.

18. Source Term - references

Insert

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19. Energy Release Mechanisms

The fuel salt is relatively inert and not vulnerable to oxidative reactions.
This is an area where SM-MSThR ranks highly compared with conventional reactors because of the absence of fuel cladding that can undergo energetic oxidation.

Assessed as 'Significant Benefit'

19. Energy Release Mechanisms

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.

19. Energy Release Mechanisms - references

Insert

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20. System response times

The system response for SM-MSThR depends on the specific rating, which in some designs may be higher than LWR. A large mass of fuel salt in a pool-type arrangement would increase system response times. This suggests fuel thermal response times somewhat larger than LWRs, but with high specific ratings extended thermal response times cannot be expected.

Assessed as 'Minor Benefit'

20. System response times

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.

20. System response times - references

Insert

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21. Effective Holdup

This refers to the holdup of volatile fission products in accident scenarios. The containment for SM-MSThR will differ considerably conventional reactors and the uncertainties associated with holdup calculations will require extensive integral systems testing.

Assessed as 'Significant Challenge'

21. Effective Holdup

Effective hold-up refers to mechanisms in the design of a plant for containing radioactive material following an accident condition. The hold-up of volatile fission product will impact the containment design will affect whether there is a requirement for off-site evacuation procedures to be in place.

21. Effective Holdup - references

Insert

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34. Benefits or challenges for security

In SM-MSThR the molten fuel salt, either in the reactor or in the associated fuel cycle plant, is in principle more vulnerable to fissile material diversion than a solid fuel form. Therefore inherent self-protection might be considered to be reduced relative to the Reference System. Security requirements will not be affected by considerations of inherent self-protection.

Assessed as 'Minor Challenge'

34. Benefits or challenges for security

Inherent Proliferation Resistance and Proliferation Protection PRPP is an area which needs to be assessed for new reactor systems according with best practice set out by IAEA INPRO and GIF. The threats considered are diversion of fissile material by a state and acquisition of radioactive materials by an illegal sub-national group. Both threats are considered by OCNS as part of defining the security and safeguards requirements and these requirements are not affected in inherent PRPP. Inherent PRPP is simply to be regarded as a fall-back protective feature that would apply in the hypothetical case of a nuclear system falling outside national controls.

34. Benefits or challenges for security - references

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1a.2 Timescale required to demonstrate that Safety Regulation Requirements can be satisfied

In the UK the Generic Design Approval (GDA) process is new and only EPR has been through it in its entirety. The process for EPR took almost 6 years, but the experience gained should allow future LWRs to gain approval within 4 years or so. ONR already had expertise in PWR safety assessment and this must have been helpful for the GDA. For MSR there is currently no expertise within ONR. ONR would require an application for a GDA from an MSR designer before building up an assessment team. It is unlikely that the GDA process would be as straightforward as EPR because the safety case approach will be substantially different to conventional reactors and may require a reinterpretation of the Safety Assessment Principles.

A reasonable expectation might be that the SM-MSThR designer would already have developed the design and safety justification to a very mature stage before applying for GDA, with a significant amount of development testing having already taken place to support the design and safety justification. Given the immature present state of design, this is not considered likely in less than 20 years. Assuming a minimum 5 years for ONR to assess the design, this lead to a minimum timescale of 25 years for a GDA to be completed for SM-MSThR.

.

Assessed as 'Major Challenge'

1a.2 Timescale required to demonstrate that Safety Regulation Requirements can be satisfied

1a.2 assesses how long it might reasonably be expected to take to demonstrate that the system can satisfy stringent Safety Regulation Requirements**.** Levels of challenge would be expected to increase as the system examined moves further away from current experience, for example:

- Systems which are already deployed commercially or whose designs are already licensed in other countries.
- Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.
- Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.
- Systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

Assessments will assume that regulatory effort is available when and as required

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1a.2 Timescale required to demonstrate that SAPs can be satisfied - references

Insert

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1a.3 Effort to meet radiological regulations

In the absence of engineered designs, it is not possible at this stage to assess the ability of SM-MSThR to meet radiological regulations. There are likely to be major challenges with maintenance of primary circuit components (moderator, pumps, valves and heat exchangers) which will be highly contaminated with fission products and will need to be engineered for remote inspection and maintenance. Radiological doses in the gas and solid fission product processing plants will also need to be addressed, as will doses in the plants used to condition and dispose of the fuel salt.

.

Assessed as 'Major Challenge'

Metric - 11. Worker Exposures

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Description

References

1a.3 Effort to meet radiological regulations

1a.3 assesses the difficulty likely to be experienced in meeting the worker radiological protection requirements defined by regulators, noting that this includes the reactor and its fuel cycle. Levels of challenge would be expected to increase as the system examined moves further away from current experience, for example:

- Systems which are already deployed commercially or whose designs are already licensed in other countries.
- Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.
- Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.
- Systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

Assessments will assume that regulatory effort is available when and as required

1a.3 Effort to meet radiological regulations - references

Insert

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11. Worker Exposures

It is difficult to assess worker exposures for SM-MSThR because none of the proposed designs have yet been developed to the stage where detailed understanding of the maintenance requirements and dose uptake is available. Given that SM-MSThR deviates considerably from solid fuel reactors and the large radionuclide inventories in the fuel salt in the primary circuit, this is assessed as posing a Major Challenge.

Assessed as 'Major Challenge'

11. Worker Exposures

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.

11. Worker Exposures - references

Insert

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1b. Time and Effort for Environmental Permitting

Summary

SM-MSThR is assessed to require considerable further design and development in order to be able to satisfy environmental permitting requirements.

Assessed as 'Major Challenge'

Attribute – 1b.1 Effort to meet environmental regulations

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Description

References

1b. Time and Effort for Environmental Permitting

Nuclear facilities in the UK are required to comply with the requirements set down by the appropriate regulatory bodies. Environmental regulations are the responsibility of the Environment Agencies (EA,NRW, SEPA) and are implemented through the granting of site aerial and liquid Discharge Authorisations. The Environment Agencies are also responsible for the authorisation of solid waste disposal.

1b. Time and Effort for Environmental Permitting - References

Insert

1b.1 Effort to meet environmental regulations

It is too soon to judge whether SM-MSThR and its associated fuel cycle will be able to meet environmental regulatory requirements. MSR represents a major departure from solid fuel experience and environmental discharge routes for gases are insufficiently understood.

With respect to doses to the workforce, it is likely that small modular SM-MSThR will display substantial differences. The details will be design specific and currently none of the proposed small modular LWR designs are likely to be mature enough for this requirement to be addressed.

Assessed as 'Major Challenge'

Metric – 06 Environmental Impact

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Description

References

1b.1 Effort to meet environmental regulations

1b.1 assesses the challenge faced by a reactor system in meeting the environmental impact requirements defined by the regulators, noting that this includes the reactor and its fuel cycle. This parameter is assumed to refer to routine operational environmental discharges. Levels of challenge would be expected to increase as the system examined moves further away from current experience, for example:

- Systems which are already deployed commercially or whose designs are already licensed in other countries.
- Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.
- Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.
- Systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

Assessments will assume that regulatory effort is available when and as required

1b.1 Effort to meet environmental regulations - references

Insert

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06. Environmental Impact

It is too soon to know if SM-MSThR and its associated fuel cycle plants are capable of meeting environmental regulations. In terms of discharges to the environment and doses to members of the public, the proposed are not yet developed to the point where discharges can be reliably estimated.

Assessed as 'Major Challenge'

06. Environmental Impact

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.

06. Environmental Impact - references

Insert

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1c. Proliferation Resistance and Physical Protection (PRPP) Acceptability

Summary

The once-through LWR fuel cycle is internationally recognised as the reference system for inherent PRPP assessments. Given that the fuel form of SM-MSThR makes access to fissile material and other radioactive materials potentially more accessible than spent fuel from solid fuel reactors, there is the potential for the inherent PRPP performance to be less favourable.

PRPP is taken to have a dual meaning, with Proliferation Resistance referring to state involvement in diversion of fissile materials and Physical Protection concerned with the threat of acquisition of nuclear materials by a sub-national group. The assessments are potentially different for the two aspects.

Assessed as 'Significant Challenge'

Attributes

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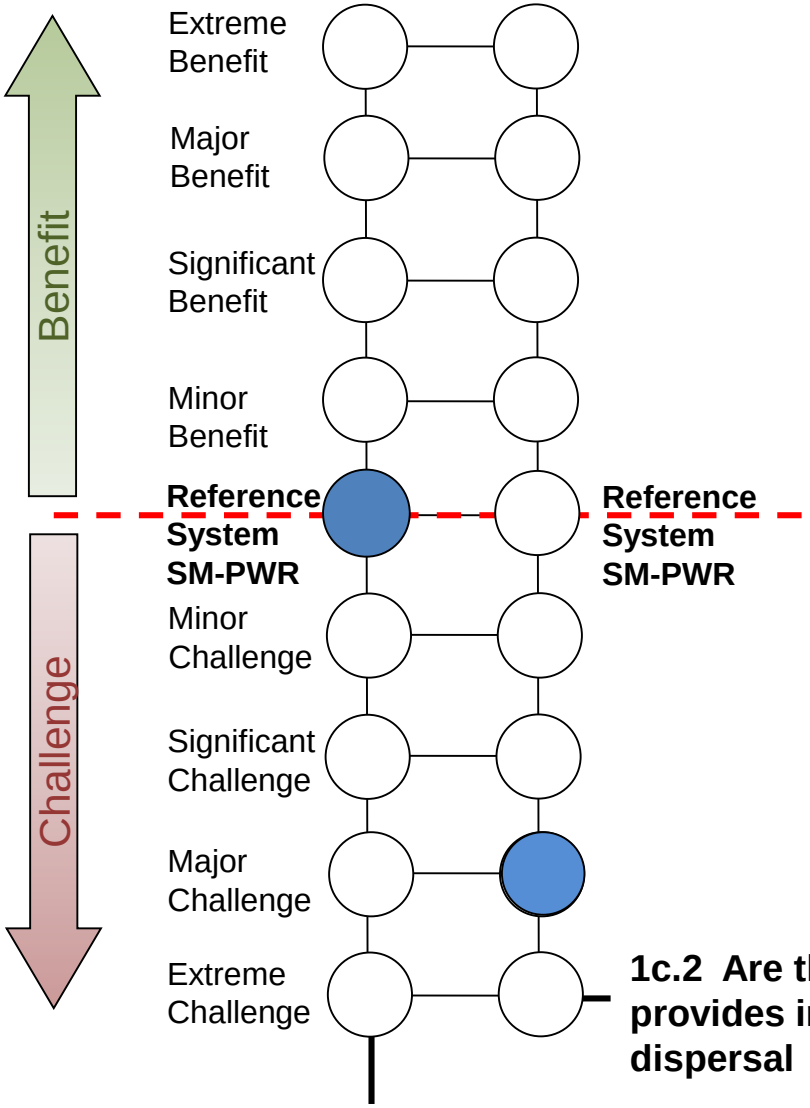
Description

1c. Proliferation Resistance and Physical Protection (PRPP) Acceptability



1c.2 Are the nuclear materials in a form that provides inherent self-protection against theft or dispersal

1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage

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1c. Proliferation Resistance and Physical Protection (PRPP) Acceptability

Any new system deployed in the UK will be required to satisfy the Nuclear Industries Security Regulations 2003. This is a system which responds to the nuclear processes being carried out and the amount and form of nuclear materials being used, and ensures that a system is in place which will “prevent the theft or sabotage of nuclear material or the sabotage of nuclear facilities”. The Office of Civil Nuclear Security (OCNS) is the responsible regulator.

UK situation is that, while systems may not accord with the ideals of PRPP, yet there are systems, monitored and enforced by OCNS, which ensure risks of theft or sabotage are maintained at acceptably low levels. Thus while it is highly relevant to monitor the PRPP characteristics of nuclear reactor systems, the value of this Attribute in the UK context is predominantly to be judged by policy makers. The assessment will, however, give an indication of the challenges to be met in order to generate an approved Security Plan for the candidate system.

The top level PRPP criterion can be posed as: *“Are the nuclear materials produced in the fuel cycle difficult to access?”*

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1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage

Depending on the specific fuel cycle SM-MSThR may produce separated fissile material by irradiation of fertile material, which is unfavourable relative to the once-through LWR fuel cycle. SM-MSThR is assumed not to separate fissile material and therefore is assessed as Reference.

Assessed as 'Reference'

Metrics

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Description

References

1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage

This attribute accounts for the physical forms of fissile materials in the fuel cycle. The levels of challenge will vary between:

Fuel cycles in which high grade fissile materials are present at any stage, for example high enriched uranium (HEU) or plutonium, which will be considered to present considerable PRPP challenges. Examples would include a fuel cycle based on HEU fuel or the separation of pure plutonium for recycle (as in conventional PUREX reprocessing).

A LWR fuel cycle with low enriched uranium (LEU) and a once-through fuel cycle will present a lower level of PRPP challenge.

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1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage - references

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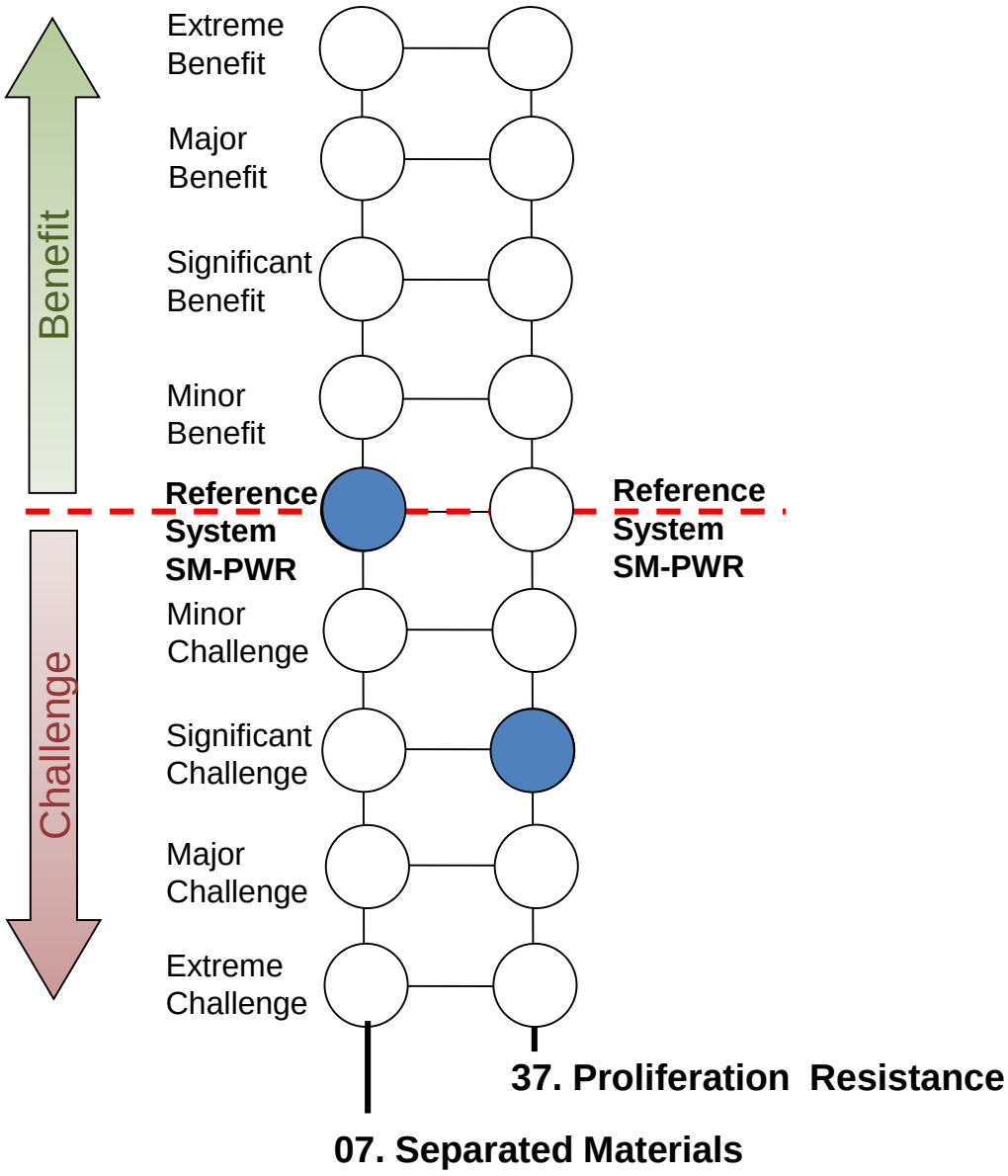
1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage



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07. Separated Materials

Depending on the specific fuel cycle SM-MSThR may produce separated fissile material by irradiation of fertile material, which is unfavourable relative to the once-through LWR fuel cycle. SM-MSThR is assumed not to separate fissile material and therefore is assessed as Reference.

Assessed as 'Reference'

07. Separated Materials

One of the PRPP goals of advanced systems is that they 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.

07. Separated Materials - references

Insert

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37. Proliferation Resistance

The once-through LWR fuel cycle is internationally recognised as the reference system for inherent PRPP assessments. Given that the fuel form of SM-MSThR makes access to fissile material and other radioactive materials potentially more accessible than spent fuel from solid fuel reactors, there is the potential for the inherent PRPP performance to be less favourable.

Assessed as 'Significant Challenge'

37. Proliferation Resistance

There is increasing interest in international reactor systems development to be able to demonstrate increased proliferation resistance by design, and different reactor systems may be considerably differentiated by inherent proliferation resistance. 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. SM-MSThR fuel comprises molten salt where the fissile material is relatively easily separated in an on-line reprocessing plant.

37. Proliferation Resistance – references

Insert

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1c.2 Are the nuclear materials in the fuel cycle in a form which provides inherent self-protection against theft or dispersal

The nuclear materials from a SM-MSThR may potentially be in a form which offers substantially less self-protection than the LWR once-through fuel cycle. The presence of fissile materials in a liquid phase makes tracking more difficult and, potentially, makes illicit extraction easier.

The reference system does not include reprocessing, but depending on the fuel cycle adopted, SM-MSThR may produce separated U-233. Although the U-233 would be expected to be contaminated with U-232, the daughter products of which produce a strong gamma emitter. However, the radiation field so produced, although too intense to allow unshielded handling in a licensed fuel cycle plant, would be insufficient to result in rapid incapacitation in a scenario where a sub-national group attempted to acquire fissile material without shielding measures.

Assessed as 'Major Challenge'

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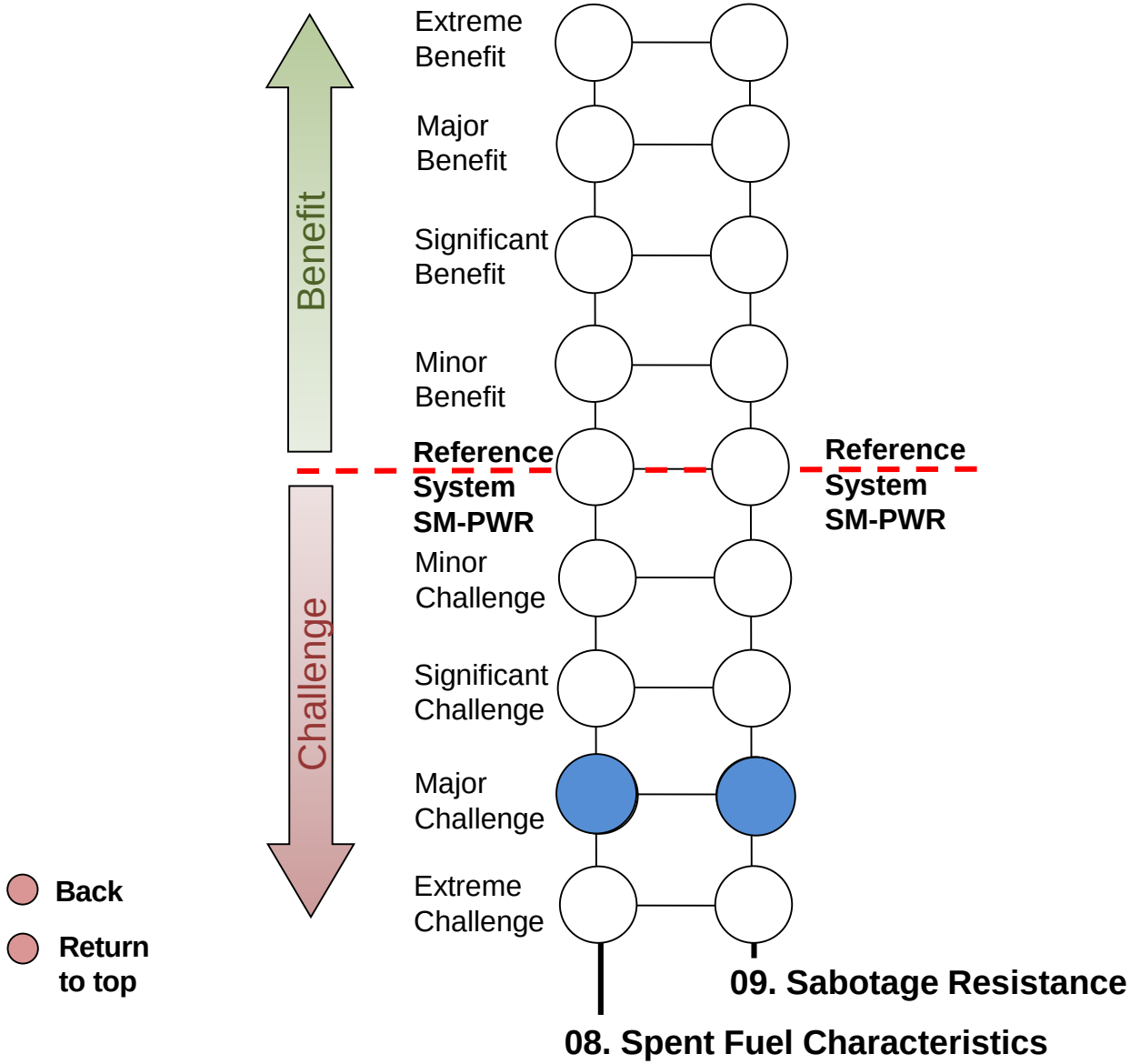
Description

References

1c.2 Are the nuclear materials in the fuel cycle in a form which provides inherent self-protection against theft or dispersal



1c.2 Are the nuclear materials in the fuel cycle in a form which provides inherent self-protection against theft or dispersal

1c.2 (Inherent PRPP). This attribute tests whether nuclear material is inherently protected by physical or chemical form, or by a strong self-protective radiation field. It is also intended to test whether the material is in a form that could be readily dispersed. Illustrations of levels of challenge are:

- a once-through fuel cycle with uranium oxide fuel in which there are multiple inherent barriers to accessing fissile material.
- fuel cycles which involve the production at some stage of unirradiated HEU fuel or plutonium oxide powder which present no inherent barriers.

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1c.2 Are the nuclear materials in the fuel cycle in a form which provides inherent self-protection against theft or dispersal - references

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08. Spent fuel characteristics

In SM-MSThR spent salt may require interim storage, transport, immobilisation and disposal. MSR designs to date have not reached the stage of maturity where detailed design consideration of spent fuel salt management has been made. Pyro-processing technology is at a low stage of technology readiness. Detailed assessment of potential immobilisation forms for spent fuel salt will be required.

Assessed as 'Major Challenge'

08. Spent fuel characteristics

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. SM-MSThR fuel comprises molten salt where the fissile material is relatively easily separated in an on-line reprocessing plant.

08. Spent fuel characteristics - references

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09. Sabotage resistance

A detailed design assessment of the vulnerability of SM-MSThR to sabotage/missile attack will need to be made. The designs currently proposed are not at the stage where such an assessment can be made. By nature, fuel salt is very different to solid fuel reactors and this is assessed as posing a Major Challenge.

Assessed as 'Major Challenge'

09. Sabotage resistance

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 but in some of the systems, for example small modular PWRs, the nuclear island is largely sited underground and therefore exceptionally well protected.

09. Sabotage resistance - references

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2a. Economic Competitiveness

Summary

Although SMRs have the theoretical potential to improve economic competitiveness, there are some significant challenges that will need to be addressed. SM-MSThR are likely be penalised by historic scaling laws that favour large plants and will need to rely on new compensating mechanisms, such as cost savings from factory replication, lower risk financing and more favourable grid connection charges. In the absence of evidence to the contrary, SM-MSThR is assumed subject to the same scaling laws as the SM-PWR reference system. SM-MSThR is assessed at different levels for economic competitiveness, with R&D costs penalising it, which leads to an overall assessment as Significant Challenge.

Assessed as 'Significant Challenge'

Attributes
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Description

2a. Economic Competitiveness

The electrical generation cost is one of the principal criteria against which a nuclear system will be assessed – without a demonstrably economically competitive system, utilities are unlikely to invest.

The top level economics Attribute can be posed as: *Will the reactor system be economically competitive in the electricity generation market or in possible future heat generation markets?*

From this Strategic Attribute, the following Criteria are obtained:

Overnight construction cost. The cost of building and financing the nuclear system, usually expressed as £/MWe.

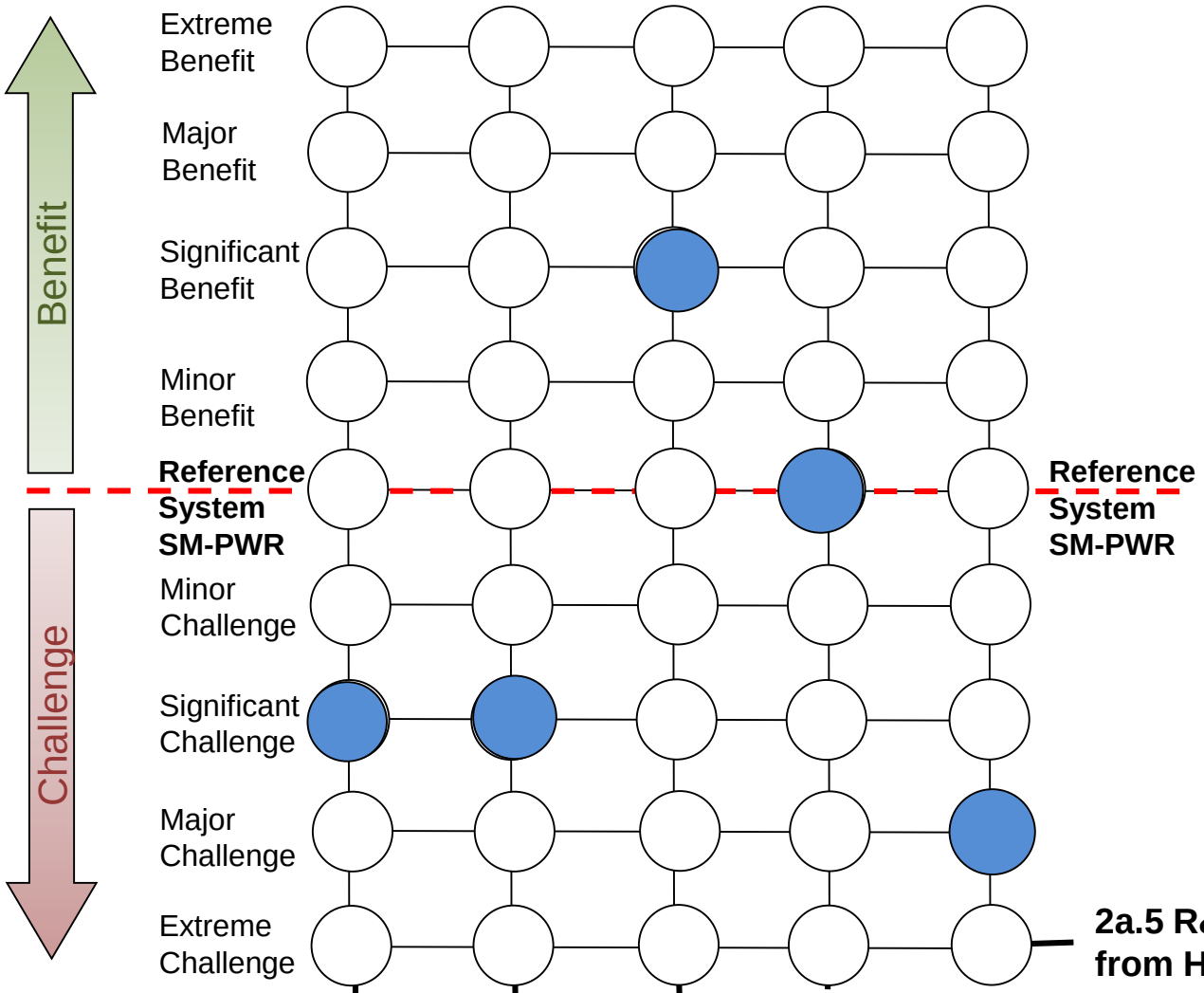
Operating and maintenance cost: This is the cost of operating and maintenance (O&M), taken to include staffing costs, operating costs (excluding fuel), the cost of routine maintenance and other related costs, usually expressed as a levelised cost in £/MWh.

Fuel cycle cost: This criterion is intended to capture the cost of operating the fuel cycle, both procuring new fuel and all the back-end costs associated with spent fuel management or reprocessing/recycle, usually expressed as a levelised cost in £/MWh.

Decommissioning cost: This is the actual cost of decommissioning *without* applying financial discounting, expressed as £/MWe.

R&D cost: This is the cost of the research and development programme needed to bring a system to commercial readiness. This will generally be an infeed into this attribute from High Level Discriminator 1 – Regulatory Challenges and Timescales.

2a. Economic Competitiveness



2a.5 R&D cost – feed from HLD1

2a.4 Decommissioning cost

2a.3 Fuel cycle cost – front and back end combined

2a.2 Operating and Maintenance cost

2a.1 Overnight construction cost

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Description

2a1. Overnight construction cost

For SMR generally there is an economy of scale penalty (for which there is a consensus), but with potential for savings from replication, factory build and increased modularisation. There is also the Potential for first module to finance later modules but note need for common infrastructure to be in place for the first module.

SM-MSThR is considered equivalent to the SM-PWR Reference System in this respect, with no evidence available that there will be different scaling laws on account of the design differences. However, the requirement for a secondary salt circuit takes the assessment to Significant Challenge.

Assessed as 'Significant Challenge'

Metrics

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Description

References

2a.1 Overnight construction cost

2a.1 (Overnight construction cost). The cost of building and financing the nuclear system, usually expressed as £/MWe. This attribute is the cost of construction and of financing construction, usually taken as the overnight construction cost with all financing costs discounted to the date at which the plant becomes operational. Included in this context, is the construction cost of any fuel cycle plants needed for fuel reprocessing, recycle or waste management. Illustrations of levels of challenge are:

- Plants with a high degree of modularisation and short construction times.
- Plants with a limited degree of modularisation and moderate construction times. This might apply to current large PWRs operating a once-through fuel cycle, for example.
- Complex plants with long and difficult construction demands. This might apply to systems involving extensive reprocessing and recycle.

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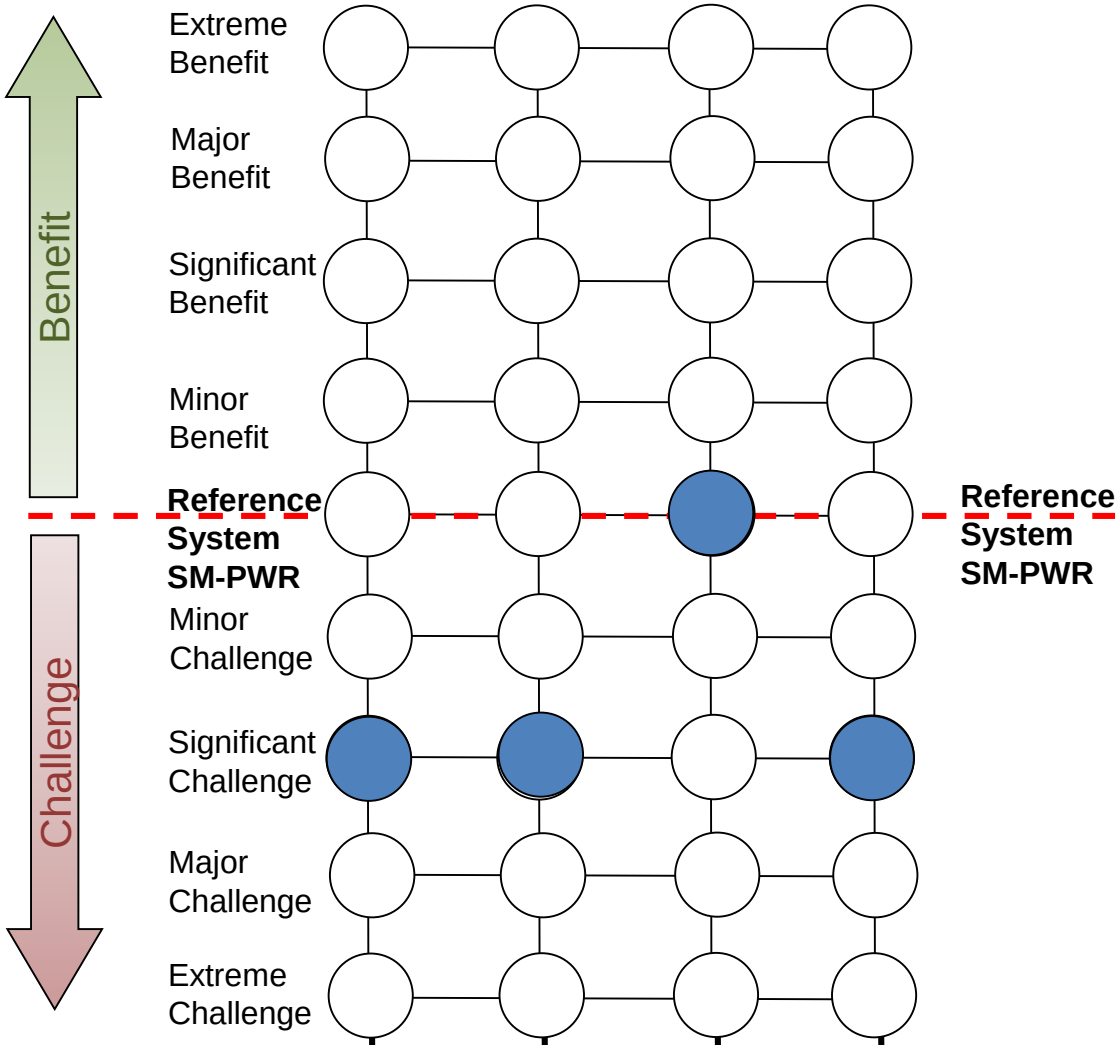
2a.1 Overnight construction cost



34. Ease of Construction

29. Scaleability

24. Construction Duration

22. Overnight construction cost

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Description

22. Overnight construction cost

For SMR generally there is an economy of scale penalty (for which there is a consensus), but with potential for savings from replication, factory build and increased modularisation. There is also the Potential for first module to finance later modules but note need for common infrastructure to be in place for the first module.

SM-MSThR is considered equivalent to the SM-PWR Reference System in this respect, with no evidence available that there will be different scaling laws on account of the design differences. However, the requirement for a secondary salt circuit takes the assessment to Significant Challenge.

Assessed as 'Significant Challenge'

22 Overnight construction cost

22 (Overnight construction cost). The cost of building and financing the nuclear system, usually expressed as £/MWe. This attribute is the cost of construction and of financing construction, usually taken as the overnight construction cost with all financing costs discounted to the date at which the plant becomes operational. Included in this context, is the construction cost of any fuel cycle plants needed for fuel reprocessing, recycle or waste management. Illustrations of levels of challenge are:

- Plants with a high degree of modularisation and short construction times.
- Plants with a limited degree of modularisation and moderate construction times. This might apply to current large PWRs operating a once-through fuel cycle, for example.
- Complex plants with long and difficult construction demands. This might apply to systems involving extensive reprocessing and recycle.

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22. Overnight construction costs - references

None of the SM-MSThR designs currently being developed have reached the stage where there is a detailed breakdown of construction costs.

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24. Construction duration

Short construction times reduces finance cost and risk with theoretically lower £/kWe. SM-MSThR designs currently being developed are not yet at the stage where short construction times are demonstrated. The goal of achieving short construction times can be considered no more than an aspiration at present. SM-MSThR is assessed as Significant Challenge compared with the generic SM-PWR because the plant layout is judged to be more complex on account of the requirement for a secondary circuit that would make short construction times more difficult to achieve.

Assessed as 'Significant Challenge'

24. Construction duration

The duration of plant construction has already been discussed under Item 22 (overnight construction cost) and the same assessment applies.

References

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24. Construction duration - references

Insert here

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29. Scaleability

Better fit to small grid systems. Not applicable to current UK grid. SM-MSThR is regarded equivalent to the SM-PWR Reference System in this respect.

Assessed as 'Reference'

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Description

References

29. Scaleability

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.

29. Scaleability - references

Insert

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34. Ease of Construction

Potential for SM-MSThR to reduce finance costs through lower risk in exactly the same way as the SM-PWR Reference System. SM-MSThR is assessed as Significant Challenge compared with the generic SM-PWR because the plant layout is judged to be more complex on account of the requirement for a secondary circuit that would make short construction times more difficult to achieve.

Assessed as 'Significant Challenge'

34. Ease of Construction

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.

34. Ease of Construction - references

Insert here

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2a.2 Operating and maintenance cost

Economy of scale penalty potentially offset by reduced maintenance requirements . Minimum manning level agreed with regulator a potential issue.
Grid connection cited as an area where SMRs can be beneficial, but not demonstrated. Operating and maintenance costs are potentially very challenging for SM-MSThR with active fuel salt potentially causing heavy contamination of the primary circuit. SM-MSThR is therefore assessed as Significant Challenge compared with SM-PWR Reference System.

Assessed as 'Significant Challenge'

Metrics

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Description

References

2a.2 Operating and maintenance cost

This Attribute covers the cost of operating and maintenance, taken to include staffing costs, operating costs (excluding fuel), the cost of routine maintenance and other related costs. Illustrations of levels of O&M costs are:

- Plants such as LWRs with long operating lives and no requirement for mid-life refurbishment of major plant items
- Plants with a requirement for through-life replacement of major components
- Complex plants with difficult operational requirements

2a.2 Operating and maintenance cost - references

None of the SM-MSThR designs currently being developed have reached the stage where there is a detailed breakdown of O&M costs.

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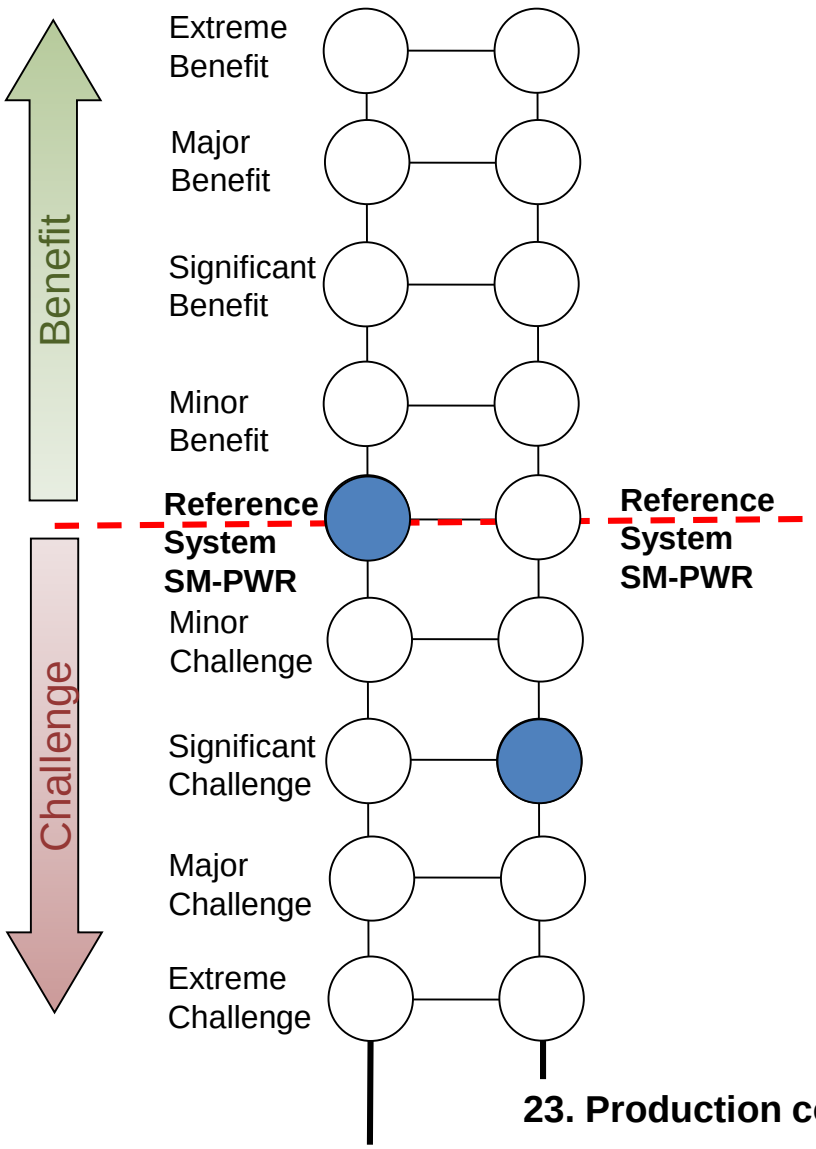
2a.2 Operating and maintenance cost



23. Production costs (O&M)

10. Reliability

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10. Reliability

Potential reduction in grid connection charge due to smaller loss of capacity from a single unit. But risk of loss of capacity of entire power station from common factors (eg loss of grid connection) unaffected. SM-MSThR equivalent to Reference SM-PWR Reference System in this respect.

Assessed as 'Reference'

10. Reliability

This is the forced outage rate, which should be very low. It is an operational safety and reliability issue, but it is also important for economics. Best operational practice at modern PWRs 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.

10. Reliability - references

Insert

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23. Production costs (O&M)

Economy of scale penalty potentially offset by reduced maintenance requirements .
Minimum manning level agreed with regulator a potential issue.
Grid connection cited as an area where SMRs can be beneficial, but not demonstrated.
SM-MSThR assessed as Significant Challenge compared with SM-PWR Reference System.

Assessed as 'Significant Challenge'

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Description

References

23. Production costs (O&M)

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. There is no distinction here between SM-MSThR and the SM-PWR Reference System.

23. Production costs (O&M) - references

None of the SM-MSThR designs currently being developed have reached the stage where there is a detailed breakdown of O&M costs.

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2a.3 Fuel cycle costs (front and back-end combined)

SM-MSThR designs will operate with partial fission product removal and fissile top-up leading to reduced spent fuel throughput. This is an advantage over the SM-PWR Reference System taken to use a multi-batch refuelling scheme.

Assessed as 'Significant Benefit'

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Description

References

2a.3 Fuel cycle costs (front and back-end combined)

2a.3 (Fuel cycle cost). This attribute is intended to capture the cost of operating the fuel cycle, both procuring new fuel and all the back-end costs associated with spent fuel management or reprocessing/recycle. Illustrations of varying levels of challenge with choice of fuel cycle are:

- the once-through LWR fuel cycle
- the closed LWR fuel, cycle (i.e. thermal recycle)
- a fast reactor system with recycle, especially if there was recycle of minor actinides.

2a.3 Fuel cycle costs (front and back-end combined) - references

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2a.4 Decommissioning costs

41. Decommissioning costs

No information available on decommissioning. Assumed equivalent to SM-PWR Reference System.

Assessed as 'Reference'

2a.4 Decommissioning costs

41. Decommissioning costs

2a.4 (Decommissioning cost). This attribute is intended to represent the actual cost of decommissioning without applying financial discounting. The decommissioning cost represents a significant risk element in financial analysis, even though the discounted cost is usually very low. Levels of challenge are illustrated by:

- A nuclear system with small, modular components compatible with disposal as self-contained units.
- Current LWRs where, after defueling, there are only medium active components that need to be decommissioned in the core.
- Systems with graphite moderation, such as the UK's legacy gas cooled reactors, due to the need to deal with large masses of material.

2a.4 Decommissioning costs - references

41. Decommissioning costs

Insert

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2a.5 R&D cost

R&D costs for SM-MSThR will be significant, since many aspects are currently at a very Technology Readiness Level (TRL). The time and effort needed for R&D is much higher than the SM-PWR Reference System.

Assessed as 'Major Challenge'

Metrics

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Description

References

2a.5 R&D cost

This Attribute covers the cost of the research and development programme needed to bring a system to commercial readiness. Illustrations of levels of R&D cost are:

- Those associated with an existing system or a minor development of an existing system
- Those associated with the evolution of a current system
- Those associated with novel systems involving significant innovations and long and extensive R&D

2a.5 R&D cost - references

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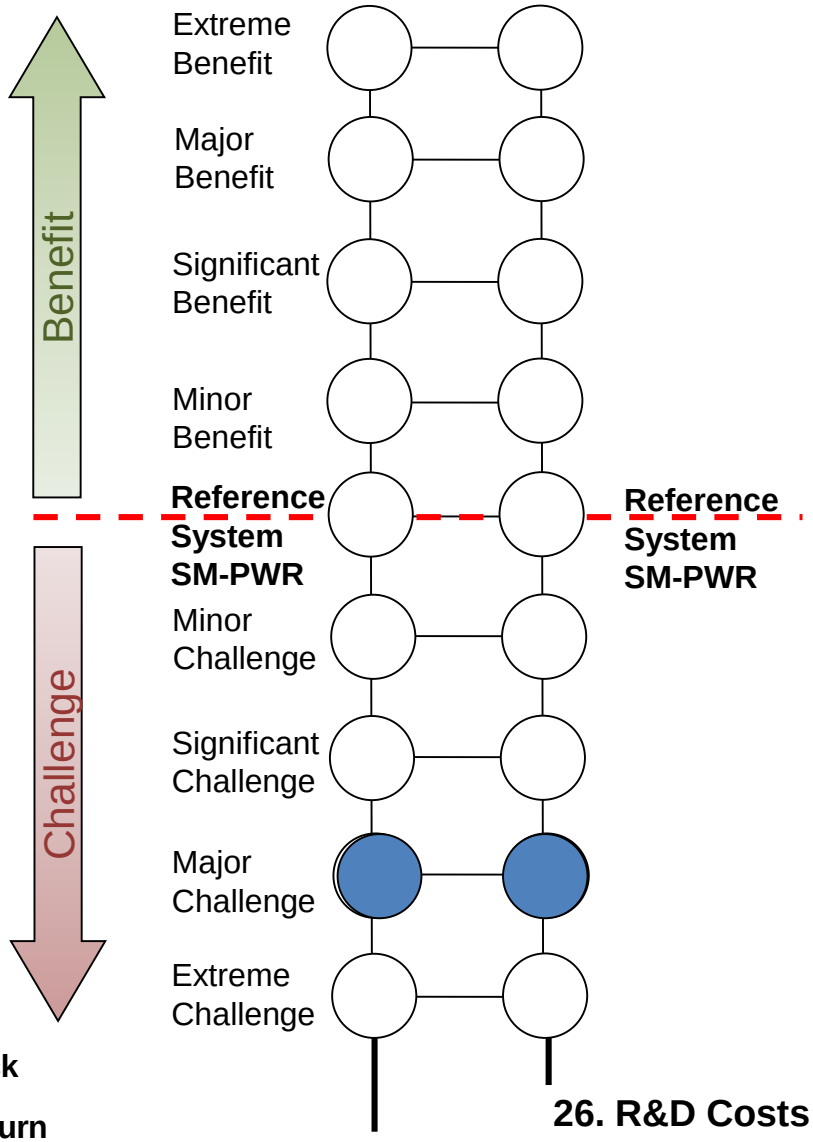
2a.5 R&D cost



26. R&D Costs

17. Integral experiment scaleability

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17. Integral experiment scaleability

Integral experiment data for SM-MSThR is confined to that obtained from operating the Molten Salt Reactor Experiment (MSRE). This was a proof of principle project that ran at a very low power density, with a total neutron fluence which would represent a very small proportion of that of the lifetime fluence of SM-MSThR. This represents a Major Challenge relative to the SM-PWR Reference System.

Assessed as 'Major Challenge'

17. Integral experiment scaleability

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.

17. Integral experiment scaleability - references

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26. R&D costs

R&D costs for SM-MSThR will be significant, since many aspects are currently at a very Technology Readiness Level (TRL). The time and effort needed for R&D is much higher than the SM-PWR Reference System.

.

Assessed as 'Major Challenge'

26. R&D costs

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. However, if the UK was to buy into technology that was not being developed elsewhere, the UK could incur the R&D costs and risks.

26. R&D costs - references

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3a. Fuel Security

Summary

If utilising a Th/U233 fuel cycle, SM-MSThR could in principle operate with a high conversion ratio or breeding cycle. In this instance, the system could operate independent of the world uranium market, which is beneficial for fuel security. Also, the fuel form does not require fuel assembly fabrication and so is less tied to specific fuel vendors. SM-MSThR can operate with a U-Pu or a Th-U fuel cycle. However SMThR is assessed as only a Minor Benefit because the reference system is specified as not having full reprocessing.

Assessed as 'Minor Benefit'

Attributes

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Description

References

3a. Fuel Security

Summary

This Strategic Attribute assesses whether fissile materials are available to start up a reactor system, and whether the supplies are sufficient and secure enough to fuel the reactor(s) over their projected lifetime

3a. Fuel Security - references

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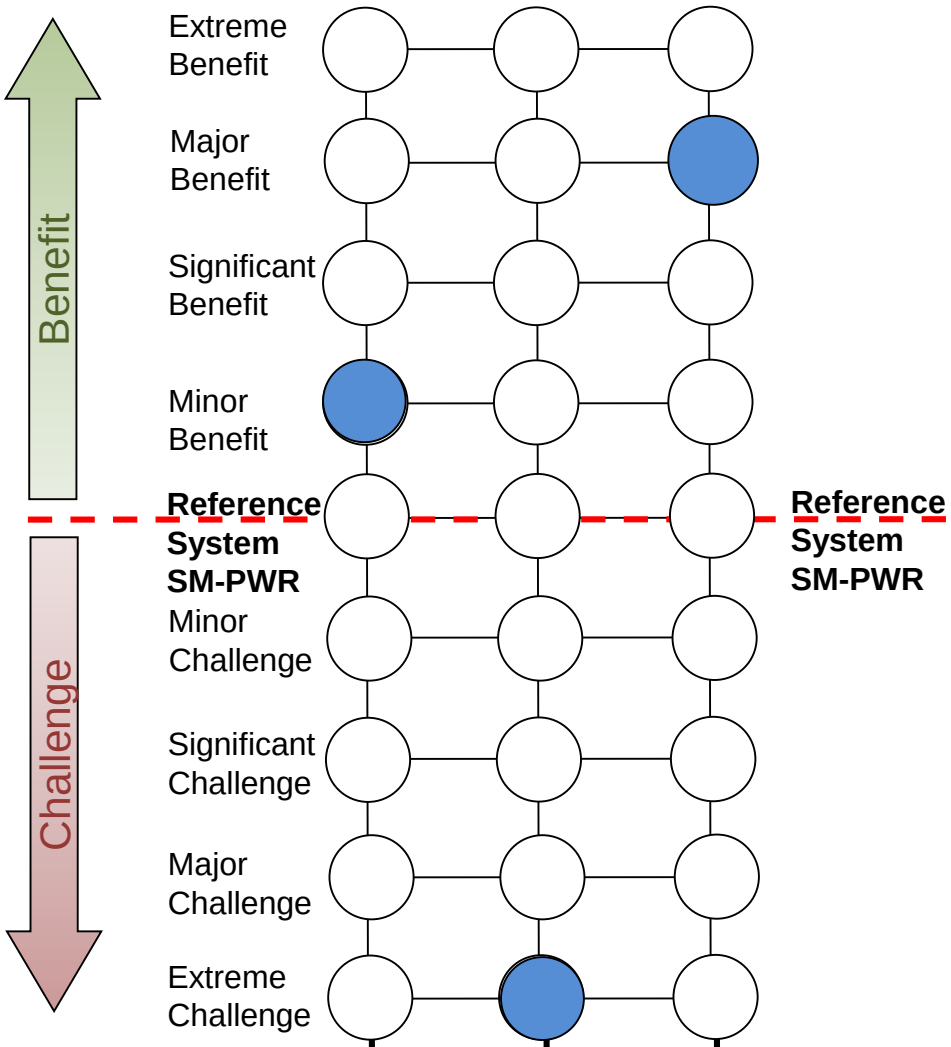
3a. Fuel Security



3a.3 Uranium dependence

3a.2 Spent fuel characteristics – compatible with existing reprocessing technology?

3a.1 Ability to deploy – fissile material availability

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Description

3a.1 Ability to deploy – fissile material availability

SM-MSThR is in principle capable of operating a breeder cycle or a high conversion cycle when operating with thorium as a fertile material and full recycle of U-233. In this case, its dependence on uranium available on the international market would be eliminated or considerably reduced in the very long term. In the shorter term, SM-MSThR would remain dependent on uranium or plutonium to provide the neutrons needed to convert Th-232 to U-233 until the equilibrium fuel cycle is established. However SMThR is assessed as only a Minor Benefit because the reference system is specified as not having full reprocessing.

Assessed as 'Minor Benefit'

3a.1 Ability to deploy – fissile material availability

3a.1 (Fissile material availability) applies specifically to closed fuel cycle systems which may have limitations on the rate at which new reactors could be deployed because of the need to acquire and/or build up the necessary fissile material. The levels of challenge vary between open and closed fuel cycle systems:

OPEN - this designates an open fuel cycle in which reactors are fuelled by LEU, which as natural uranium or LEU is available on the world market. In this instance the deployment rate would not be restricted, provided that world market supplies are sufficient and sufficient reactor build capacity was available.

CLOSED – this designates a closed fuel cycle which will eventually operate virtually independently of uranium availability, but which may be subject to constraints on the initial rate of deployment depending on the availability of fissile material. Limitations to closed cycle deployment can be calculated for any assumed future nuclear generation scenario.

3a.1 Ability to deploy – fissile material availability - references

Insert

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3a.2 Spent fuel characteristics – compatible with existing reprocessing technology?

No. The spent fuel characteristics of SM-MSThR are incompatible with existing reprocessing technology and will demand an entirely new fuel cycle infrastructure based on pyro processing. The waste forms will also be different and will need to be assessed for compatibility with disposal in the GDF.

Assessed as 'Extreme Challenge'

3a.2 Spent fuel characteristics – compatible with existing reprocessing technology?

3a.2 (Spent fuel characteristics).
Spent fuel characteristics: Is the spent fuel of a form that is compatible with established reprocessing methods, or are there features that would preclude its reprocessing using current reprocessing methods? This Attribute tests whether or not the spent fuel form is compatible with established reprocessing technologies and gives a measure of the accessibility of the contained fissile material and hence the ability to affect any closed cycle deployment limitations in 3a.1.

Conventional spent oxide or metallic fuel, irrespective of whether the main fissile material is uranium or plutonium, are compatible with existing reprocessing technologies.

Unconventional fuels, such as fuels based on thorium matrix or coated particle TRISO fuels (used in high temperature gas reactors) are incompatible with established reprocessing methods. Fuel which is not straightforward to reprocess represents an intrinsic barrier to accessing fissile material.

3a.2 Spent fuel characteristics – compatible with existing reprocessing technology?

References

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3a.3 Uranium dependence

SM-MSThR is in principle capable of operating a breeder cycle or a high conversion cycle when operating with thorium as a fertile material and full recycle of U-233. In this case, its dependence on uranium available on the international market would be eliminated or considerably reduced in the very long term, putting it in the LOW uranium dependence category. In the shorter term, SM-MSThR would remain dependent on uranium or plutonium to provide the neutrons needed to convert Th-232 to U-233 until the equilibrium fuel cycle is established. Therefore the Major Benefit applies only in the very long term and is not immediately accessible during the transition to equilibrium.

Assessed as 'Major Benefit'

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Description

References

3a.3 Uranium dependence

The uranium usage Attribute poses the questions: "*Will there be sufficient uranium available on the world market to meet the requirements of the reactor system over its operational lifetime?"* and therefore *"Is the system more or less dependent on uranium ore availability/supply on the world market?*"

3a.3 therefore categorises the dependence of the nuclear system on uranium obtained from the world market. Illustrations of levels of uranium usage are:

LWRs have a specific uranium requirement of approximately 200 tU/GWye. CANDU reactors have a lower specific uranium requirement of approximately 160 tU/GWye.

Systems with high conversion ratios or with partial recycle of fissile materials are less dependent on uranium ore, defined as specific uranium requirements in the range 20 to 160 tU/GWye.

The lower range is set arbitrarily to 20 tU/GWye to allow for systems with high conversion ratios that are not quite self-sustained. Systems which have full recycle of fissile materials and operate a breeding cycle totally independent of external uranium supplies.

3a.3 Uranium dependence - References

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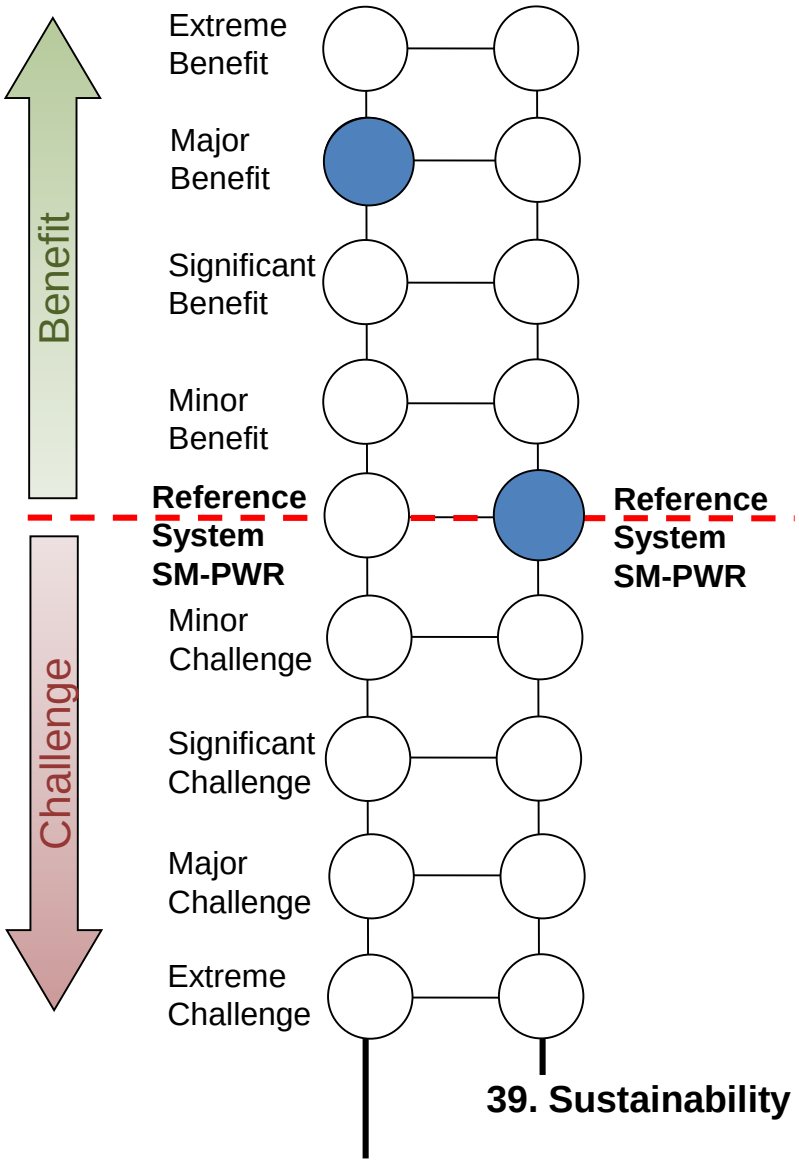
3a.3 Uranium dependence



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Description

01. Fuel utilisation

SM-MSThR is in principle capable of operating a breeder cycle or a high conversion cycle when operating with thorium as a fertile material and full recycle of U-233. In this case, its dependence on uranium available on the international market would be eliminated or considerably reduced in the very long term, putting it in the LOW uranium dependence category. In the shorter term, SM-MSThR would remain dependent on uranium or plutonium to provide the neutrons needed to convert Th-232 to U-233 until the equilibrium fuel cycle is established. Therefore the Major Benefit applies only in the very long term and is not immediately accessible during the transition to equilibrium.

Assessed as 'Major Benefit'

01. Fuel utilisation

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.

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.

01. Fuel utilisation - references

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39. Sustainability

This is potentially a broad area encompassing the uranium ore requirement, environmental impact, waste arisings and others. SM-MSThR operating a thorium fuel cycle with U-233 recycle is assessed as 'Major Benefit' with respect to uranium ore demand, once the equilibrium fuel cycle is established. However, it is too soon to assess other areas such as environmental impact and waste arisings, both of which are likely to require significant design and development work. For this reason, SM-MSThR is assessed 'As Reference' against sustainability, with the long term benefits on uranium demand balanced by challenges on the other issues.

Assessed as 'Reference'

39. Sustainability

Sustainability is potentially a broad area encompassing the uranium ore requirement, environmental impact, waste arisings and others.

39. Sustainability - references

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3b. Waste storage and disposability

Summary

The spent fuel characteristics of SM-MSThR are incompatible with existing reprocessing technology and will demand an entirely new fuel cycle infrastructure based on pyro processing. There may be benefits in terms of reduced waste volume and radiotoxicity, but the waste forms will be different and will need to be assessed for compatibility with disposal in the GDF. Although there are aspects which would give a Significant Benefit, the overall assessment is dominated by the Extreme Challenge posed by the waste form. Overall assessment Major Challenge

Assessed as 'Major Challenge'

Attributes

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Description

References

3b. Waste storage and disposability

Summary

All nuclear reactors generate nuclear waste that needs to be managed as part of the fuel cycle. The management and disposability of nuclear waste is one of the key long term considerations for the nuclear power industry. The current solution sought for long term disposability is to encapsulate waste into solid forms which are then protectively packaged and placed into a geological disposal facility (GDF). It is therefore required that any spent fuel, high level or intermediate level waste arising must be suitable for encapsulation and safe long term disposal in a GDF.

The waste management Strategic Attribute can be posed as: *Can the waste arisings from reactor systems be managed and eventually disposed of in a safe manner that is compatible with the acceptance criteria for existing or anticipated waste treatment plants and disposal facilities?*

From this top level Strategic Attribute, the following attributes are obtained:

Compatibility of waste forms: The masses and volumes of waste forms for disposal.

Suitability for disposal in GDF: Waste incorporation rate, long term decay heat and radiotoxicity.

3b. Waste storage and disposability - References

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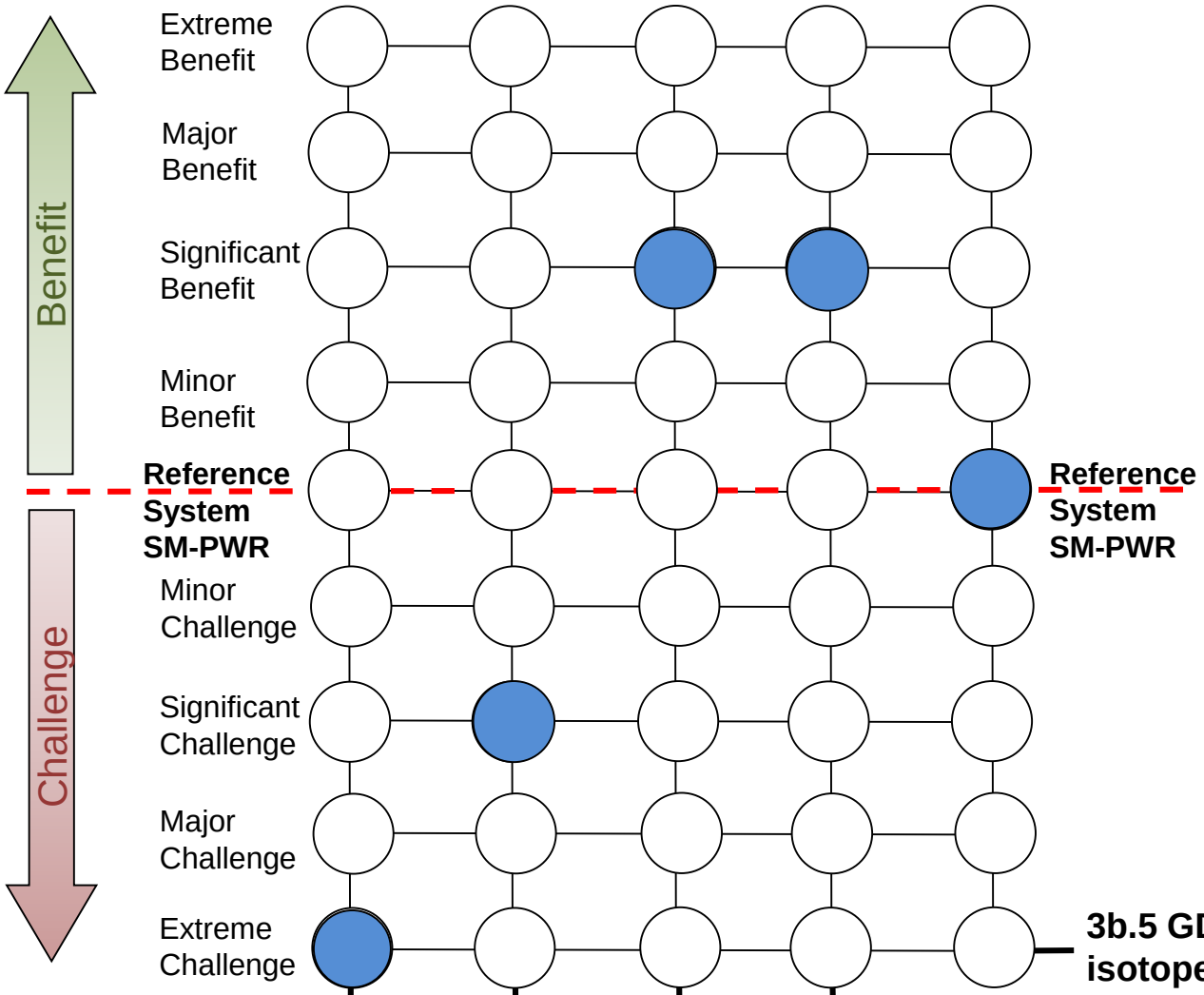
3b. Waste storage and disposability



3b.5 GDF disposal impact – isotopes driving safety case

3b.4 GDF disposal impact – long term radiotoxicity

3b.3 GDF disposal impact – long term decay heat

3b.2 GDF disposal impact – waste incorporation rate

3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology?

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3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology?

There may be benefits in terms of reduced waste volume and radiotoxicity. However, the The spent fuel characteristics of SM-MSThR are incompatible with existing reprocessing technology and will demand an entirely new fuel cycle infrastructure based on pyro processing. The waste forms will also be different and will need to be assessed for compatibility with disposal in the GDF. Although there are aspects which would give a Significant Benefit, the overall assessment is dominated by the Extreme Challenge posed by the waste form, which will comprise of the salt inventory remaining when the reactor is finally shutdown.

Assessed as 'Extreme Challenge'

3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology?

3b.1 (Number and type of waste forms). This attribute accounts for the number of different waste forms produced. It is intended to take account of waste forms that are incompatible with existing or expected future waste packaging and disposal facilities. Any incompatible waste forms produced will require the construction and operation of new facilities to deal with them, and this will be noted.

3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology? References

Insert

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3b.2 GDF disposal impact – waste incorporation rate

SM-MSThR is insufficiently developed to understand the impact of fuel disposal and waste incorporation. This leads to it being assigned as 'Significant Challenge' in recognition of the effort that will be required to underpin its performance against this attribute.

.

Assessed as 'Significant Challenge'

Metric - 33. Waste arisings – volumes of HLW, ILW, LLW

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Description

References

3b.2 GDF disposal impact – waste incorporation rate

3b.2 (Waste Incorporation rate). Waste packages for disposal in the GDF mass may consist of spent fuel assemblies or immobilised high level waste forms (such as glass blocks) depending upon the fuel cycle. For the disposal of spent fuel assemblies, disposal canisters would normally be designed to accommodate uranium fuel assemblies with a relatively low long term decay heat output. Other types of fuel assemblies, for example MOX assemblies, would have a higher long term decay heat output and the disposal canister might be able to accommodate fewer of them, giving a low incorporation rate. Immobilised high level waste from reprocessing of low burnup fuels contains relatively low amounts of transuranics contributing to heat and neutron output and therefore can give a high incorporation rate. High burnup fuels are characterised by high transuranic content, with high heat and neutron outputs that may results in reduced incorporation rates. Illustrations of levels of waste incorporation rate are:

HIGH – Applies to reactor systems producing waste forms with relatively low heat and neutron outputs compatible with current waste forms.

LOW – Applies to reactor systems producing waste forms with relatively high heat and neutron outputs that are incompatible with current waste forms.

3b.2 GDF disposal impact – waste incorporation rate - references

Insert

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References

33. Waste arisings – volumes of HLW, ILW, LLW

SM-MSThR is insufficiently developed to understand the HLW, ILW and LLW waste volumes. This leads to it being assigned as 'Significant Challenge' in recognition of the effort that will be required to underpin its performance against this attribute.

Assessed as 'Significant Challenge'

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Description

References

33. Waste arisings – volumes of HLW, ILW, LLW

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.

33. Waste arisings – volumes of HLW, ILW, LLW - references

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3b.3 GDF disposal impact – long term decay heat

A SM-MSThR operated with Th-232/U-233 recycle would produce much reduced quantities of heat producing transuranics once equilibrium was established. This applies in the period from 100 years to 1E4 years during which transuranics dominate the heat output in the SM-PWR Reference System.

Assessed as 'Significant Benefit'

Metrics

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Description

References

3b.3 GDF disposal impact – long term decay heat

This is a measure of the long term decay heat of spent fuel or high level waste in interim storage pending disposal and in the GDF. Decay heat is important, because it determines how long spent fuel or immobilised high level waste will need to be held in interim storage prior to final disposal. Also, decay heat loading is the principal determinant of repository footprint. Spent uranium fuel or immobilised high level waste derived from uranium fuels sets the baseline for low long term decay heat. Spent fuel containing higher inventories of transuranics (such as MOX fuels) or immobilised high level waste originating from such fuels will have elevated decay heat output. Immobilised high level waste from fast spectrum systems with recycle of transuranics and from thorium systems would be expected to have a low inventory of transuranics and therefore low decay heat.
Illustrations of levels of long term decay heat are:

LOW – Applies to reactor systems producing waste forms with relatively low long term decay heat output consistent with long, but manageable interim storage times.

HIGH – Applies to reactor systems producing waste forms with relatively high long term decay heat output that would lead to unfeasibly long interim storage times.

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3b.3 GDF disposal impact – long term decay heat - references

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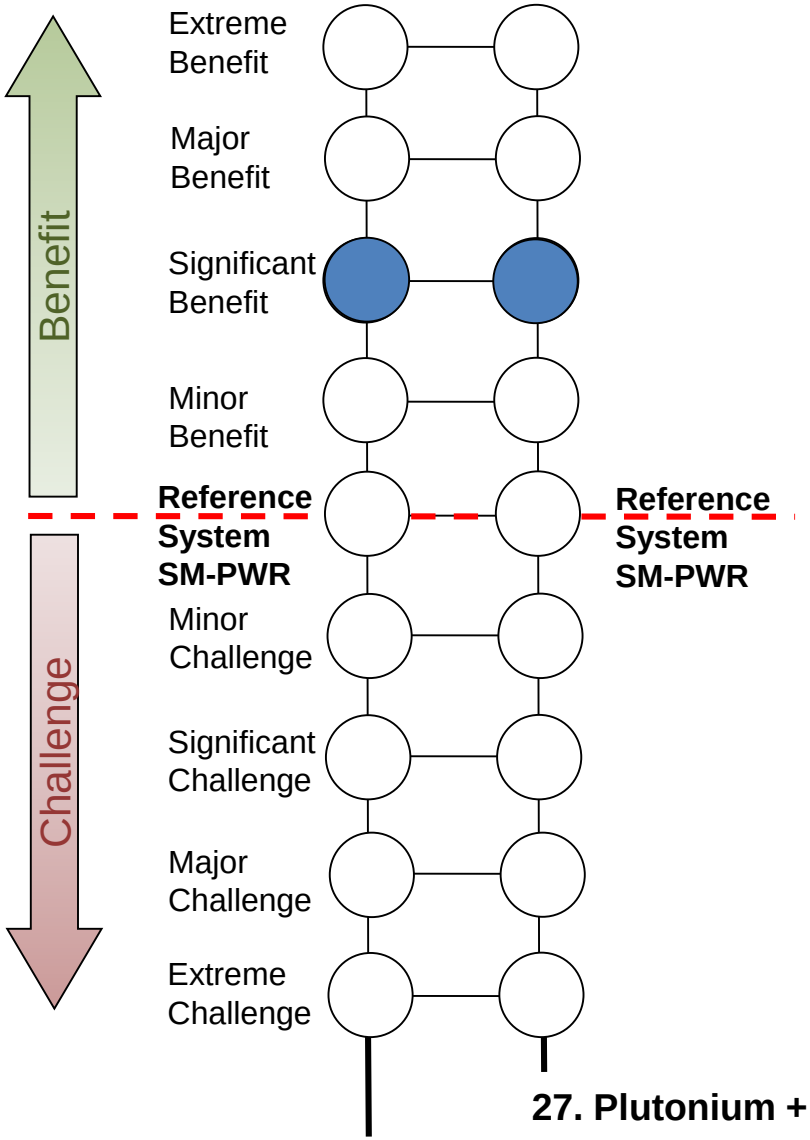
3b.3 GDF disposal impact – long term decay heat



27. Plutonium + minor actinide management

04. Long term heat output

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04. Long term heat output

A SM-MSThR operated with Th-232/U-233 recycle would produce much reduced quantities of heat producing transuranics once equilibrium was established. This applies in the period from 100 years to 1E4 years during which transuranics dominate the heat output in the SM-PWR Reference System.

Assessed as 'Significant Benefit'

04. Long term heat output

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.

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

04. Long term heat output - references

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27. Plutonium and minor actinide management

SM-MSThR is expected to be more flexible at plutonium and minor actinide management than the SM-PWR Reference System, because there is no requirement for fuel fabrication and the system's inherent tolerance of different fuel compositions. However, the thermal spectrum has limitations as to how effectively plutonium and minor actinides are fissioned.

Assessed as 'Significant Benefit'

27. Plutonium and minor actinide management

Most systems are capable in principle of recycling plutonium and some would also be capable of destroying minor actinides (principally neptunium and americium). This ability to manage plutonium and minor actinides is assessed in this attribute.

27. Plutonium and minor actinide management - references

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3b.4 GDF Disposal Impact – Long Term Radiotoxicity

A SM-MSThR Th-232/U-233 breeder of high converter will have lower radiotoxicity than the SM-PWR Reference System in the period between 100 years and 1E5 years, but after 1E5 years, radiotoxicity will be higher. A SM-MSThR reactor with U/Pu fuel will have a long term radiotoxicity comparable to the SM-PWR Reference System.

Assessed as 'Significant Benefit'

Metrics

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References

3b.4 GDF Disposal Impact – Long Term Radiotoxicity

For cooling times up to approximately 500 years, it is the fission products that determine the radiotoxicity of spent fuel or immobilised high level waste and only marginal differences are expected between different systems. Beyond 500 years, where there are transuranics present in the spent fuel or immobilised high level waste, it is these that dominate radiotoxicity for up to 10^5 years. Low radiotoxicity on a timeframe of the order of 500 years is sometimes regarded as a desirable attribute of a fuel cycle because it might be feasible to argue that engineering barriers might retain their effectiveness up to that point. Spent uranium or MOX fuel assemblies and immobilised high level waste from uranium or MOX fuels will have high inventories of transuranics and therefore high long term radiotoxicity. Recycling transuranics in fast reactors can reduce the inventory in repository, possibly leading to low long term radiotoxicity. Fuel cycles based on the Th-232/U-233 fuel cycle have low transuranic inventories which give an intermediate level of radiotoxicity for spent thorium assemblies (in the once-through thorium cycle) and a lower level for immobilised waste from a closed Th-232/U-233 fuel cycle. Th-232/U-233 generally have higher radiotoxicities after 1E5 years.

3b.4 GDF Disposal Impact – Long Term Radiotoxicity - references

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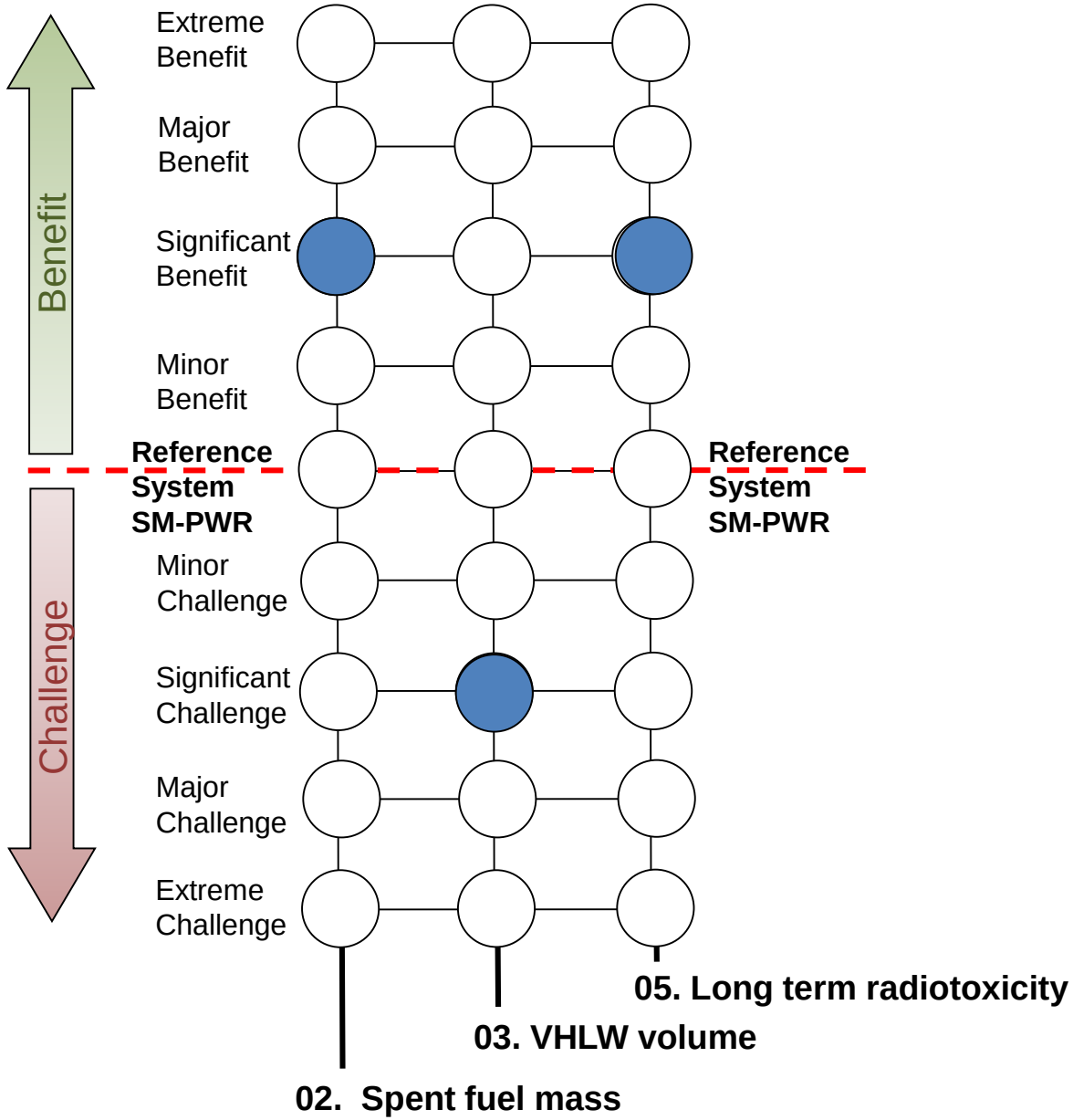
3b.4 GDF disposal impact – long term radiotoxicity



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02. Spent fuel mass

SM-MSThR will have lower spent fuel arisings than the SM-PWR Reference System on account that the fuel salt remains in the reactor for the entire design life. Fission products are removed and fertile material added to make up for heavy metal mass destroyed by fission.

Assessed as 'Significant Benefit'

02. Spent fuel mass

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).

For the recycle options the spent fuel arising is important only in that it determines the throughput and capacity of reprocessing plants,

02. Spent fuel mass - references

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03. VHLW volume

VLHW arisings from SM-MSThR are not known. The mass of fission products is closely equivalent to that of the SM-PWR Reference System (there is some variation depending on the relative thermal efficiencies), but the fact that the fuel cycle is entirely new introduces a Significant Challenge in developing a new high level waste form that is compatible with molten salt fuel.

Assessed as 'Significant Challenge'

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References

03. VHLW volume

This is the volume of high activity (heat generating) waste, expressed in m3 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.

03. VHLW volume - references

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05. Long term radiotoxicity

A SM-MSThR Th-232/U-233 breeder of high converter will have lower radiotoxicity than the SM-PWR Reference System in the period between 100 years and 1E5 years, but after 1E5 years, radiotoxicity will be higher. A SM-MSThR reactor with U/Pu fuel will have a long term radiotoxicity comparable to the SM-PWR Reference System.

Assessed as 'Significant Benefit'

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Description

References

05. Long term radiotoxicity

The radiotoxicity is a measure of the hazard potential of radioactive material. Radiotoxicity can be measured as the potential dose from the waste in Sieverts (Sv) per Gwye, or by Toxic Potential, which measures the dilution required to allow dissolved waste to meet dose standards if used for drinking.

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 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.

05. Long term radiotoxicity - references

Insert

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3b.5 GDF disposal impact – isotopes driving safety case

SM-MSThR is assessed to be essentially equivalent to large PWRs.
The reason for this is that the isotopes driving the repository safety case are fission and activation products and the fission product spectrum for SM-MSThR and SM-PWR are similar.

Assessed as 'Reference'

3b.5 GDF disposal impact – isotopes driving safety case

As GDF safety cases are generally driven by long-lived mobile fission and activation products rather than by radiotoxicity per se, this attribute assesses any material differences in mobile isotope yields on a per GWye basis.

3b.5 GDF disposal impact – isotopes driving safety case - references

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3c. Siting

Summary

SM-MSThR is assessed to be equivalent to the SM-PWR Reference System with respect to siting. SM-MSThR assumes there is minimum scope reprocessing and therefore no issues associated with a co-located reprocessing plant.

Assessed as 'Reference'

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3c. Siting

Reactor systems can be commercially available, competitive, and reliable but all require sites with adequate access to cooling water, power transmission. This Strategic Attribute therefore examines the relative technical suitability of siting reactors and fuel cycle plants across the range of total generation capacity which may be required.

3c Siting - references

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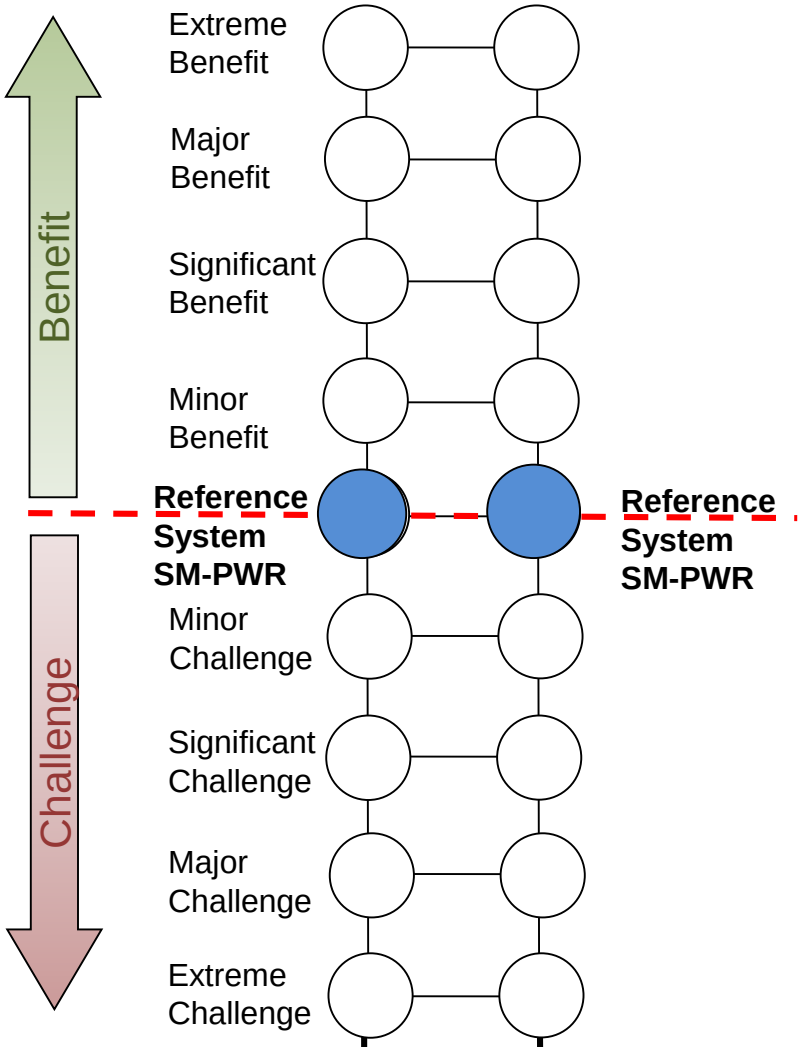
3c. Siting



3c.2 Siting – associated fuel cycle plants

3c.1 Siting - number and size of reactors c/f likely site availability

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Description

3c.1 Siting – number and size of reactors c/f likely site availability

SM-MSThR is equivalent to SM-PWR wrt siting. SM-MSThR assumes there is minimum scope reprocessing and therefore no issues associated with a co-located reprocessing plant.

Assessed 'Reference'

Metrics

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Description

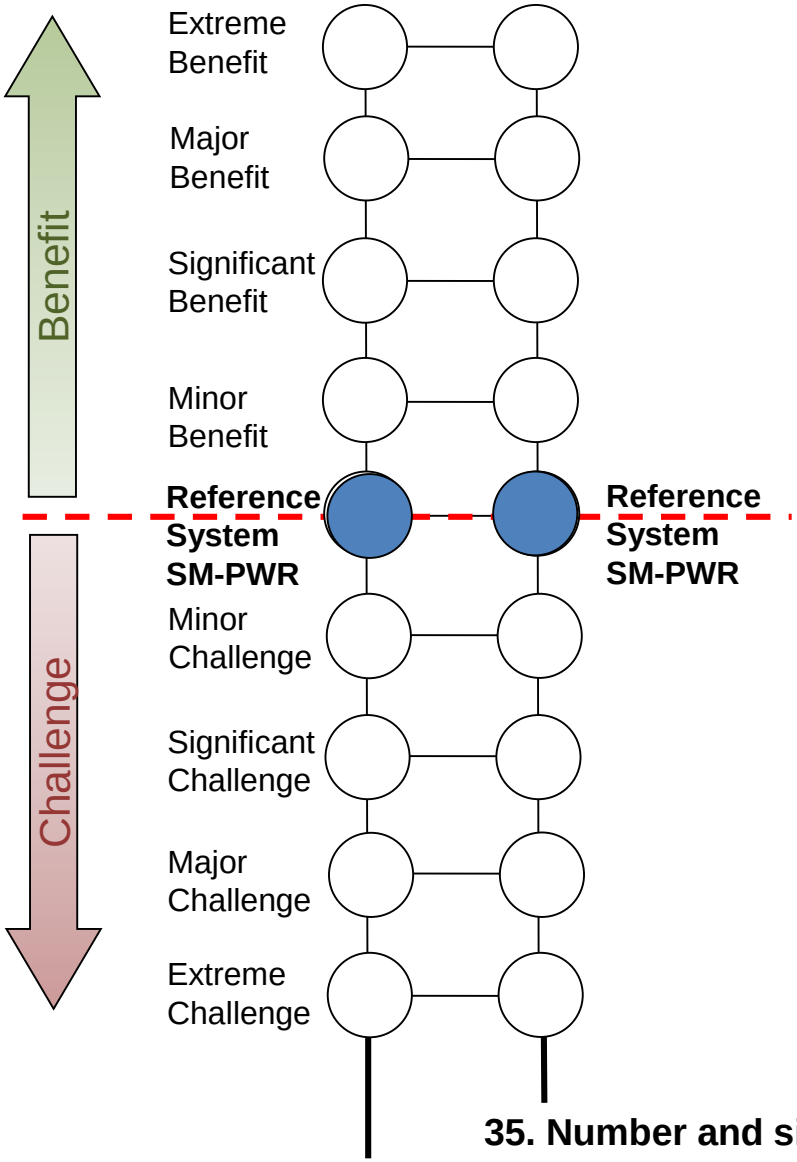
3c.1 Siting – number and size of reactors

3c.1 is intended to measure of how flexible reactor siting would be. It may be possible for small reactors to be sited at locations that would be unsuitable for large reactors on account of reduced land area required and reduced cooling water requirement. It may be possible for a reactor system which, in the event of Design Basis accidents, does not require evacuation outside the site boundary, to be sited more closely to dense concentrations of population.

3c.1 Siting – number and size of reactors - references

Insert

3c.1 Siting - number and size of reactors c/f likely site availability



35. Number and size of reactors needed

32. Flexibility of location

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32. Flexibility of location

Significant improvement for small power station outputs. Less so for large outputs (>0.5 GWye). Potential benefits for small modular LWRs with respect to cooling water availability, ultimate heat sink (for decay heat), grid connections and avoidance of off-site evacuation zone and transmission infrastructure compatibility.

Small modular LWRs may offer increased scope for development on alternative locations, such as former coal fired power stations or other former industrial sites.

Assessed as 'Significant Benefit' (dispersed siting) to 'Reference' (GWe-sized groupings)

32. Flexibility of location

Reactors will have varying siting demands depending on their output and any dependence of co-siting with, for example, fuel cycle plants. Small reactors will make smaller demands on cooling water and grid connections, but will require more sites to reach the same installed output.

32. Flexibility of location - references

Insert

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Return to top

35. Number and size of reactors needed

SM-MSThR is equivalent to the SM-PWR Reference System

Assessed as 'Reference'

Back

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Description

References

35. Number and size of reactors needed

The size of individual reactors will directly affect the number of reactors needed per GWe installed. The effects on numbers of sites and on economics are examined elsewhere,

35. Number and size of reactors needed - references

Insert

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Return to top

3c.2 Siting – associated fuel cycle plants

SM-MSThR is assessed as equivalent to the SM-PWR Reference System, because there is minimum scope reprocessing and the only requirement is to manage spent fuel salt on-site after final closure of the reactor.

Assessed as 'Reference' for centrally located fuel cycle plants

Metric - 36. Fuel cycle plants

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Description

References

3c.2 Siting – associated fuel cycle plants

3c.2 covers the need of closed reactor systems for reprocessing, waste processing and fuel refabrication plants. Many outline schemes assume co-location of reactor and fuel cycle plants – but, in nuclear scenarios with large contributions from closed systems, this carries the consequence of either (a) very large generation capacity at one site or (b) multiple sites and fuel cycle plants.

3c.2 Siting – associated fuel cycle plants - references

Insert

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36. Fuel cycle plants

Sm-MSThR would require entirely new fuel cycle plants.

Assessed as 'Extreme Challenge'

Back

Return to top

Description

References

36. Fuel cycle plants

The fuel cycle plants needed for the various reactor system options are potentially very different.

36. Fuel cycle plants - references

Insert

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4a. Access to international programmes

SM-MSThR offers strong potential for international collaboration, on account of its low TRL. UK engagement in design, modelling and testing would be a fertile area for maintaining and developing expertise. It would help provide a positive focus for UK nuclear R&D.

Assessed as 'Significant Benefit'

Metric - 4a.1 Re-engagement in international programmes

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Description

References

4a. Access to international programmes

This Strategic Attribute assesses whether access to (or indeed the formation of) international programmes could aid the eventual deployment of a reactor system. The single Attribute assesses the information on the credibility of the route and on its possible timescale for deployment.

4a. Access to international programmes - references

Insert

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Return to top

4a.1 Re-engagement in international programmes

Strong potential for international collaboration. SM-MSThR would help provide a positive focus for UK nuclear R&D.

Assessed as 'Significant Benefit'

4a.1 Re-engagement in international programmes

This Attribute assesses whether access to (or indeed the formation of) international programmes could aid the eventual deployment of a reactor system. The single Attribute assesses the information on the credibility of the route and on its possible timescale for deployment.

4a.1 Re-engagement in international programmes - references

Insert

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4b. Time and Cost to Deployment

Summary

SM-MSThR is judged to be at TRL 5 and is estimated to have an earliest deployment date of 2060.

This represents a Major Challenge when compared to the SM-PWR Reference System.

Assessed as 'Major Challenge'

Attributes

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Description

References

4b. Time and Cost to Deployment

This Strategic Attribute takes in information from the assessment of Strategic Attributes 1a, 1b, 1c and from Attribute 4a above, to assess the overall timescale on which the system could be deployed. This will be placed in the context of the relative economics of the system and its match to the market, which are examined under High Level Discriminator 2 – Competitiveness. The Technology Readiness level will be an assessment, with the grounds for that assessment given, while the Deployment Time should be a time in years, with the reasons and uncertainties stated.

In determining the timescale, funding for R&D activities will be assumed to be available as required, and regulatory effort will also be assumed to be available. Funding for reactor build will also be assumed to be available as required. The estimated time to deployment will be the time from the GFA to the time of power production by the first UK reactor

4b. Time and Cost to Deployment - references

NNL 12415 – Manchester Report on TRL of Gen IV Systems

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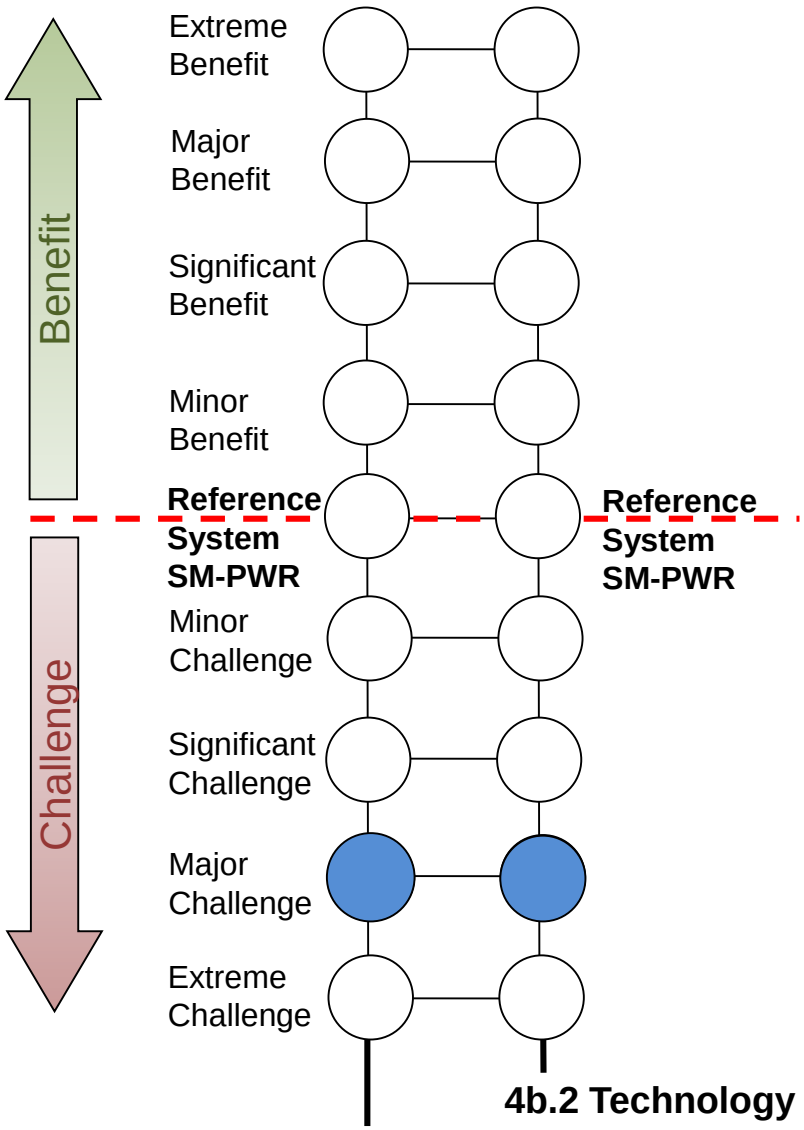
4b. Time and Cost to Deployment



4b.2 Technology Readiness level

4b.1 Commercial availability. Deployment time, plus feed from 1 and 2a

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Description

4b.1 Commercial availability – Deployment Time

Deployment in the UK will involve completing the development and testing of a design to the extent that it can apply for GDA, going through the GDA process, and then building the reactor on a selected UK site. A prototype is considered necessary and which is judged to require 20 years to make ready for construction. A prototype would require 5 years build time and 10 years to obtain the necessary operating experience before proceeding with commercial deployment. Current designs of SM-MSThR are judged to be at least 35 years from being ready for GDA. The GDA process itself has been seen to last around 5 years, so a build time of 5 years after approval would give reactors operational around 2060.

Assessed as 'Major Challenge'

Metrics

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Description

References

4b.1 Commercial availability – Deployment Time

4b.1 (Deployment time) is the earliest time until the first unit could become operational. It builds on the assessment under in Strategic Attributes 1a, 1b, 1c and 2, and the effect of any international programmes available from 4a.1.

4b.1 Commercial availability – Deployment Time - references

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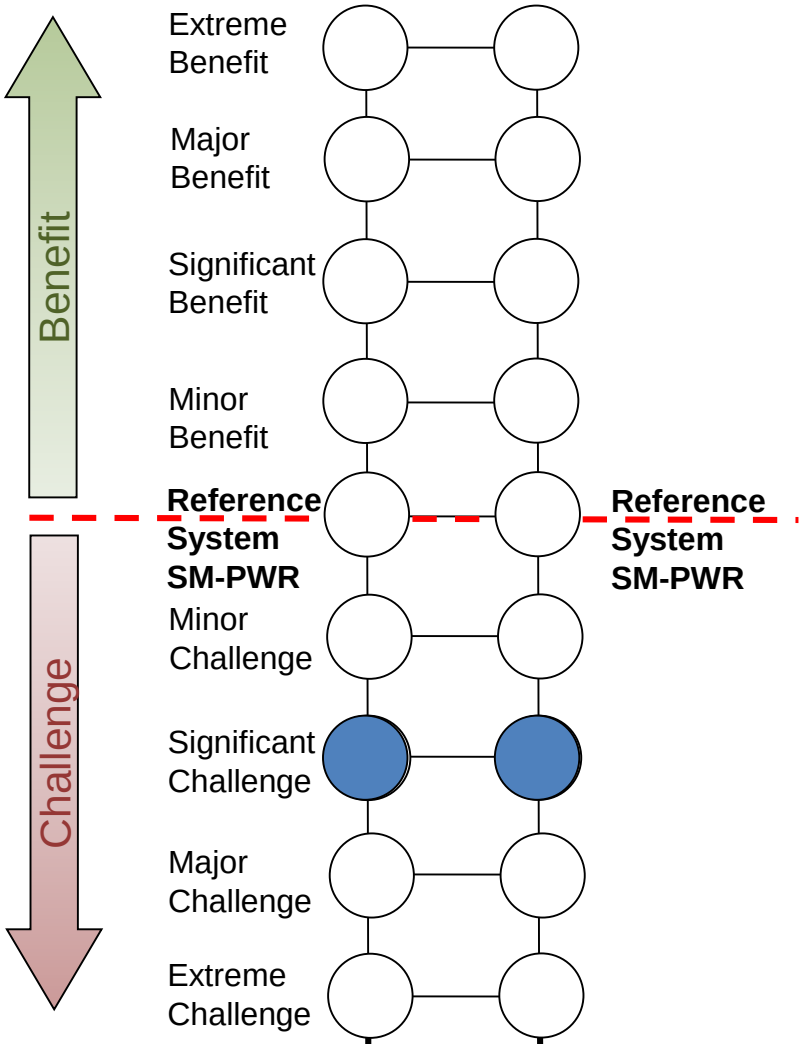
4b.1 Commercial availability



30. Timescales for deployment

25. Development costs

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25. Development costs

SM-MSThR will have significant development costs, more onerous than the SM-PWR Reference System. Beyond reach for reactor vendors without help from governments and/or consortia.

Assessed as 'Significant Challenge'

Back

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Description

References

25. Development costs

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.

25. Development costs - references

Insert

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30. Timescales to deployment

SM-MSThR will require an estimated minimum 35 years to complete licensing. See 4b.1 Timescale required to demonstrate that SAPs can be satisfied.

Allowing 5 years for GDA and a FOAK build time of 5 years would give a current timescale for a reactor ‘on the bars’ of 2060.

Assessed as ‘Significant Challenge’

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Description

References

30. Timescales to deployment

The timescale at which any new system could be deployed would be of high relevance to strategic planning in the UK.

In determining the timescale, funding for R&D activities will be assumed to be available as required, and regulatory effort will also be assumed to be available. Funding for reactor build will also be assumed to be available as required. The estimated time to deployment will be the time from the GFA to the time of power production by the first UK reactor

30. Timescales to deployment - references

Insert

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4b.2 Technology Readiness Level

SM-MSThR is assessed at TRL 5 (Demonstration of a basic system). This determines the minimum timescale to deployment. The timescales for progressing from TRL 5 to TRL 9 increase progressively.

Assessed as 'Major Challenge'

Metric - 31 Technology Readiness Level

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Description

References

4b.2 Technology Readiness Level

4b.1. and 4b.2 combine to give a likely timescale for deployment in the UK. For reactor systems which are already commercially available, this is determined by the lead time for pre-licensing in the UK, the lead time for site approval and the construction time. For systems which are not yet commercially available, an additional lead time would be required for the system to be developed to commercial readiness, with the lead time being longest for systems which are at an early stage of R&D.

This assessment will give an idea of the likely deployment time in the UK. This needs to be compared with the timescales indicated in the Strategic Attributes 1a, 1b and 1c, to come to a consolidated overall view.

4b.2 Technology Readiness Level - references

NNL 12415 – Manchester Report on TRL of Gen IV Systems

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31. Technology Readiness Level

SM-MSThR is assessed at TRL 5 (Demonstration of a basic system). This determines the minimum timescale to deployment. The timescales for progressing from TRL 5 to TRL 10 increase progressively.

Assessed as 'Major Challenge'

31. Technology Reference Level

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

31. Technology Readiness Level - - references

NNL 12415 – Manchester Report on TRL of Gen IV Systems

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4c. Meet and enable UK supply chain

Summary

SM-MSThR presents increased opportunity for UK involvement in the supply chain, but the ability of the UK to realise this potential will be challenging.

The deployment of more mature SMR technology would seem to offer limited potential for UK supply chain involvement, with the UK largely restricted to manufacturing components to a given design/specification.

By contrast, less mature designs may offer increased potential for UK supply chain, with the possibility of UK design expertise being input to develop component designs from the beginning and higher value.

Assessed as 'Significant Benefit'

Attribute - 4c.1 Supply chain opportunities

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Description

References

4c. Meet and enable UK supply chain

Summary

This Strategic Attribute examines the possibility of opportunities for the UK supply chain, providing an additional incentive for UK involvement in any particular reactor system.

4c. Meet and enable UK supply chain - references

Insert here

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4c.2 Supply chain opportunities

On account of its low TRL, SM-MSThR presents increased opportunity for UK involvement in the supply chain, but the ability of the UK to realise this potential will be challenging.

Assessed as 'Significant Benefit'

4c.2 Supply chain opportunities

This Attribute should attempt to assess the level of UK supply chain involvement that could accompany the development and deployment of a given system

4c.2 Supply chain opportunities - references

Insert

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5a Meets Energy Requirements - load follow capability

SM-MSThR is not limited in load-follow operation by fuel thermal limits. However, thermal cycling effects are likely to be more onerous than the SM-PWR Reference System on account of the higher temperature changes experienced in the Primary Circuit. Overall assessment as Minor Benefit.

Assessed as 'Minor Benefit'

Attribute - 5a.1 Flexibility – load follow capability

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Description

References

5a Meets Energy Requirements - load follow capability

This Strategic Attribute assesses the ability of systems to respond to particular features of a future energy market. For example, if the percentage of nuclear electricity on the grid is high, and coupled with a significant randomly variable output from renewables, then nuclear systems may be required to load follow. Some systems are much more amenable to this than others.

4c.2 Supply chain opportunities - references

Insert

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5a.1 Flexibility – load follow capability

Market mechanisms will be needed accommodate load follow operation, otherwise nuclear utilities will suffer significant loss of revenue. The market mechanisms would recognise that providing a load-follow capability helps support the grid system. SM-MSThR is not limited in load-follow operation by fuel thermal limits. However, thermal cycling effects are likely to be more onerous than the SM-PWR Reference System on account of the higher temperature changes experienced in the Primary Circuit. Overall assessment as Minor Benefit.

Assessed as 'Minor Benefit'

Metric – 28. Load follow capability

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Description

References

5a.1 Flexibility – load follow capability

5a.1 measures the ability of the reactor system to operate in non-baseload or load-follow mode. This is the ability of the reactor to increase or decrease output either in response to short term grid demands or in pre-planned load scheduling. If the total installed capacity of nuclear stations in the UK is only a small or modest fraction of the grid capacity, there is unlikely to be a major requirement for load-follow capability. However, if the nuclear capacity grows sufficiently, with only limited electricity storage capacity, there may come a point at which load-follow will be required, as is the case currently in France. Many current reactors are able to load-follow, but with limitations. Future reactor systems may be able to operate in load-follow mode without such restrictions, hence their ability to load follow will be compared, both from one system to another, and with the current LWR reference systems.

5a.1 Flexibility – load follow capability - references

Insert

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28. Load follow capability

Market mechanisms will be needed accommodate load follow operation, otherwise nuclear utilities will suffer significant loss of revenue. The market mechanisms would recognise that providing a load-follow capability helps support the grid system. SM-MSThR is not limited in load-follow operation by fuel thermal limits. However, thermal cycling effects are likely to be more onerous than the SM-PWR Reference System on account of the higher temperature changes experienced in the Primary Circuit. Overall assessment as Minor Benefit.

Assessed as 'Minor Benefit'

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Description

References

28. Load follow capability

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.

28. Load follow capability - references

Insert

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Description

5b. Meets energy requirements – Process Heat

SM-MSThR is expected to operate at much higher working temperatures than the SM-PWR Reference System, which is capable of supplying only low grade heat. Therefore SM-MSThR is assessed as offering Significant Benefit.

Assessed as 'Significant Benefit'

Attribute - 5b.1 Industrial process heat – potential to drive thermal processes

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Description

References

5b. Meets energy requirements – Process Heat

This Strategic Attribute assesses the ability of systems to respond to particular features of a future energy market. For example If sectors such as transport are to be decarbonised, for example by use of hydrogen as an energy vector, then the ability of a reactor system to provide high grade heat (rather than electricity) to power chemical processes could be a significant advantage.

5b. Meets energy requirements – Process Heat - references

Insert

Back

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Description

5b.1 Industrial process heat – potential to drive thermal processes

Not relevant to current UK market, but potential for future market to develop. SM-MSThR can potentially supply higher temperature processes than the SM-PWR Reference System

Assessed as 'Significant Benefit'

Metrics

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Description

References

5b. 1 Industrial process heat – potential to drive thermal processes

5b.1 indicates whether the system has the potential to drive thermal processes, such as combined heat and power (CHP), hydrogen production, synthetic fuel production and as a heat source for other industrial processes to displace carbon emitting fossil fuel heating. For thermal applications, a high operating temperature is beneficial, which leads to a simple description based on three levels of temperature:

- LOW TEMPERATURE – Low operating temperatures similar to those of current Light Water Reactors (LWRs) ~300-320°C.
- MEDIUM TEMPERATURE – Medium operating temperatures in range 320-600°C beyond the range accessible with LWRs.
- HIGH TEMPERATURE – High operating temperatures >600°C.

5b. 1 Industrial process heat – potential to drive thermal processes - references

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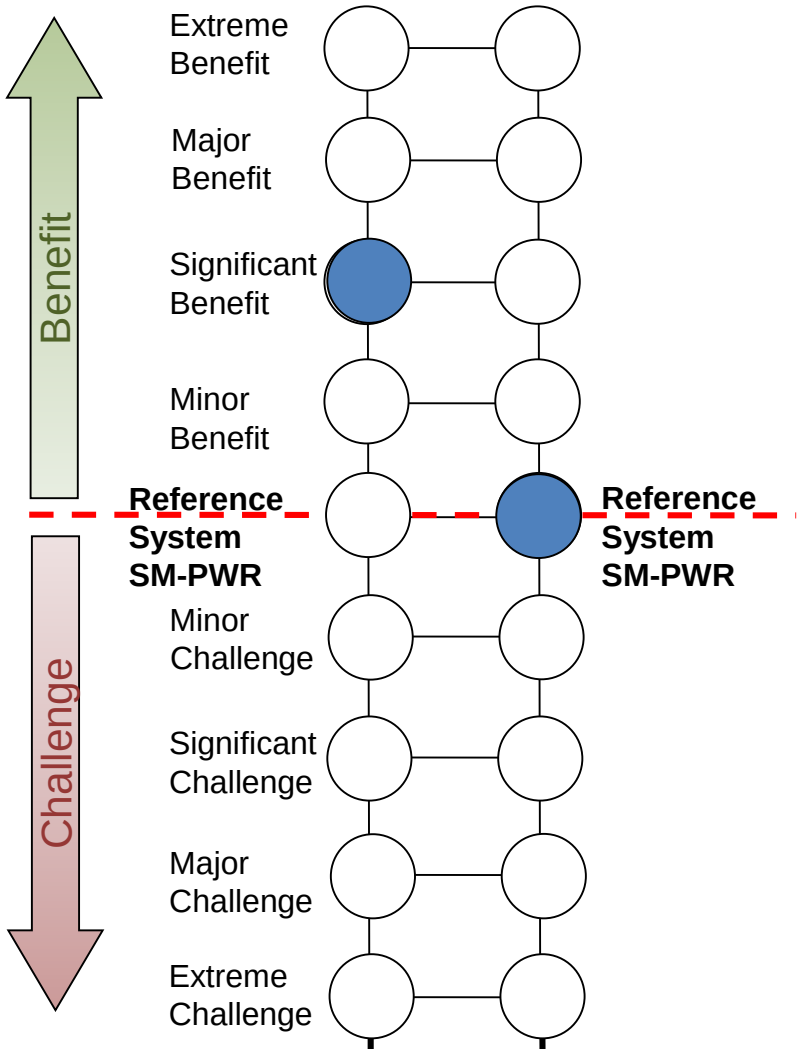
Description

5b.1 Industrial process heat – potential to drive thermal processes



42. Primary purpose

40. Potential to drive thermal processes

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Description

40. Potential to drive thermal processes

Not relevant to current UK market, but potential for future market to develop. SM-MSThR can potentially supply higher temperature processes than the SM-PWR Reference System

Assessed as 'Significant Benefit'

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Description

References

40. Potential to drive thermal processes

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 systems (eg GFR, MSR and VHTR) have very primary circuit operating temperatures compatible with high temperature process heat applications.

40. Potential to drive thermal processes - references

Insert

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42. Primary purpose

Not relevant to current UK market, but potential for future market to develop. Widespread adoption of electric cars may change grid demand.

Assessed as 'Reference'

42. Primary purpose

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.

42. Primary purpose - references

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NATIONAL NUCLEAR LABORATORY

The Generic Feasibility Assessment:
An Essential Ingredient in Nuclear Policy making

Assessment Matrix with Descriptions

Subject System: **SM-SFR**

Reference System: **Generic SM-PWR**

Template: **13**

Date of Assessment: **24th February 2016** Modified to generalise references to Regulators. 20th December 2017

Skip to Assessment

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IDM
integrated decision management

MANCHESTER 1824
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Dalton Nuclear Institute

Work in Progress

NATIONAL NUCLEAR LABORATORY

Reference and Subject Systems

Reference System:

Small Modular PWR (SM-PWR)

Subject System:

A Small Modular pool configuration Sodium Fast Reactor (SM-SFR) with an electric capacity of less than 300 MWe. It should be capable of being deployed in multiple units. SM-SFR is assumed to operate with a self-sufficient breeding cycle with U and U-Pu fuels.

IDM
integrated decision management

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Version Development

2015.08.08 Initial GFA of Generic SMR based on 2014 assessment inserted into updated format Template 12

2015.12.08 Kevin Hesketh & Aiden Peakman

2015.12.13 Gregg Butler – removal of spread of Fuel Security assessments

2016.01.03 Slide 214, 218 changed to 2035 (addition!)

2016.01.11 Incorporates Juan Mathews and Neil Irvine comments from workshop on 2015.12. 11

2016.02.08 Minor connection glitches removed – slides 62-82

2016.02.24 Checked/mods accepted for Draft Report

2016.03.15 Mods to Flexibility wording

2017.12.20 Modified to generalise references to Regulators

References

This Generic Feasibility Assessment draws upon extensive work by NNL on nuclear energy technology assessment, IAEA, OECD/NEA, USDOE and other international literature. Individual references have not been included in the current draft GFA. It is anticipated that as more information becomes available relating to specific Attributes or Metrics, this might either further validate or modify the GFA. This additional information can then be referenced in the appropriate places in the GFA Template.

IDM
integrated decision management

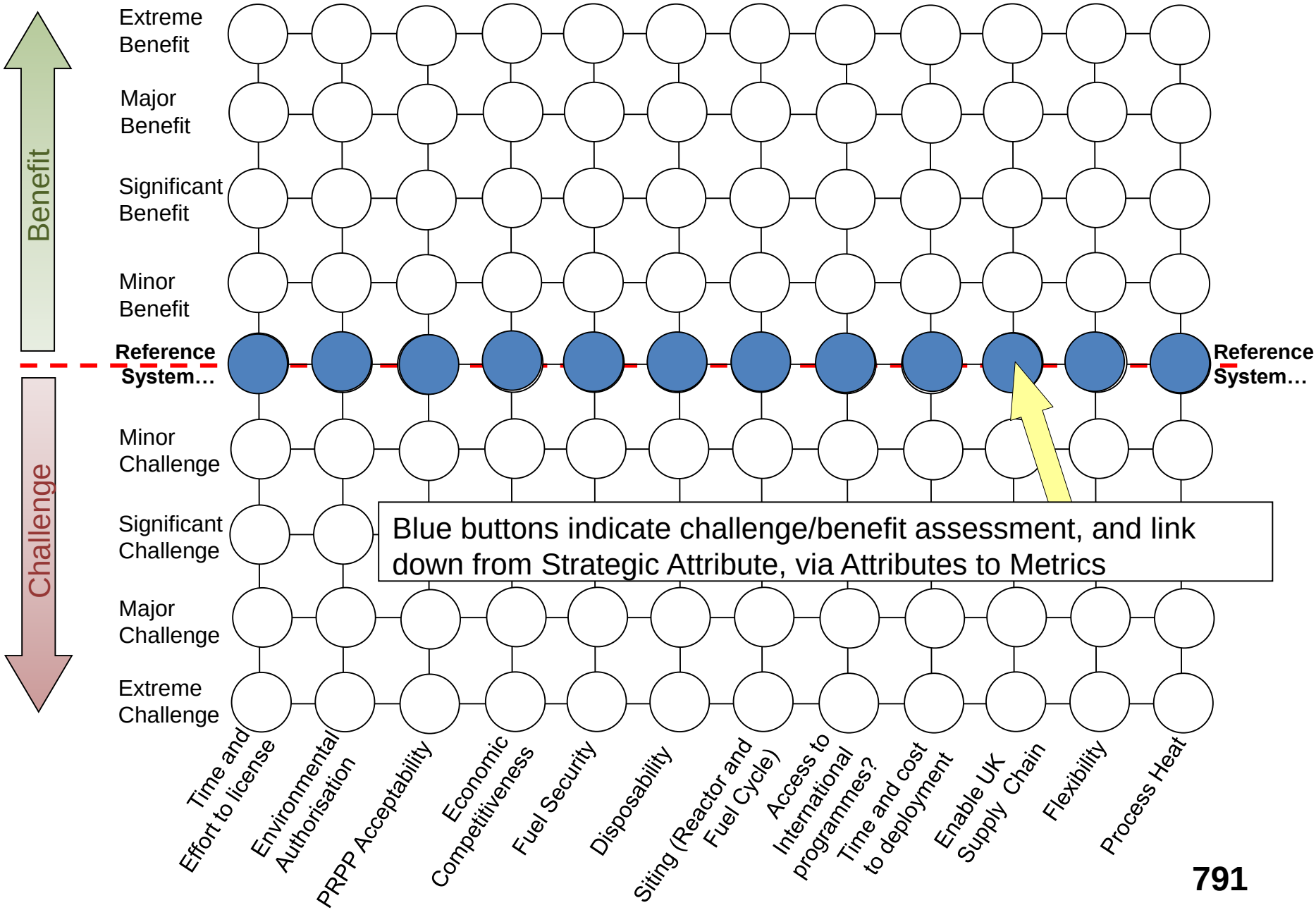
What is Generic Feasibility Assessment?

- GFA was developed for DECC to provide a high level strategic evaluation of nuclear reactor and fuel cycle systems
- It operates by making comparisons between the 'Subject System' and a Reference System, initially 'once-through LWR' as envisaged for new nuclear build in the UK
- The analysis uses 12 Strategic Attributes, using public domain information and informed professional judgement to assess the relative degree of benefit or challenge offered by the Candidate System.

What is Generic Feasibility Assessment?

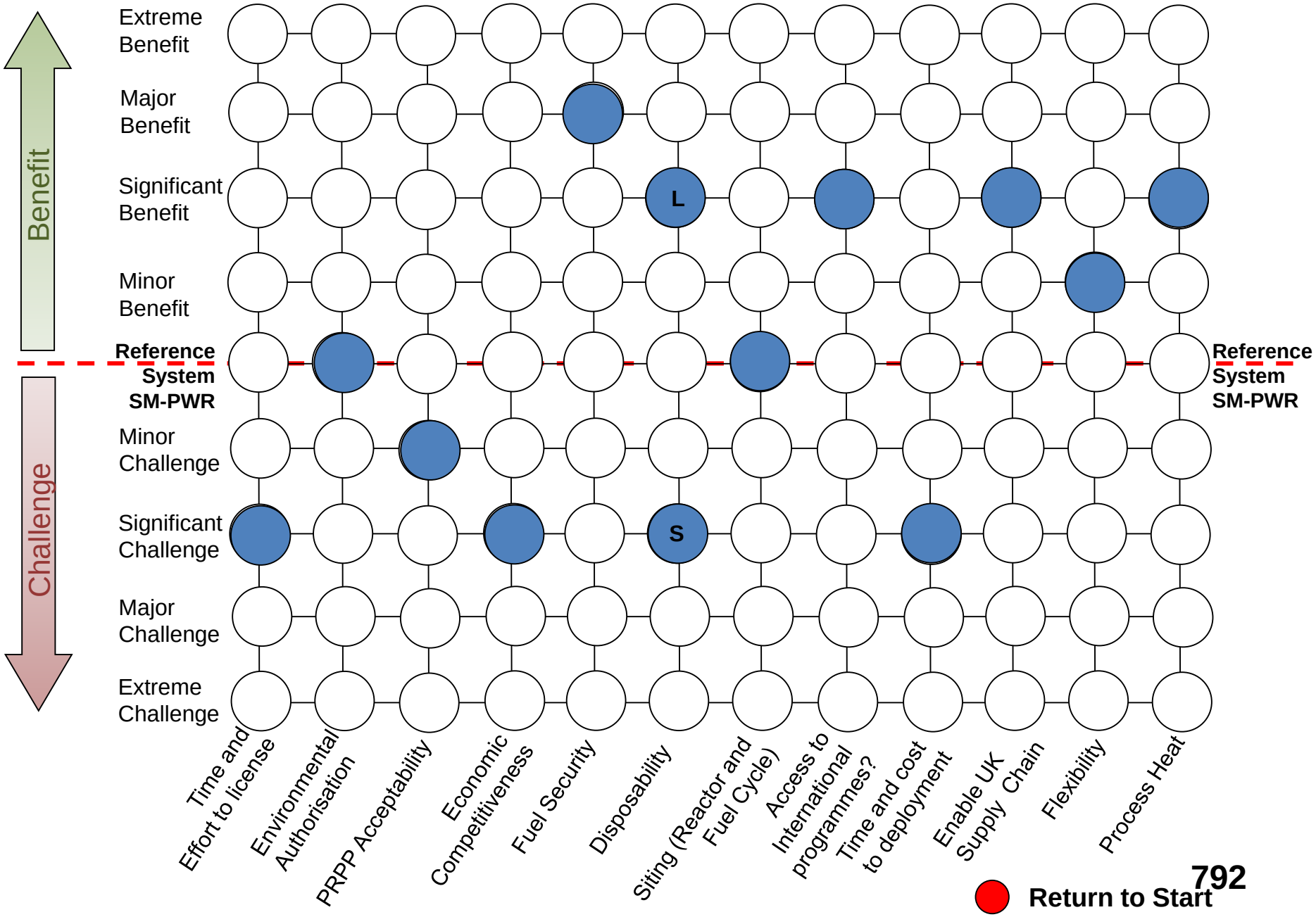
- GFA presents a high level, accessible visual representation of benefits and challenges, while allowing more detailed interrogation of the underpinning rationale and data
- As all information is public domain, any additional evidence can, and will, lead to modification of the assessment: GFA assessments are always 'Work in Progress'
- A full description of how GFA was derived and developed is available at: www.dalton.manchester.ac.uk/gfa
- This Visualisation provides a guide to how GFA is built up, the definitions of Strategic Attributes, Attributes and Metrics, and demonstrates how the information and logic tree can be navigated.

GFA Assessment Subject System: SM-SFR Reference System: Generic SM-PWR – *Work in Progress*



Blue buttons indicate challenge/benefit assessment, and link down from Strategic Attribute, via Attributes to Metrics

GFA Assessment Subject System: SM-SFR Reference System: Generic SM-PWR – *Work in Progress*



1a. Time and Effort to License

Summary

The overall assessment is that SM-SFR will require considerably more design and development effort than the SM-PWR Reference System and the timescales for commercial readiness will be correspondingly longer. However, the timescales are likely to be shorter than most other emerging systems because of substantial experience with demonstration reactors at an appropriate size.

Assessed as 'Significant Challenge'

Attributes

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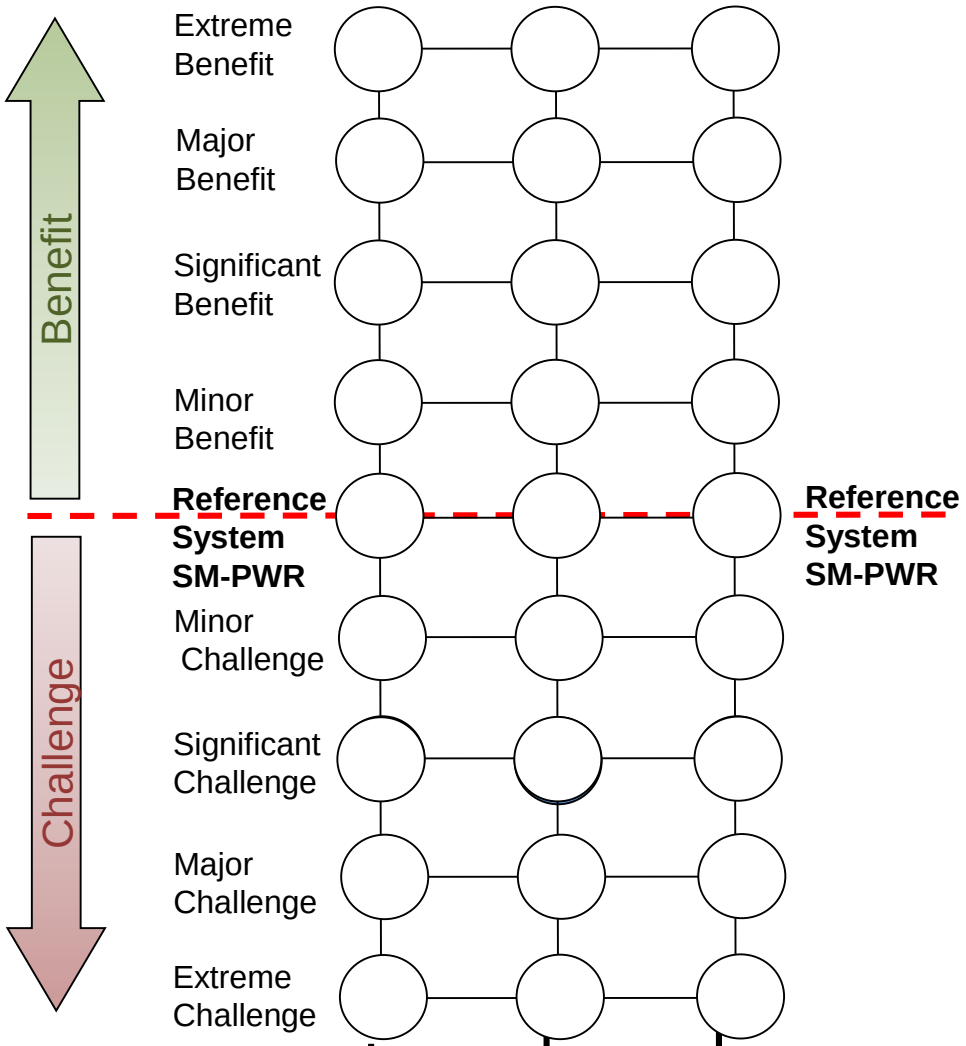
Description

1a. Time and Effort to License



1a.3 Effort to meet radiological regulations

1a.2 Timescale required to demonstrate that Safety Regulation Requirements can be satisfied

1a.1 Effort to satisfy ONR Safety Assessment Principles

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Description

1a. Time and Effort to License

Nuclear facilities in the UK are required to comply with the requirements set down by the appropriate regulatory bodies. Safety and licensing requirements are the responsibility of the Office of Nuclear Regulation (ONR), which also sets the radiological protection requirements for occupational exposure and members of the public.

Any reactor system to be deployed in the UK must be demonstrated to be safe, and to do so the reactor system must adhere to the fundamental safety principles as laid down by the licensing regulator. ONR has defined a series of Safety Assessment Principles known by the acronym 'SAPs'. These SAPs are seen as the top level goals which any system for deployment in the UK must be able to meet. The SAPs framework provides ONR with a set of guidelines by which ONR inspectors can make consistent judgements on nuclear safety assessment.

The top level safety criterion can be posed as: ***How much time and effort will be involved to allow the reactor system to meet the various UK safety regulatory requirements?***

From this top level criterion, the following attributes are obtained:

- ***Nuclear safety and regulation. What challenges must be met to enable the reactor system meet to meet well developed*** **Safety Regulation Requirements** ***(Button 1a.1)and on what timescale can such compliance be demonstrated? (Button 1a.2)***
- ***Radiological regulation. What challenges must be met to enable the reactor system to comply with the radiological dose limits defined by regulators for workers and members of the public? (Button 1a.3)***

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1a.1 Effort to satisfy Safety Regulation Requirements

Summary

SM-SFR will require a long term design and development programme before it is ready licensing. Although SFR prototypes have been designed and operated world-wide, so that many aspects of the technology are already demonstrated, integral systems testing will be needed with SM-SFR and aspects of the technology will need further development than SM-PWR. In terms of effort to licensing, this implies a Significant Challenge relative to the SM-PWR Reference System. The degree of the challenge will depend on the choice of fuel design and the details of the energy conversion system.

Assessed as 'Significant Challenge'

Metrics

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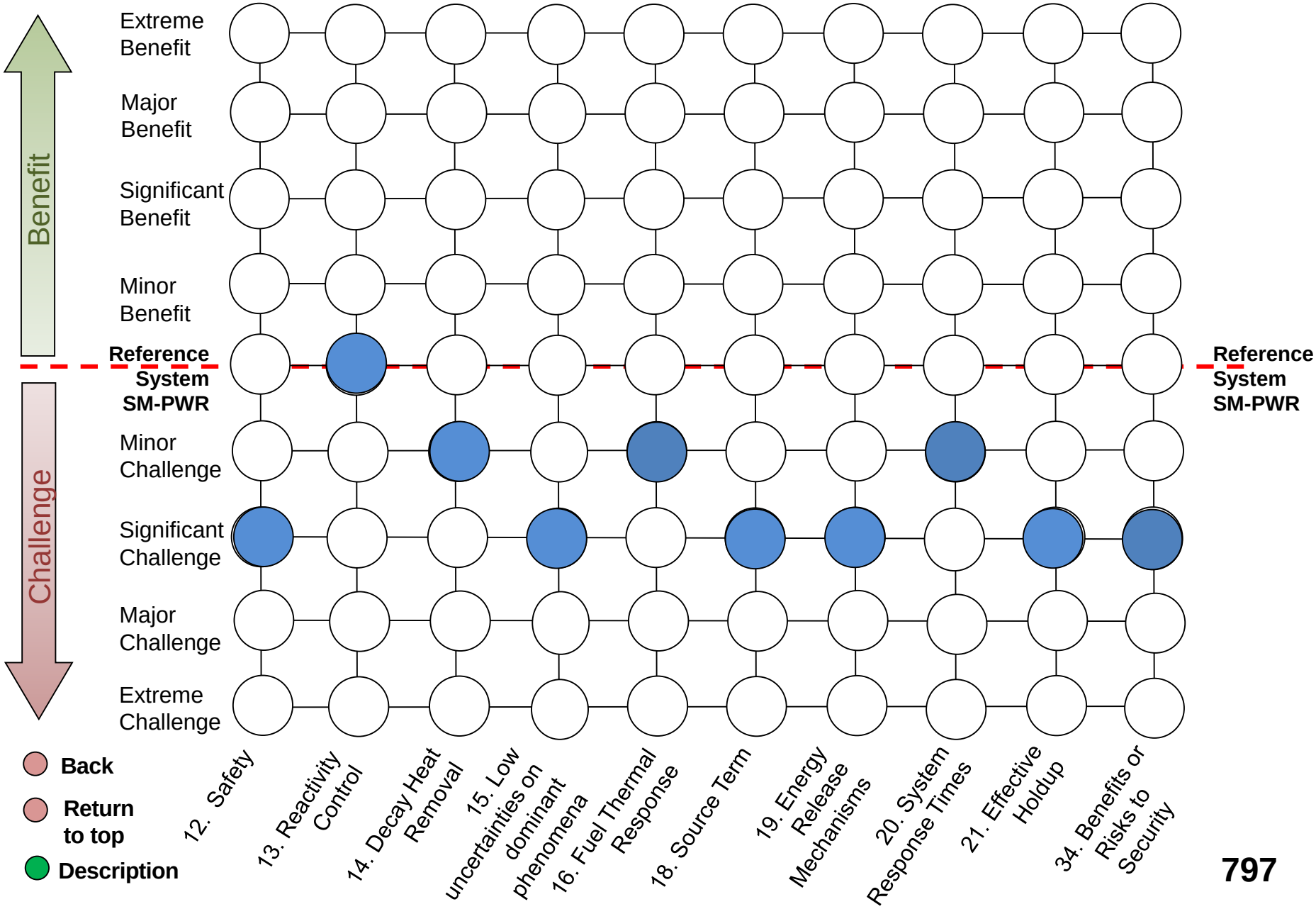
Description

References

1a.1 Effort to satisfy Safety Regulation Requirements



1a.1 Effort to satisfy Safety Regulation Requirements

1a.1 assesses the challenge faced by a reactor system in meeting the goals defined by the Safety Regulation Requirements. Levels of challenge would be expected to increase as the system examined moves further away from current experience, for example:

- Systems which are already deployed commercially or whose designs are already licensed in other countries.
- Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.
- Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.
- Systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

Assessments will assume that regulatory effort is available when and as required

12. Safety

SM-SFR requires significantly more design and development effort to license than the SM-PWR Reference System. Although a number of SFR demonstration reactors have been designed and operated in the size range of interest, they did so against different regulatory requirements to those which apply today. Also the concepts that may be offered as SM-SFRs are likely to have significant differences in the designs of the fuel, safety systems and energy conversion.

Assessed as 'Significant Challenge'

12. Safety

Any new reactor system deployed in the UK would need to meet very stringent safety standards. Some of the systems considered will rely on passive safety and this might distinguish them from other systems that rely on conventional active safety systems.

12. Safety - references

Insert here

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13. Reactivity Control

SFR cores have historically been shown to have benign reactivity control characteristics, though there are designs where an excessively positive sodium void coefficient needs mitigation and there may also be an issue over diversity of shutdown mechanisms. The small cores of SM-SFRs are likely to have better reactivity control characteristics than larger SFRs. Generally oxide fuelled systems tend to have more favourable reactivity characteristics than metal fuelled systems, but at the expense of neutron economy and breeding ratio. Assessed as equivalent to the SM-PWR Reference System.

Assessed as 'Reference'

13. Reactivity Control

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. Shutdown means that the reactor must be demonstrated to be sub-critical (k-eff < 0.95), taking account of calculation uncertainties and one stuck control/shutdown rod with the reactor cooled to ambient temperature.

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.

13. Reactivity Control - references

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14. Decay Heat Removal

The generic SM-SFR is assumed to have passive decay heat removal, as does the Reference System. It is assumed that additional design and development effort, including test data will be needed to support the safety case for decay heat removal in SM-SFR than SM-PWR.

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Assessed as 'Minor Challenge'

14. Decay Heat Removal

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. SM-SFR would typically rely on passive decay heat removal, which is the same as the Reference System.

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.

14. Decay Heat Removal - references

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15. Low uncertainties on dominant phenomena

The safety behaviour of specific SM-SFR designs is not demonstrated, but the dominant phenomena have been explored in demonstration reactor operation and in safety tests in pile and in the laboratory.

Assessed as 'Significant Challenge'

15. Low uncertainties on dominant phenomena

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.

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15. Low uncertainties on dominant phenomena - references

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16. Fuel Thermal Response

SM-SFR would be expected to have a substantial thermal inertia on account of the mass and specific heat capacity of the sodium coolant and the large coolant mass in pool-type core designs. However, the ratio of fuel to coolant volume in the core, smaller fuel rod diameter and although a high power density means that the fuel response times are faster that the reference system.

Assessed as 'Minor Challenge'

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Description

References

16. Fuel Thermal Response

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.

16. Fuel Thermal Response - references

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18. Source Term

The source term for SM-SFR requires significant design and development work. The plant layout for SM-SFR will be different to that for a GWe-sized SFR, so that source term estimates will need to be developed afresh. Also, it will be necessary to update to meet current regulatory requirements.

Assessed as 'Significant Challenge'

18. Source Term

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.

18. Source Term - references

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19. Energy Release Mechanisms

SM-SFRs do not have issues with large exothermic reactions between the coolant and structural materials as in the SM-PWR case. Neither is there a large reaction between the coolant and fuel. There is, however, the issue of the reaction between the coolant and air or steam. This is a real hazard as seen in many incidents with SFR operation. Steam generators need to have fast acting isolation systems in the case of leaks to ensure that propagation to large scale reactions does not occur and also to minimise the generation of hydrogen.

Assessed as 'Significant Challenge'

19. Energy Release Mechanisms

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.

19. Energy Release Mechanisms - references

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20. System response times

SM-SFRs have significant mass of coolant in the pool designs but the size of this varies with the specific design and integral PWRs also have larger in-vessel coolant inventories. The benefits of a large coolant in-vessel mass are offset by a higher fuel to coolant ratio in the core and higher power densities (and mass ratings) and also smaller diameter fuel rods.

Assessed as 'Minor Challenge'

20. System response times

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.

20. System response times - references

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21. Effective Holdup

This refers to the holdup of volatile fission products in accident scenarios. The containment for SM-SFR will require extensive integral systems testing.

Assessed as 'Significant Challenge'

21. Effective Holdup

Effective hold-up refers to mechanisms in the design of a plant for containing radioactive material following an accident condition. The hold-up of volatile fission product will impact the containment design will affect whether there is a requirement for off-site evacuation procedures to be in place.

21. Effective Holdup - references

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34. Benefits or challenges for security

The use of separated plutonium in natural or depleted uranium fuel or the use of high enrichment uranium will provide additional security challenges compared to the reference case.

Assessed as 'Significant Challenge'

34. Benefits or challenges for security

Inherent Proliferation Resistance and Proliferation Protection PRPP is an area which needs to be assessed for new reactor systems according with best practice set out by IAEA INPRO and GIF. The threats considered are diversion of fissile material by a state and acquisition of radioactive materials by an illegal sub-national group. Both threats are considered by OCNS as part of defining the security and safeguards requirements and these requirements are not affected in inherent PRPP. Inherent PRPP is simply to be regarded as a fall-back protective feature that would apply in the hypothetical case of a nuclear system falling outside national controls.

34. Benefits or challenges for security - references

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1a.2 Timescale required to demonstrate that Safety Regulation Requirements can be satisfied

In the UK the Generic Design Approval (GDA) process is new and only EPR has been through it in its entirety. The process for EPR took almost 6 years, but the experience gained should allow future LWRs to gain approval within 4 years or so. ONR already had expertise in PWR safety assessment and this must have been helpful for the GDA. For SFR there is currently no expertise within ONR. ONR would require an application for a GDA from an SFR designer before building up an assessment team. It is unlikely that the GDA process would be as straightforward as EPR because the safety case approach will be substantially different to conventional reactors and may require a reinterpretation of the Safety Assessment Principles.

A reasonable expectation might be that the SM-SFR designer would already have developed the design and safety justification to a very mature stage before applying for GDA, with a significant amount of development testing having already taken place to support the design and safety justification. Given the immature present state of design, for SM-SFRs and even considering the considerable experience with SFRs in demonstration reactors, this is not considered likely in less than 15 years. Assuming a minimum 5 years for ONR to assess the design, this lead to a minimum timescale of 20 years for a GDA to be completed for SM-SFR.

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Assessed as 'Significant Challenge'

1a.2 Timescale required to demonstrate that Safety Regulation Requirements can be satisfied

1a.2 assesses how long it might reasonably be expected to take to demonstrate that the system can satisfy stringent Safety Regulation Requirements**.** Levels of challenge would be expected to increase as the system examined moves further away from current experience, for example:

- Systems which are already deployed commercially or whose designs are already licensed in other countries.
- Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.
- Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.
- Systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

Assessments will assume that regulatory effort is available when and as required

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1a.2 Timescale required to demonstrate that SAPs can be satisfied - references

Insert

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1a.3 Effort to meet radiological regulations

There is significant experience with radiological issues with the operation of demonstration reactors, including experience in the UK with PFR. SFRs have been found to have operator doses lower or at the low end of those found with PWRs. Also the radioactive emissions from SFRs are found to be comparable of lower than those from PWRs. In practice fuel failure rates are low and sodium has only low levels of activation. The one area with significantly higher emission rates is from tritium. Ternary fission of Pu in a fast neuron flux has a higher tritium production rates compared with thermal reactor fuel. Also tritium is produced as one of the neuron reactions with B-10 which is used as an absorber in fast reactors. The tritium production is much lower than that found in heavy water moderated reactors.

Assessed as 'Reference'

Metric - 11. Worker Exposures

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Description

References

1a.3 Effort to meet radiological regulations

1a.3 assesses the difficulty likely to be experienced in meeting the worker radiological protection requirements defined by regulators, noting that this includes the reactor and its fuel cycle. Levels of challenge would be expected to increase as the system examined moves further away from current experience, for example:

- Systems which are already deployed commercially or whose designs are already licensed in other countries.
- Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.
- Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.
- Systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

Assessments will assume that regulatory effort is available when and as required

1a.3 Effort to meet radiological regulations - references

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11. Worker Exposures

There is significant body of data experience on operator doses from the operation of demonstration SFRs most of which are in relevant sizes for SM-SFRs, including experience in the UK with PFR. SFRs have been found to have operator doses lower or at the low end of those found with PWRs. This is because of the relatively low activation of sodium, essentially zero fuel failure rates, the enclosure of the primary circuit in the reactor vessel for pool designs and the need for remote, inert atmosphere refuelling and maintenance.

Assessed as 'Reference'

11. Worker Exposures

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.

11. Worker Exposures - references

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1b. Time and Effort for Environmental Permitting

Summary

SM-SFRs will require further design and development in order to be able to satisfy environmental permitting requirements. However, SFRs have some favourable characteristics on radiological performance and the work required is likely to be similar to that for the reference SMR-PWR.

Assessed as 'Reference'

Attribute – 1b.1 Effort to meet environmental regulations

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Description

References

1b. Time and Effort for Environmental Permitting

Nuclear facilities in the UK are required to comply with the requirements set down by the appropriate regulatory bodies. Environmental regulations are the responsibility of the Environment Agencies (EA ,NRW, SEPA) and are implemented through the granting of site aerial and liquid Discharge Authorisations. The Environment Agencies are also responsible for the authorisation of solid waste disposal.

1b. Time and Effort for Environmental Permitting - References

Insert

1b.1 Effort to meet environmental regulations

SM-SFRs will require further design and development in order to be able to satisfy environmental permitting requirements. However, SFRs have some favourable characteristics on radiological performance and the work required is likely to be similar to that for the reference SMR-PWR.

Assessed as 'Reference'

Metric – 06 Environmental Impact

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Description

References

1b.1 Effort to meet environmental regulations

1b.1 assesses the challenge faced by a reactor system in meeting the environmental impact requirements defined by the regulators, noting that this includes the reactor and its fuel cycle. This parameter is assumed to refer to routine operational environmental discharges. Levels of challenge would be expected to increase as the system examined moves further away from current experience, for example:

- Systems which are already deployed commercially or whose designs are already licensed in other countries.
- Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.
- Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.
- Systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

Assessments will assume that regulatory effort is available when and as required

1b.1 Effort to meet environmental regulations - references

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06. Environmental Impact

Discharges to the atmosphere from a significant number of demonstration SFRs most of which are in sizes relevant to SMS-FRs, have shown lower or comparable levels compared to PWRs. The environmental impact will be influenced by the choice of fuel (metal or oxide) and the management of spent fuel including reprocessing if a closed fuel cycle is chosen. For these reason Environmental Impact is assess as a Minor Challenge.

Assessed as 'Minor Challenge'

06. Environmental Impact

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.

06. Environmental Impact - references

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1c. Proliferation Resistance and Physical Protection (PRPP) Acceptability

Summary

The once-through LWR fuel cycle is internationally recognised as the reference system for inherent PRPP assessments. Given that the spent fuel from SM-SFR will be reprocessed, there is the potential for the inherent PRPP performance to be less favourable (this applies even if the reprocessing flowsheet avoids the separation of pure plutonium). Overall, the security and safeguards will be designed to offer adequate protection and inherent PRPP is seen as posing a Minor Challenge.

PRPP is taken to have a dual meaning, with Proliferation Resistance referring to state involvement in diversion of fissile materials and Physical Protection concerned with the threat of acquisition of nuclear materials by a sub-national group. The assessments are potentially different for the two aspects.

Assessed as 'Minor Challenge'

Attributes

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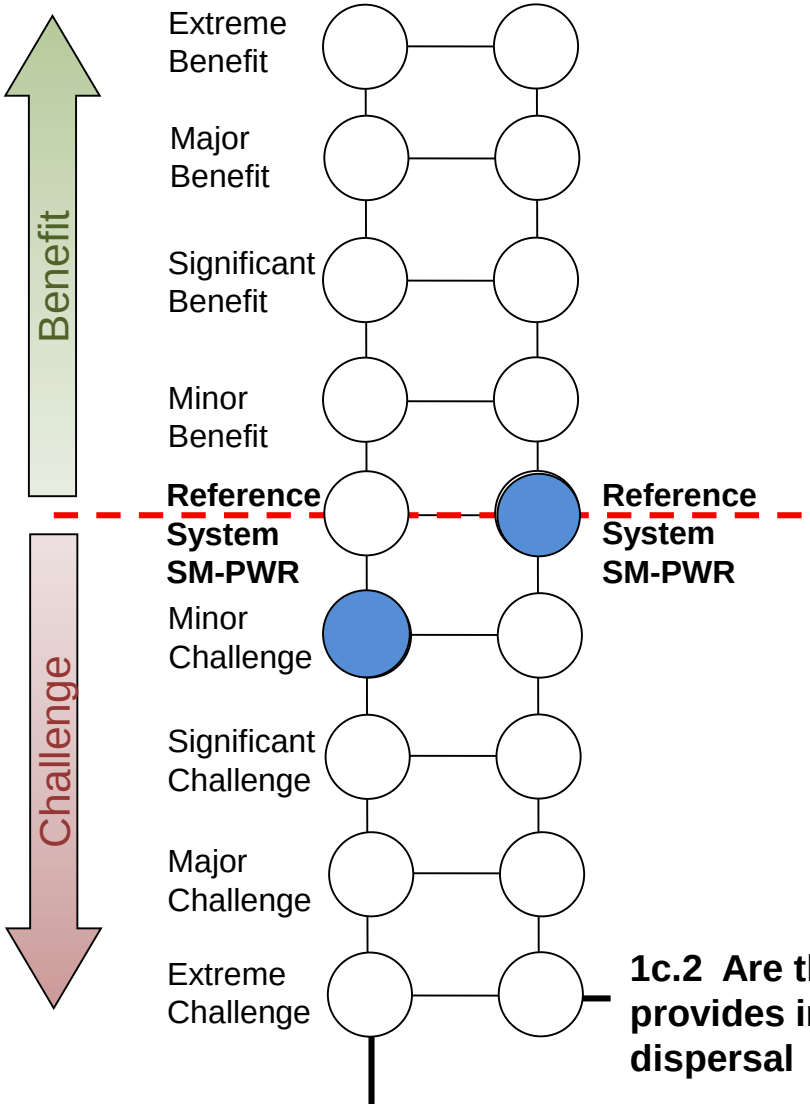
Description

1c. Proliferation Resistance and Physical Protection (PRPP) Acceptability



1c.2 Are the nuclear materials in a form that provides inherent self-protection against theft or dispersal

1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage

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1c. Proliferation Resistance and Physical Protection (PRPP) Acceptability

Any new system deployed in the UK will be required to satisfy the Nuclear Industries Security Regulations 2003. This is a system which responds to the nuclear processes being carried out and the amount and form of nuclear materials being used, and ensures that a system is in place which will "prevent the theft or sabotage of nuclear material or the sabotage of nuclear facilities". The Office of Civil Nuclear Security (OCNS) is the responsible regulator.

UK situation is that, while systems may not accord with the ideals of PRPP, yet there are systems, monitored and enforced by OCNS, which ensure risks of theft or sabotage are maintained at acceptably low levels. Thus while it is highly relevant to monitor the PRPP characteristics of nuclear reactor systems, the value of this Attribute in the UK context is predominantly to be judged by policy makers. The assessment will, however, give an indication of the challenges to be met in order to generate an approved Security Plan for the candidate system.

The top level PRPP criterion can be posed as: *"Are the nuclear materials produced in the fuel cycle difficult to access?"*

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1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage

Depending on the specific fuel cycle SM-SFR may produce separated fissile material by irradiation of fertile material, which is unfavourable relative to the once-through LWR fuel cycle.

Assessed as 'Minor Challenge'

Metrics

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Description

References

1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage

This attribute accounts for the physical forms of fissile materials in the fuel cycle. The levels of challenge will vary between:

Fuel cycles in which high grade fissile materials are present at any stage, for example high enriched uranium (HEU) or plutonium, which will be considered to present considerable PRPP challenges. Examples would include a fuel cycle based on HEU fuel or the separation of pure plutonium for recycle (as in conventional PUREX reprocessing).

A LWR fuel cycle with low enriched uranium (LEU) and a once-through fuel cycle will present a lower level of PRPP challenge.

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1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage - references

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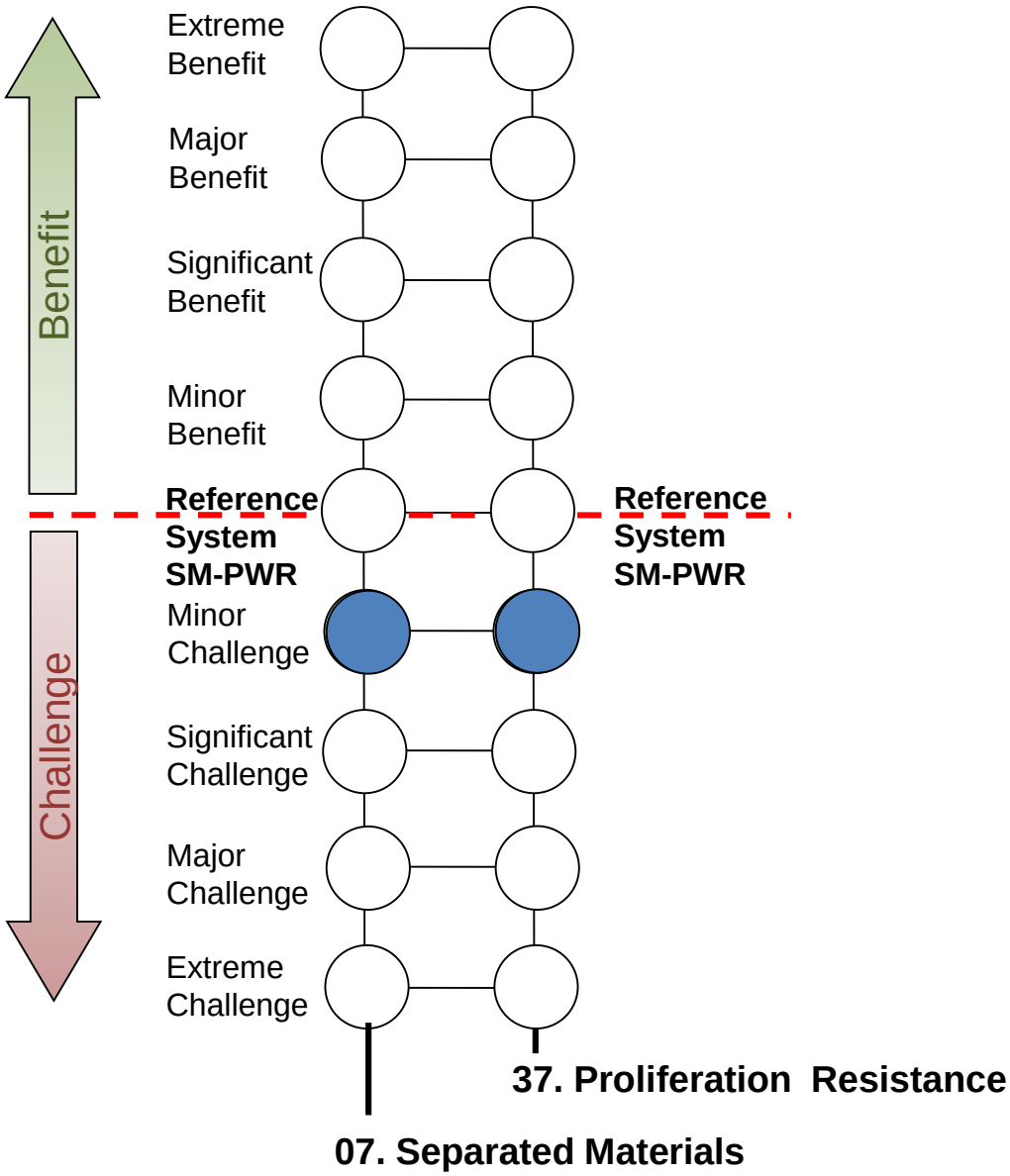
1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage



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07. Separated Materials

Depending on the specific fuel cycle SM-SFR will involve reprocessing which is unfavourable relative to the once-through LWR fuel cycle, as the production of fissile material even as a co-product reduces the level of inherent protection relative to irradiated fuel.

Assessed as 'Minor Challenge'

07. Separated Materials

One of the PRPP goals of advanced systems is that they 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.

07. Separated Materials - references

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37. Proliferation Resistance

The once-through LWR fuel cycle is internationally recognised as the reference system for inherent PRPP assessments. Depending on the specific fuel cycle SM-SFR will involve reprocessing which is unfavourable relative to the once-through LWR fuel cycle, as the production of fissile material even as a co-product makes potential diversion scenarios simpler to enact.

Assessed as 'Minor Challenge'

37. Proliferation Resistance

There is increasing interest in international reactor systems development to be able to demonstrate increased proliferation resistance by design, and different reactor systems may be considerably differentiated by inherent proliferation resistance. 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.

37. Proliferation Resistance – references

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1c.2 Are the nuclear materials in the fuel cycle in a form which provides inherent self-protection against theft or dispersal

SM-SFR reprocessing will generate fissile material in a form which offers less self-protection than the LWR once-through fuel cycle. Even if an advanced separation process is deployed that avoids the production of pure fissile material, the degree of self-protection is less than that of irradiated fuel.

Assessed as 'Minor Challenge'

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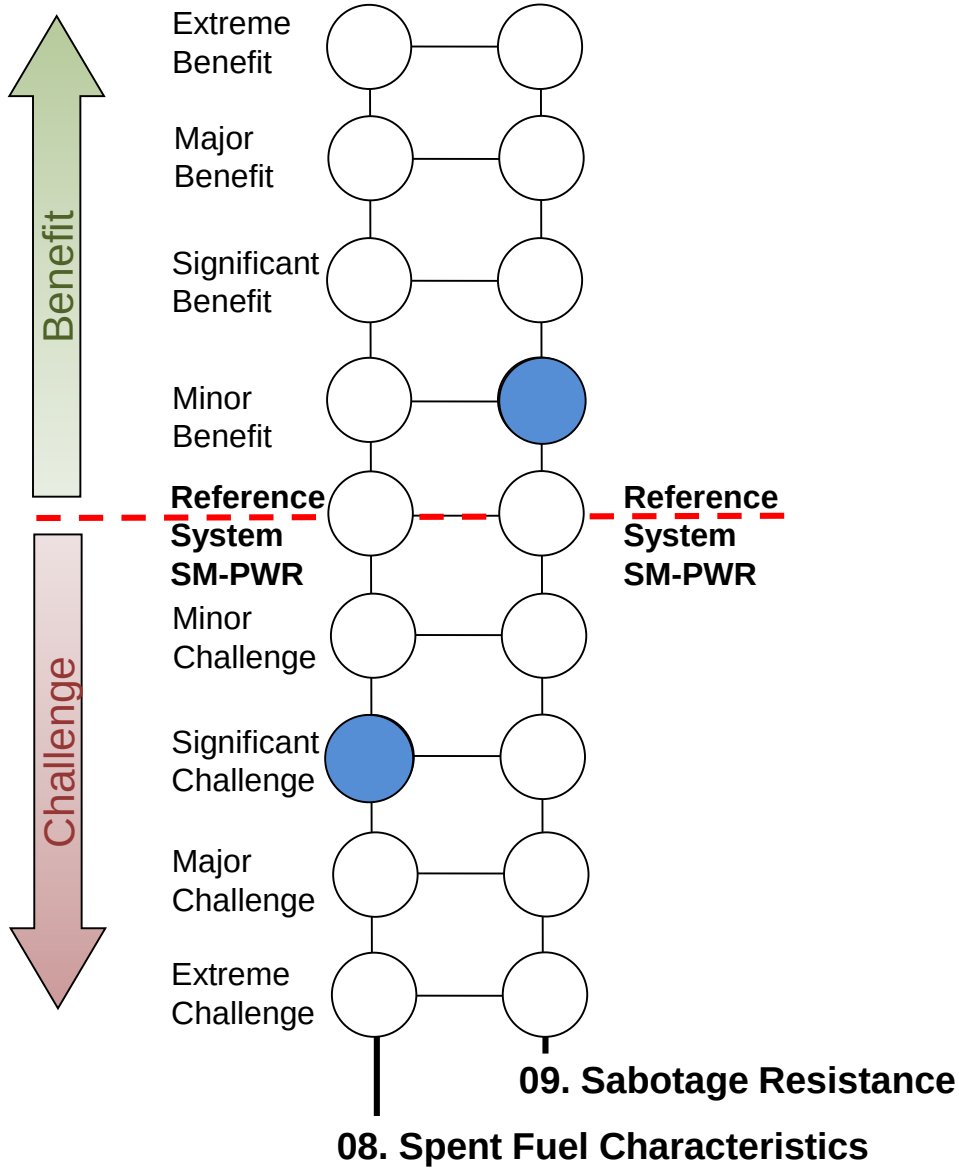
Description

References

1c.2 Are the nuclear materials in the fuel cycle in a form which provides inherent self-protection against theft or dispersal



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Description

1c.2 Are the nuclear materials in the fuel cycle in a form which provides inherent self-protection against theft or dispersal

1c.2 (Inherent PRPP). This attribute tests whether nuclear material is inherently protected by physical or chemical form, or by a strong self-protective radiation field. It is also intended to test whether the material is in a form that could be readily dispersed. Illustrations of levels of challenge are:

- a once-through fuel cycle with uranium oxide fuel in which there are multiple inherent barriers to accessing fissile material.
- fuel cycles which involve the production at some stage of unirradiated HEU fuel or plutonium oxide powder which present no inherent barriers.

1c.2 Are the nuclear materials in the fuel cycle in a form which provides inherent self-protection against theft or dispersal - references

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08. Spent fuel characteristics

The spent fuel from SM-SFR may pose challenges for transport and reprocessing, especially if there is a requirement for it to be reprocessed after a short cooling time, on account of the decay heat load.

Assessed as 'Significant Challenge'

08. Spent fuel characteristics

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.

08. Spent fuel characteristics - references

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09. Sabotage resistance

A detailed design assessment of the vulnerability of SM-SFR to sabotage/missile attack will need to be made. The designs currently proposed are not at the stage for such an assessment.

Assessed as 'Major Challenge'

09. Sabotage resistance

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 but in some of the systems, for example small modular PWRs, the nuclear island is largely sited underground and therefore exceptionally well protected.

09. Sabotage resistance - references

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2a. Economic Competitiveness

Summary

Although SMRs have the theoretical potential to improve economic competitiveness, there are some significant challenges that will need to be addressed. SM-SFR is likely be penalised by historic scaling laws that favour large plants and will need to rely on new compensating mechanisms, such as cost savings from factory replication, lower risk financing and more favourable grid connection charges. In the absence of evidence to the contrary, SM-SFR is assumed subject to the same scaling laws as the SM-PWR reference system, but to be economically disadvantaged on account of the secondary sodium circuit and demanding fuel cycle. SM-SFR is assessed as Significant Challenge. However, there may be some advantage for SM-SFRs as they have the potential to be more compact than SM-PWR and operate at low pressure that could give savings on steel and concrete – but see slide 88.

Assessed as 'Significant Challenge'

Attributes
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Description

2a. Economic Competitiveness

The electrical generation cost is one of the principal criteria against which a nuclear system will be assessed – without a demonstrably economically competitive system, utilities are unlikely to invest.

The top level economics Attribute can be posed as: *Will the reactor system be economically competitive in the electricity generation market or in possible future heat generation markets?*

From this Strategic Attribute, the following Criteria are obtained:

Overnight construction cost. The cost of building and financing the nuclear system, usually expressed as £/MWe.

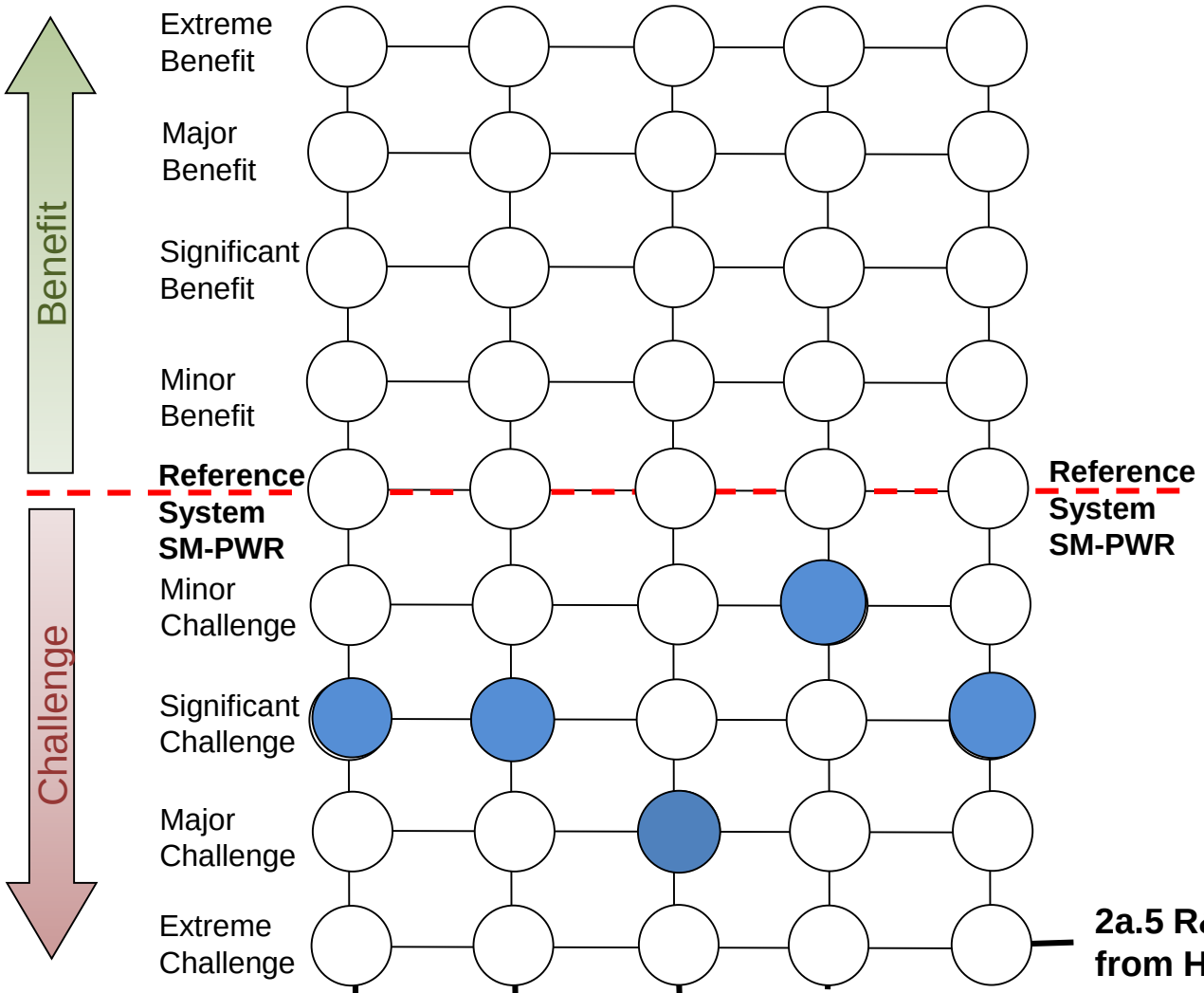
Operating and maintenance cost: This is the cost of operating and maintenance (O&M), taken to include staffing costs, operating costs (excluding fuel), the cost of routine maintenance and other related costs, usually expressed as a levelised cost in £/MWh.

Fuel cycle cost: This criterion is intended to capture the cost of operating the fuel cycle, both procuring new fuel and all the back-end costs associated with spent fuel management or reprocessing/recycle, usually expressed as a levelised cost in £/MWh.

Decommissioning cost: This is the actual cost of decommissioning *without* applying financial discounting, expressed as £/MWe.

R&D cost: This is the cost of the research and development programme needed to bring a system to commercial readiness. This will generally be an infeed into this attribute from High Level Discriminator 1 – Regulatory Challenges and Timescales.

2a. Economic Competitiveness



2a.5 R&D cost – feed from HLD1

2a.4 Decommissioning cost

2a.3 Fuel cycle cost – front and back end combined

2a.2 Operating and Maintenance cost

2a.1 Overnight construction cost

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Description

2a1. Overnight construction cost

For SMR generally there is an economy of scale penalty (for which there is a consensus), but with potential for savings from replication, factory build and increased modularisation. There is also the Potential for first module to finance later modules but note need for common infrastructure to be in place for the first module.

SM-SFR is considered equivalent to the SM-PWR Reference System in respect of scaling, but penalised because of the requirement for a secondary sodium circuit, which equates to a Significant Challenge on overnight construction cost. However, the higher power density and the lack of pressurised primary system has the potential for reducing construction costs, though offset by the possible need for a second tier heat transport system (eg IHX in sodium/water heat transport).

Assessed as 'Significant Challenge'

Metrics

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Description

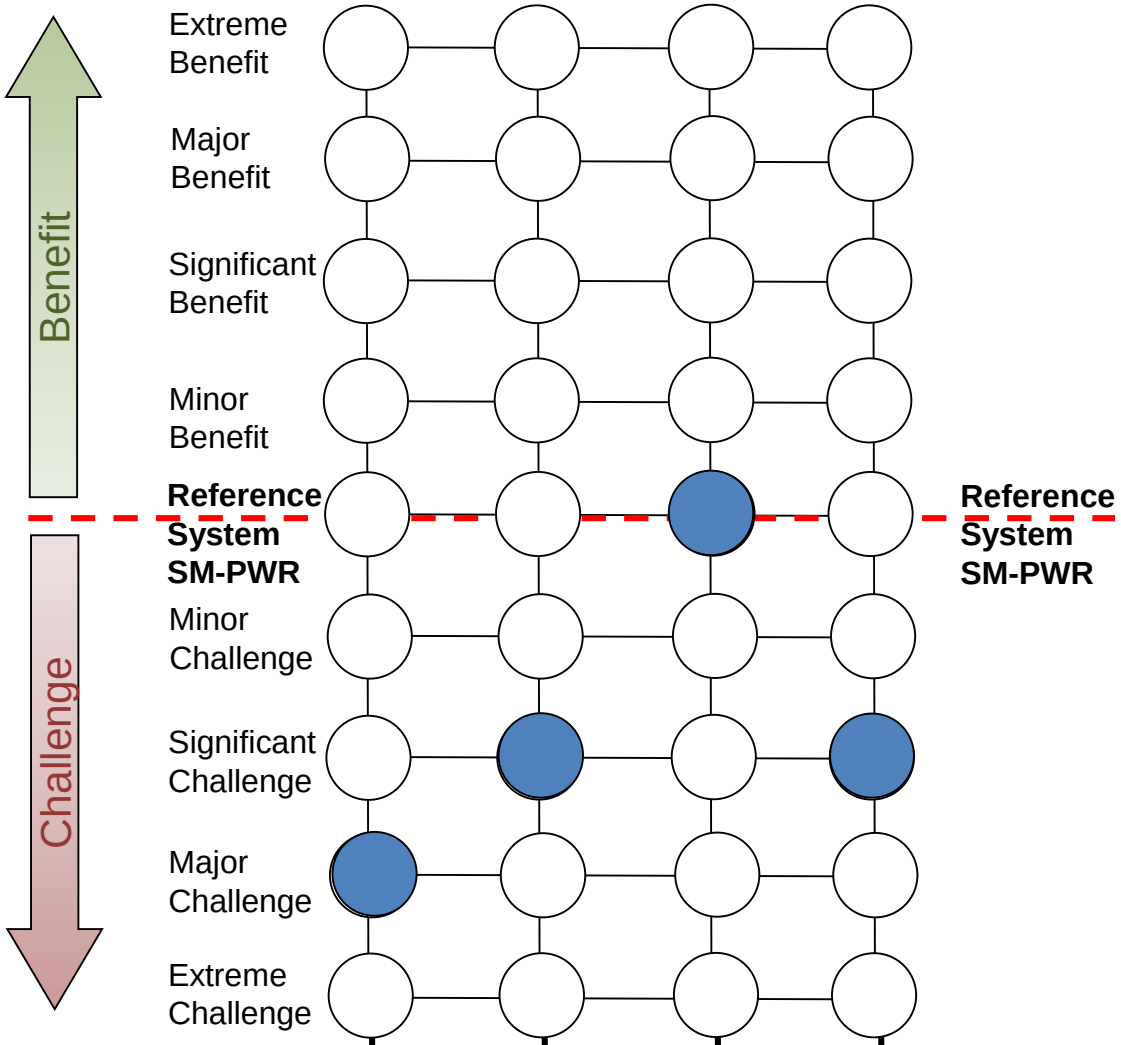
References

2a.1 Overnight construction cost

2a.1 (Overnight construction cost). The cost of building and financing the nuclear system, usually expressed as £/MWe. This attribute is the cost of construction and of financing construction, usually taken as the overnight construction cost with all financing costs discounted to the date at which the plant becomes operational. Included in this context, is the construction cost of any fuel cycle plants needed for fuel reprocessing, recycle or waste management. Illustrations of levels of challenge are:

- Plants with a high degree of modularisation and short construction times.
- Plants with a limited degree of modularisation and moderate construction times. This might apply to current large PWRs operating a once-through fuel cycle, for example.
- Complex plants with long and difficult construction demands. This might apply to systems involving extensive reprocessing and recycle.

2a.1 Overnight construction cost



34. Ease of Construction

29. Scaleability

24. Construction Duration

22. Overnight construction cost

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Description

22. Overnight construction cost

For SMR generally there is an economy of scale penalty (for which there is a consensus), but with potential for savings from replication, factory build and increased modularisation. There is also the Potential for first module to finance later modules but note need for common infrastructure to be in place for the first module.

SM-SFR is considered equivalent to the SM-PWR Reference System in respect of scaling, but penalised because of the requirement for a secondary sodium circuit, which equates to a Major Challenge on overnight construction cost.

Assessed as 'Major Challenge'

22 Overnight construction cost

22 (Overnight construction cost). The cost of building and financing the nuclear system, usually expressed as £/MWe. This attribute is the cost of construction and of financing construction, usually taken as the overnight construction cost with all financing costs discounted to the date at which the plant becomes operational. Included in this context, is the construction cost of any fuel cycle plants needed for fuel reprocessing, recycle or waste management. Illustrations of levels of challenge are:

- Plants with a high degree of modularisation and short construction times.
- Plants with a limited degree of modularisation and moderate construction times. This might apply to current large PWRs operating a once-through fuel cycle, for example.
- Complex plants with long and difficult construction demands. This might apply to systems involving extensive reprocessing and recycle.

22. Overnight construction costs - references

Most SM-SFR designs currently being developed have not yet reached the stage where there is a detailed breakdown of construction costs.

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24. Construction duration

Short construction times reduces finance cost and risk with theoretically lower £/kWe. SM-SFR designs currently being developed are not yet at the stage where short construction times can be considered demonstrated. The requirement for a secondary sodium circuit implies increased bulk for the reactor system that may impact construction times. The layout of some pool-type SFR designs may not fit as well with modular installation as the SM-PWR Reference System. Assessed as a Significant Challenge relative to SM-PWR.

Assessed as 'Significant Challenge'

24. Construction duration

The duration of plant construction has already been discussed under Item 22 (overnight construction cost) and the same assessment applies.

24. Construction duration - references

Insert here

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29. Scaleability

SM-SFR is regarded equivalent to the SM-PWR Reference System as they are both scaleable in principle and could give advantages over UK grid management.

Assessed as 'Reference'

29. Scaleability

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.

29. Scaleability - references

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34. Ease of Construction

The layout of some pool-type SFR designs may not fit as well with modular installation as the SM-PWR Reference System. Also requirement for secondary sodium circuit adds complexity. Assessed as a Significant Challenge relative to SM-PWR.

Assessed as 'Significant Challenge'

34. Ease of Construction

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.

34. Ease of Construction - references

Insert here

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2a.2 Operating and maintenance cost

Operating an maintenance costs are an area where SM-SFR is no developed sufficiently to make an informed judgement. The reliability of SFR systems in the prototypes operated to date has been poor, which suggests a possible challenge. The secondary sodium circuit adds complexity. In-service maintenance and inspection under sodium cover requires some special technology for which there is experience on various demonstration reactors. Same scaling effect of operating and maintenance as SM-PWR Reference System. Overall assessment Significant Challenge.

Assessed as 'Significant Challenge'

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Description

References

2a.2 Operating and maintenance cost

This Attribute covers the cost of operating and maintenance, taken to include staffing costs, operating costs (excluding fuel), the cost of routine maintenance and other related costs. Illustrations of levels of O&M costs are:

- Plants such as LWRs with long operating lives and no requirement for mid-life refurbishment of major plant items
- Plants with a requirement for through-life replacement of major components
- Complex plants with difficult operational requirements

2a.2 Operating and maintenance cost - references

None of the SM-SFR designs currently being developed have reached the stage where there is a detailed breakdown of O&M costs.

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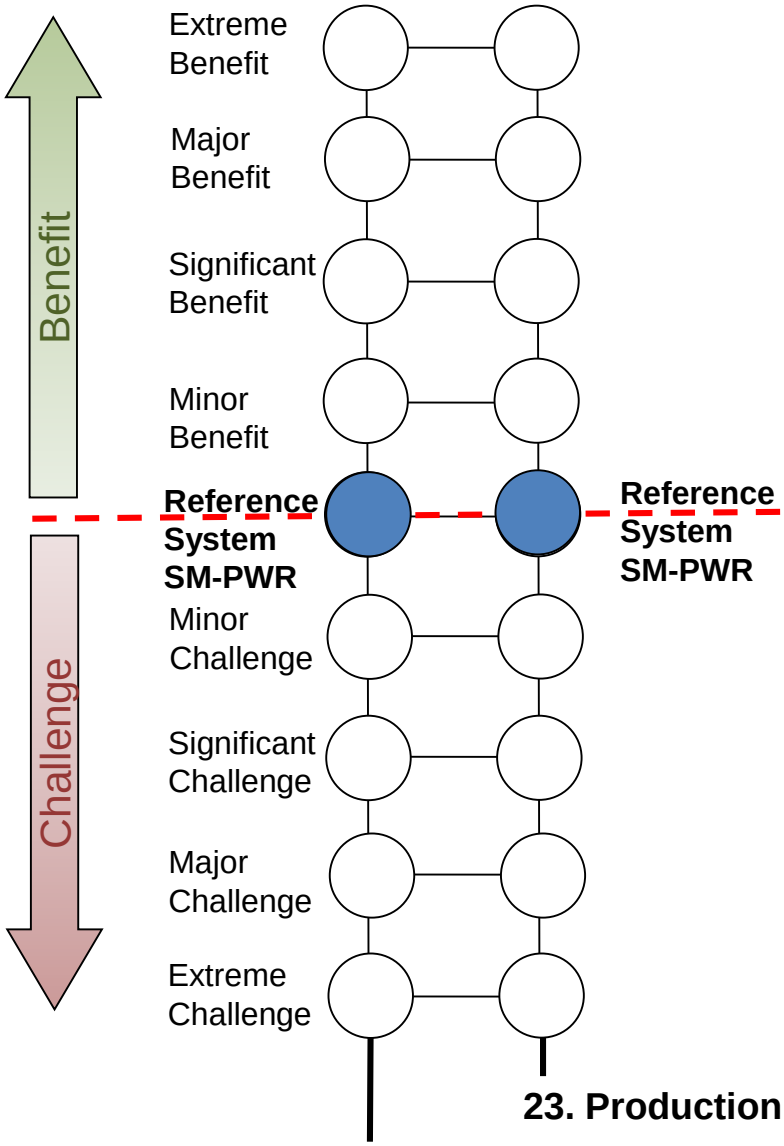
2a.2 Operating and maintenance cost



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10. Reliability

Potential reduction in grid connection charge due to smaller loss of capacity from a single unit. But risk of loss of capacity of entire power station from common factors (eg loss of grid connection) unaffected. SM-SFR is equivalent to the SM-PWR Reference System in this respect.

Assessed as 'Reference'

10. Reliability

This is the forced outage rate, which should be very low. It is an operational safety and reliability issue, but it is also important for economics. Best operational practice at modern PWRs 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.

10. Reliability - references

Insert

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23. Production costs (O&M)

Economy of scale penalty potentially offset by reduced maintenance requirements .
Minimum manning level agreed with regulator a potential issue.
Grid connection cited as an area where SMRs can be beneficial, but not demonstrated.
SM-SFR equivalent to SM-PWR Reference System.

Assessed as 'Reference'

23. Production costs (O&M)

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. There is no distinction here between SM-SFR and the SM-PWR Reference System.

23. Production costs (O&M) - references

None of the SM-SFR designs currently being developed have reached the stage where there is a detailed breakdown of O&M costs.

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2a.3 Fuel cycle costs (front and back-end combined)

SM-SFR will operate a closed fuel cycle. This is a disadvantage over the SM-PWR Reference System, which uses the once-through fuel cycle. It is expected that the SFR fuel cycle will be prove more expensive than SM-PWR due to the extra complexity and the technically demanding fuel cycle. Any new SFR plant in the UK will require a fuel fabrication facility that will need to be sited in the UK to prevent issues on Pu transport. The UK has experience on the construction of MOX plant but US technology would need to be used for metal fuel fabrication. There will be significant costs in either case. The establishment of a new reprocessing facility in today's condition is a development project. SM-SFR is assessed as a Major Challenge.

Assessed as 'Major Challenge'

2a.3 Fuel cycle costs (front and back-end combined)

2a.3 (Fuel cycle cost). This attribute is intended to capture the cost of operating the fuel cycle, both procuring new fuel and all the back-end costs associated with spent fuel management or reprocessing/recycle. Illustrations of varying levels of challenge with choice of fuel cycle are:

- the once-through LWR fuel cycle
- the closed LWR fuel, cycle (i.e. thermal recycle)
- a fast reactor system with recycle, especially if there was recycle of minor actinides.

2a.3 Fuel cycle costs (front and back-end combined) - references

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2a.4 Decommissioning costs

41. Decommissioning costs

Despite the SM-SFR being a more complex system there is significant experience in decommissioning SFR reactors and fuel cycle plant in the UK at Dounreay so the SM-SFR is assessed as a Minor Challenge relative to the SM-PWR Reference System.

Assessed as 'Minor Challenge'

2a.4 Decommissioning costs

41. Decommissioning costs

2a.4 (Decommissioning cost). This attribute is intended to represent the actual cost of decommissioning without applying financial discounting. The decommissioning cost represents a significant risk element in financial analysis, even though the discounted cost is usually very low. Levels of challenge are illustrated by:

- A nuclear system with small, modular components compatible with disposal as self-contained units.
- Current LWRs where, after defueling, there are only medium active components that need to be decommissioned in the core.
- Systems with graphite moderation, such as the UK's legacy gas cooled reactors, due to the need to deal with large masses of material.

2a.4 Decommissioning costs - references

41. Decommissioning costs

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2a.5 R&D cost

There is an extensive body of experience from demonstration reactors, fuel cycle plant and laboratory studies on SFRs at sizes relevant to SM-SFRs. Despite this R&D costs for SM-SFR will be significant, since many aspects are currently at a intermediate Technology Readiness Level (TRL). This is because current SM-SFR designs have made significant design changes to deal with issues relating to the integrity of steam generators, materials choices and the fuel cycle. This represents a Significant Challenge relative to the SM-PWR Reference System.

Assessed as 'Significant Challenge'

Metrics

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Description

References

2a.5 R&D cost

This Attribute covers the cost of the research and development programme needed to bring a system to commercial readiness. Illustrations of levels of R&D cost are:

- Those associated with an existing system or a minor development of an existing system
- Those associated with the evolution of a current system
- Those associated with novel systems involving significant innovations and long and extensive R&D

2a.5 R&D cost - references

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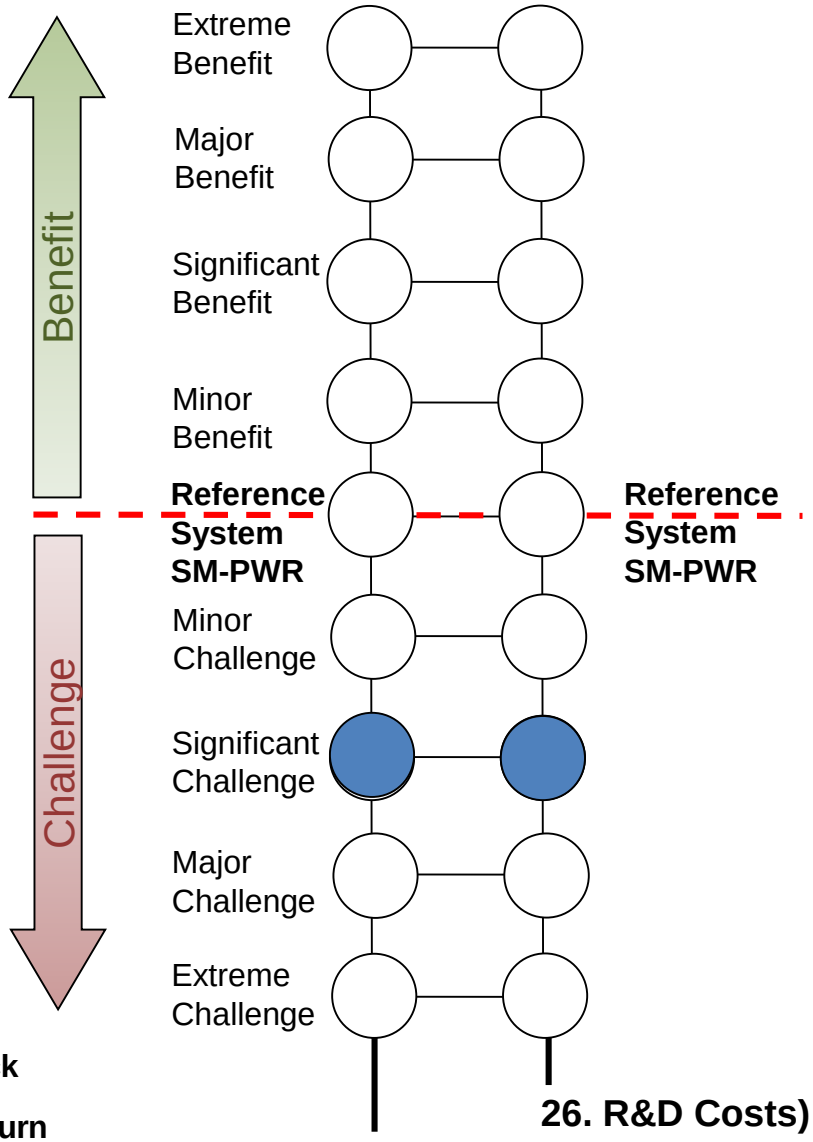
2a.5 R&D cost



26. R&D Costs)

17. Integral experiment scaleability

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17. Integral experiment scaleability

Integral experiment data, much of which is at sizes relevant to SM-SFRs, is available from historic testing work and operational data, but further testing will be needed to license to modern standards and to further investigate life limiting issues that have arisen in the operation of the demonstration reactors. Only very limited testing has been done on metal fuels at full size and there are issues remaining on the fuel dimensional stability, chemical segregations, compatibility with cladding and low melting point. This represents a Significant Challenge relative to the SM-PWR Reference System.

Assessed as 'Significant Challenge'

17. Integral experiment scaleability

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.

17. Integral experiment scaleability - references

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26. R&D costs

SMR systems at relevant sizes to the SM-SFR case have been demonstrated with substantial reactor and laboratory studies. However, although the performance of the fuels and core structures was satisfactory many problems were encountered relating to the structural integrity and materials degradation of the sodium circuits, the steam generator and to a lesser extent core structures: this position is not helped by the lack of an up to date high temperature pressure vessel/structural systems design code (as compared to an assessment code such as R5). In addition the way forward on fuel materials and the associated fuel cycle are still to be resolved. As a consequence substantial development work still needs to be done before current design concepts. This represents a Significant Challenge relative to the SM-PWR Reference System.

.

Assessed as 'Significant Challenge'

26. R&D costs

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. However, if the UK was to buy into technology that was not being developed elsewhere, the UK could incur the R&D costs and risks.

26. R&D costs - references

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3a. Fuel Security

Summary

With a closed fuel cycle SM-SFR could in principle operate with a high conversion ratio or breeding cycle. In this instance, the system could operate independent of the world uranium market, which is beneficial for fuel security. Assessed as a Major Benefit. For this assessment SM-SFR is assumed to operate with recycle of plutonium only.

Assessed as 'Major Benefit'

Attributes

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Description

References

3a. Fuel Security

Summary

This Strategic Attribute assesses whether fissile materials are available to start up a reactor system, and whether the supplies are sufficient and secure enough to fuel the reactor(s) over their projected lifetime

3a. Fuel Security - references

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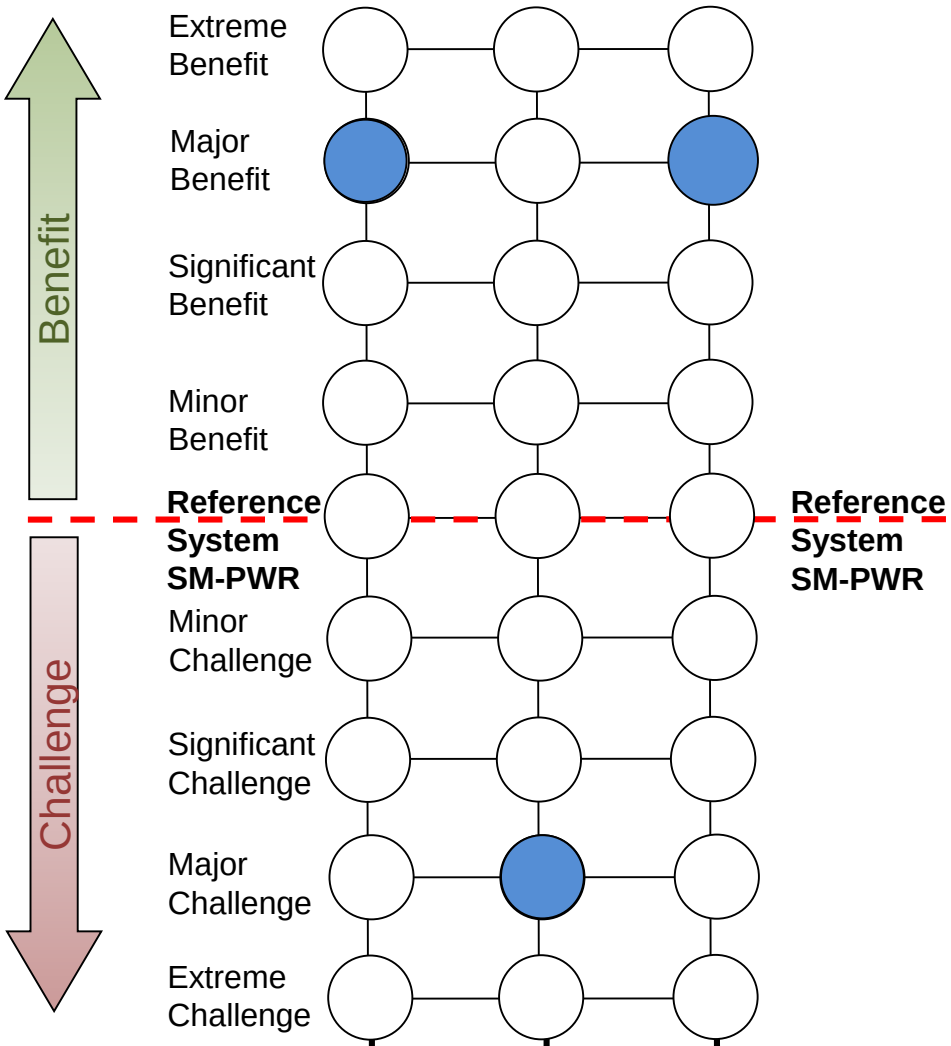
3a. Fuel Security



3a.3 Uranium dependence

3a.2 Spent fuel characteristics – compatible with existing reprocessing technology?

3a.1 Ability to deploy – fissile material availability

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Description

3a.1 Ability to deploy – fissile material availability

With a closed fuel cycle SM-SFR could in principle operate with a high conversion ratio or breeding cycle. In this instance, the system could operate independent of the world uranium market, which is beneficial for fuel security. Assessed as a Major Benefit

Assessed as 'Major Benefit'

3a.1 Ability to deploy – fissile material availability

3a.1 (Fissile material availability) applies specifically to closed fuel cycle systems which may have limitations on the rate at which new reactors could be deployed because of the need to acquire and/or build up the necessary fissile material. The levels of challenge vary between open and closed fuel cycle systems:

OPEN - this designates an open fuel cycle in which reactors are fuelled by LEU, which as natural uranium or LEU is available on the world market. In this instance the deployment rate would not be restricted, provided that world market supplies are sufficient and sufficient reactor build capacity was available.

CLOSED – this designates a closed fuel cycle which will eventually operate virtually independently of uranium availability, but which may be subject to constraints on the initial rate of deployment depending on the availability of fissile material. Limitations to closed cycle deployment can be calculated for any assumed future nuclear generation scenario.

3a.1 Ability to deploy – fissile material availability - references

Insert

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3a.2 Spent fuel characteristics – compatible with existing reprocessing technology?

The spent fuel form for SM-SFR is essentially compatible with current reprocessing technology, though metal fuel would require a different head-end treatment. However, SFR spent fuel is challenging to reprocess on account of its high initial fissile content, high burnup and associated decay heat output. Current reprocessing plants are incompatible with such fuels and new designs will need to be developed, although there is a body of experience from various project to demonstrate the closed fast reactor fuel cycle at Dounreay, Idaho National Laboratory, Marcoule and in Russia. Assessed as Major Challenge

Assessed as 'Major Challenge'

3a.2 Spent fuel characteristics – compatible with existing reprocessing technology?

3a.2 (Spent fuel characteristics).
Spent fuel characteristics: Is the spent fuel of a form that is compatible with established reprocessing methods, or are there features that would preclude its reprocessing using current reprocessing methods? This Attribute tests whether or not the spent fuel form is compatible with established reprocessing technologies and gives a measure of the accessibility of the contained fissile material and hence the ability to affect any closed cycle deployment limitations in 3a.1.

Conventional spent oxide or metallic fuel, irrespective of whether the main fissile material is uranium or plutonium, are compatible with existing reprocessing technologies.

Unconventional fuels, such as fuels based on thorium matrix or coated particle TRISO fuels (used in high temperature gas reactors) are incompatible with established reprocessing methods. Fuel which is not straightforward to reprocess represents an intrinsic barrier to accessing fissile material.

3a.2 Spent fuel characteristics – compatible with existing reprocessing technology?

References

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3a.3 Uranium dependence

SM-SFR is in principle capable of operating a breeder cycle or a high conversion cycle. In this case, its dependence on uranium available on the international market would be eliminated or considerably reduced in the very long term. Assessed as a Major Benefit.

Assessed as 'Major Benefit'

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3a.3 Uranium dependence

The uranium usage Attribute poses the questions: "*Will there be sufficient uranium available on the world market to meet the requirements of the reactor system over its operational lifetime?"* and therefore *"Is the system more or less dependent on uranium ore availability/supply on the world market?*"

3a.3 therefore categorises the dependence of the nuclear system on uranium obtained from the world market. Illustrations of levels of uranium usage are:

LWRs have a specific uranium requirement of approximately 200 tU/GWye. CANDU reactors have a lower specific uranium requirement of approximately 160 tU/GWye.

Systems with high conversion ratios or with partial recycle of fissile materials are less dependent on uranium ore, defined as specific uranium requirements in the range 20 to 160 tU/GWye.

The lower range is set arbitrarily to 20 tU/GWye to allow for systems with high conversion ratios that are not quite self-sustained. Systems which have full recycle of fissile materials and operate a breeding cycle totally independent of external uranium supplies.

3a.3 Uranium dependence - References

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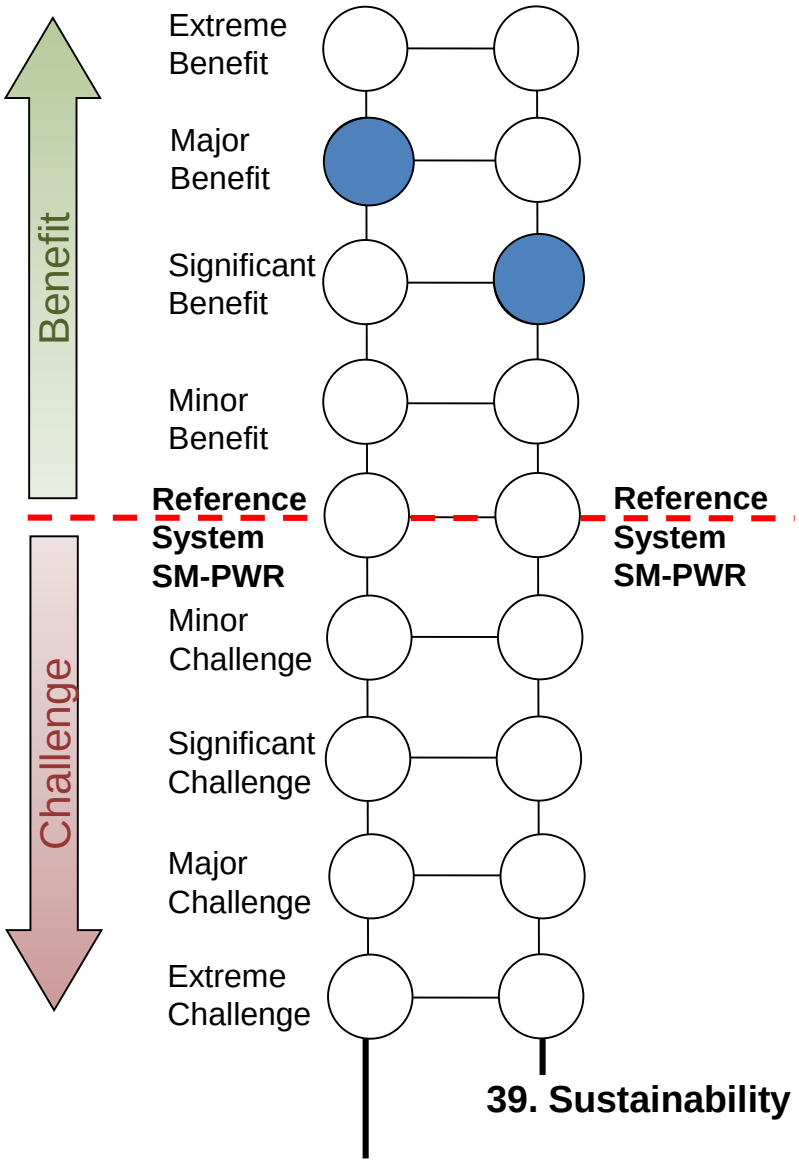
3a.3 Uranium dependence



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Description

01. Fuel utilisation

SM-SFR is in principle capable of operating a breeder cycle or a high conversion cycle. In this case, its dependence on uranium available on the international market would be eliminated or considerably reduced in the very long term. Assessed as a Major Benefit.

Assessed as 'Major Benefit'

01. Fuel utilisation

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.

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.

01. Fuel utilisation - references

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39. Sustainability

This is potentially a broad area encompassing the uranium ore requirement, environmental impact, waste arisings and others. SM-SFR operating a closed fuel cycle is assessed as 'Major Benefit' with respect to uranium ore demand. While it is too soon to assess other areas such as environmental impact, detailed assessment of waste arisings has shown considerable benefits in terms of decay heat load of waste for geological disposal. For this reason, SM-SFR is assessed as Significant Benefit against sustainability.

Assessed as 'Significant Benefit'

39. Sustainability

Sustainability is potentially a broad area encompassing the uranium ore requirement, environmental impact, waste arisings and others.

39. Sustainability - references

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3b. Waste storage and disposability

Summary

The spent fuel characteristics of SM-SFR are considerably more challenging than for the SM-PWR Reference Systems, especially if the fuel is reprocessed at short cooling times. There are aspects which may pose a Major Challenge and others which are assessed as giving a Significant Benefit. Overall assessment ranging between Significant Challenge for short cooling time requirement to Significant Benefit if there if long cooling times are allowed.

Assessed as range from 'Significant Challenge' to 'Significant Benefit'

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3b. Waste storage and disposability

Summary

All nuclear reactors generate nuclear waste that needs to be managed as part of the fuel cycle. The management and disposability of nuclear waste is one of the key long term considerations for the nuclear power industry. The current solution sought for long term disposability is to encapsulate waste into solid forms which are then protectively packaged and placed into a geological disposal facility (GDF). It is therefore required that any spent fuel, high level or intermediate level waste arising must be suitable for encapsulation and safe long term disposal in a GDF.

The waste management Strategic Attribute can be posed as: *Can the waste arisings from reactor systems be managed and eventually disposed of in a safe manner that is compatible with the acceptance criteria for existing or anticipated waste treatment plants and disposal facilities?*

From this top level Strategic Attribute, the following attributes are obtained:

Compatibility of waste forms: The masses and volumes of waste forms for disposal.

Suitability for disposal in GDF: Waste incorporation rate, long term decay heat and radiotoxicity.

3b. Waste storage and disposability - References

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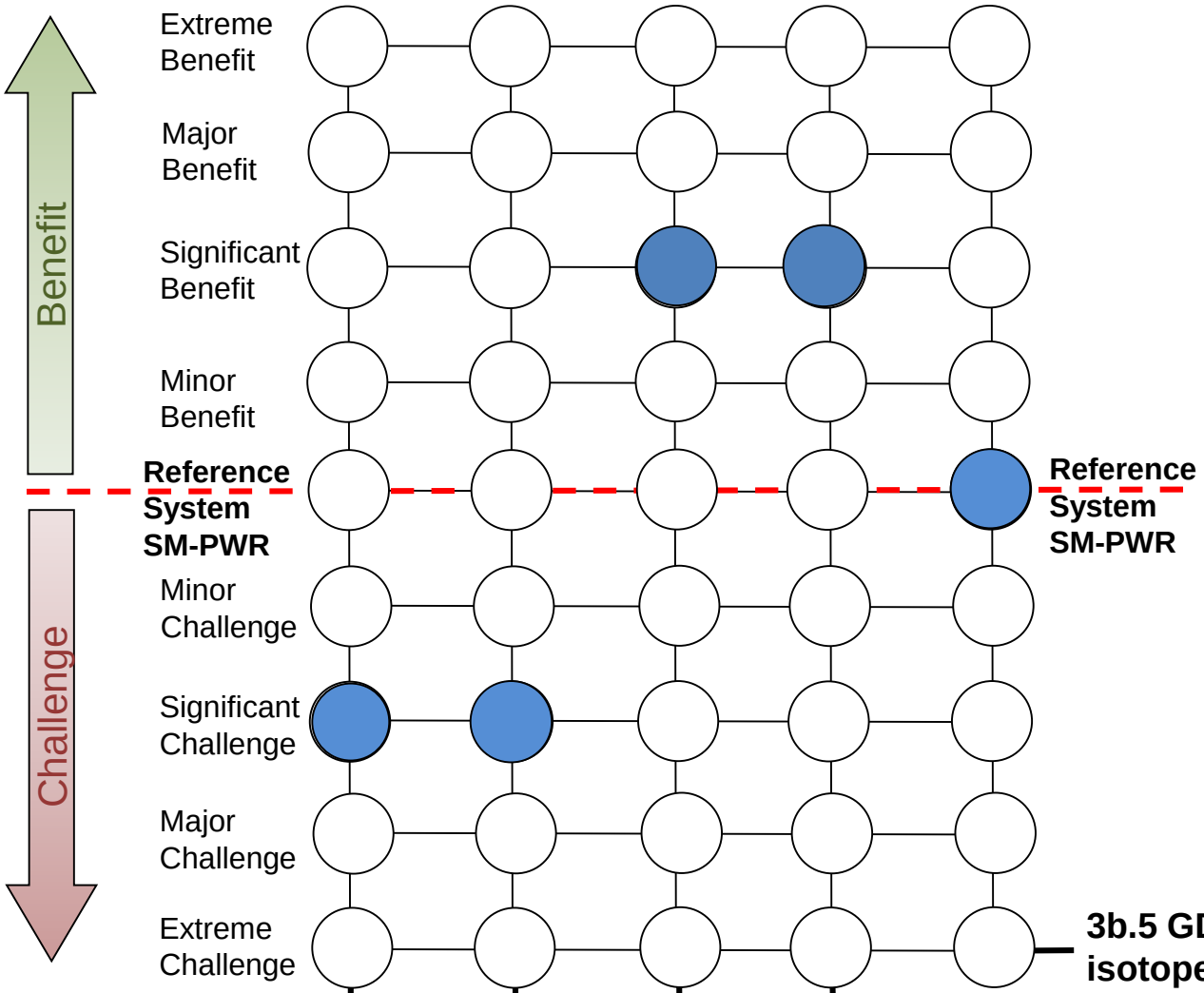
3b. Waste storage and disposability



3b.5 GDF disposal impact – isotopes driving safety case

3b.4 GDF disposal impact – long term radiotoxicity

3b.3 GDF disposal impact – long term decay heat

3b.2 GDF disposal impact – waste incorporation rate

3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology?

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3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology?

For oxide fuels with wet reprocessing the waste forms for SM-SFR would be largely compatible. But for other reprocessing routes such as pyro-processing the waste forms would be different. The spent fuel characteristics of SM-SFR are considerably more challenging than for the SM-PWR Reference Systems, especially if the fuel is reprocessed at short cooling times. This poses a Significant Challenge for the reprocessing plant design. The waste arisings from reprocessing will also be different and will pose a Major Challenge for Waste processing plants.

Fuel reprocessing and waste management is more challenging for fast reactor spent fuel than it is for thermal reactors, especially if short cooling times are required. Current PUREX reprocessing plants and their associated waste management plants are optimised to process thermal reactor spent fuels that typically have a lower discharge burnup (< 50 GWd/tHM) and longer cooling times (>5 years). The design of reprocessing and waste management plants for fast reactor fuels will need to take account of the higher burnup of fast reactor fuels (typically ~100 GWd/tHM) and short cooling times (as low as 5 years), which results in higher decay heat loads and higher neutron emissions. It cannot be assumed that current reprocessing and waste management plant designs can be simply adapted to meet the specifications for fast reactor spent fuel and significant R&D will likely be required, even for PUREX reprocessing. In particular, for a reprocessing scheme producing Vitrified High Level Waste (VHLW) is likely to pose major challenges with waste incorporation rates.

Assessed as 'Significant Challenge' for short cooling times

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Description

References

3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology?

3b.1 (Number and type of waste forms). This attribute accounts for the number of different waste forms produced. It is intended to take account of waste forms that are incompatible with existing or expected future waste packaging and disposal facilities. Any incompatible waste forms produced will require the construction and operation of new facilities to deal with them, and this will be noted..

3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology? References

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3b.2 GDF disposal impact – waste incorporation rate

SM-SFR spent fuel will pose challenges for waste incorporation if processed in plants designed to current specifications. This applies especially if short cooling times are required. A re-examination of heat producing waste specifications will be needed to see if current waste forms will be adequate or whether new waste forms will need to be developed.

Fuel reprocessing and waste management is more challenging for fast reactor spent fuel than it is for thermal reactors, especially if short cooling times are required. Current PUREX reprocessing plants and their associated waste management plants are optimised to process thermal reactor spent fuels that typically have a lower discharge burnup (< 50 GWd/tHM) and longer cooling times (>5 years). The design of reprocessing and waste management plants for fast reactor fuels will need to take account of the higher burnup of fast reactor fuels (typically ~100 GWd/tHM) and short cooling times (as low as 5 years), which results in higher decay heat loads and higher neutron emissions. It cannot be assumed that current reprocessing and waste management plant designs can be simply adapted to meet the specifications for fast reactor spent fuel and significant R&D will likely be required, even for PUREX reprocessing. In particular, for a reprocessing scheme producing Vitrified High Level Waste (VHLW) is likely to pose major challenges with waste incorporation rates.

Assessed as 'Significant Challenge' for short cooling times

Metric - 33. Waste arisings – volumes of HLW, ILW, LLW

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Description

References

3b.2 GDF disposal impact – waste incorporation rate

3b.2 (Waste Incorporation rate). Waste packages for disposal in the GDF mass may consist of spent fuel assemblies or immobilised high level waste forms (such as glass blocks) depending upon the fuel cycle. For the disposal of spent fuel assemblies, disposal canisters would normally be designed to accommodate uranium fuel assemblies with a relatively low long term decay heat output. Other types of fuel assemblies, for example MOX assemblies, would have a higher long term decay heat output and the disposal canister might be able to accommodate fewer of them, giving a low incorporation rate. Immobilised high level waste from reprocessing of low burnup fuels contains relatively low amounts of transuranics contributing to heat and neutron output and therefore can give a high incorporation rate. High burnup fuels are characterised by high transuranic content, with high heat and neutron outputs that may results in reduced incorporation rates. Illustrations of levels of waste incorporation rate are:

HIGH – Applies to reactor systems producing waste forms with relatively low heat and neutron outputs compatible with current waste forms.

LOW – Applies to reactor systems producing waste forms with relatively high heat and neutron outputs that are incompatible with current waste forms.

3b.2 GDF disposal impact – waste incorporation rate - references

Insert

33. Waste arisings – volumes of HLW, ILW, LLW

SM-SFR will require effort to understand the HLW, ILW and LLW waste volumes and the UK is well placed to resolve this issue through its current work on decommissioning SFRs and fuel cycle plant at Dounreay. This leads to it being assigned as 'Significant Challenge' in recognition of the effort that will be required to underpin its performance against this attribute.

Assessed as 'Significant Challenge'

33. Waste arisings – volumes of HLW, ILW, LLW

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.

33. Waste arisings – volumes of HLW, ILW, LLW - references

Insert

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3b.3 GDF disposal impact – long term decay heat

A SM-SFR operated with recycle of plutonium would produce significantly lower decay heat once equilibrium was established.

Assessed as 'Significant Benefit'

Metrics

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Description

References

3b.3 GDF disposal impact – long term decay heat

This is a measure of the long term decay heat of spent fuel or high level waste in interim storage pending disposal and in the GDF. Decay heat is important, because it determines how long spent fuel or immobilised high level waste will need to be held in interim storage prior to final disposal. Also, decay heat loading is the principal determinant of repository footprint. Spent uranium fuel or immobilised high level waste derived from uranium fuels sets the baseline for low long term decay heat. Spent fuel containing higher inventories of transuranics (such as MOX fuels) or immobilised high level waste originating from such fuels will have elevated decay heat output. Immobilised high level waste from fast spectrum systems with recycle of transuranics and from thorium systems would be expected to have a low inventory of transuranics and therefore low decay heat.
Illustrations of levels of long term decay heat are:

LOW – Applies to reactor systems producing waste forms with relatively low long term decay heat output consistent with long, but manageable interim storage times.

HIGH – Applies to reactor systems producing waste forms with relatively high long term decay heat output that would lead to unfeasibly long interim storage times.

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3b.3 GDF disposal impact – long term decay heat - references

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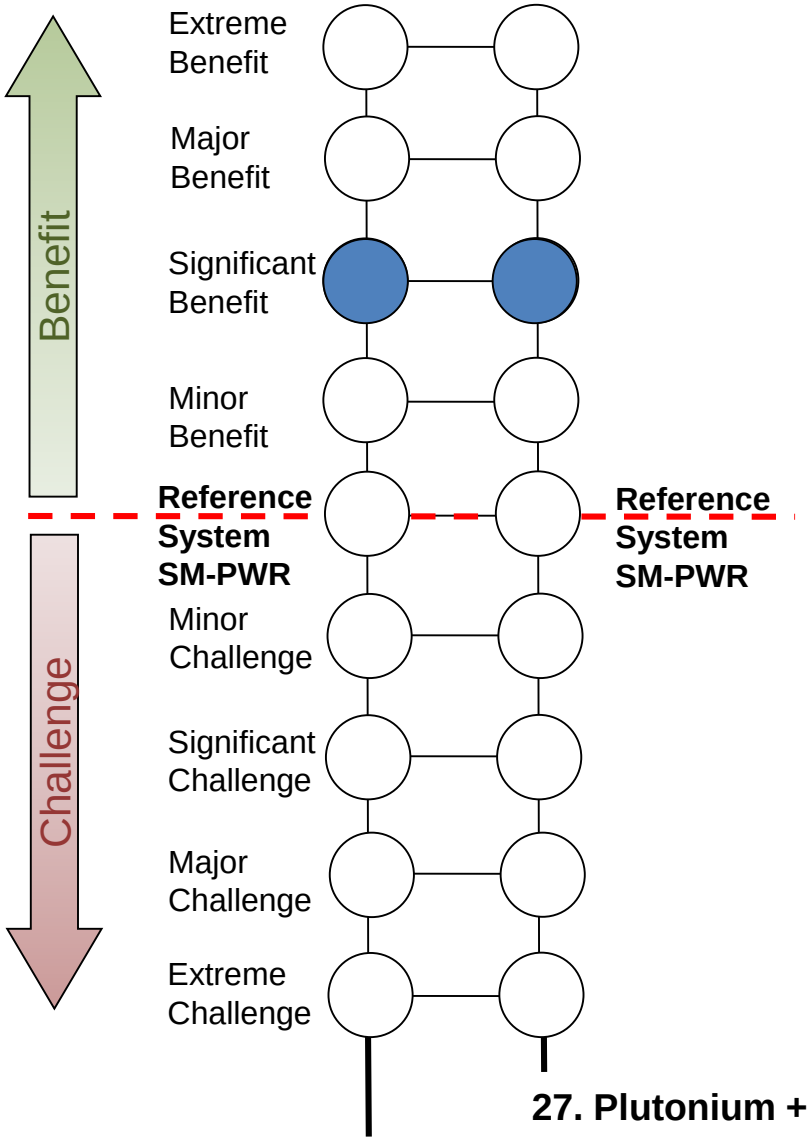
3b.3 GDF disposal impact – long term decay heat



27. Plutonium + minor actinide management

04. Long term heat output

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04. Long term heat output

A SM-SFR operated with recycle of plutonium would produce significantly lower decay heat once equilibrium was established.

Assessed as 'Significant Benefit'

04. Long term heat output

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.

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

04. Long term heat output - references

Insert

27. Plutonium and minor actinide management

SM-SFR is more flexible at plutonium and minor actinide management than the SM-PWR Reference System. Even when only operating the SM-LFR with U-Pu fuel, the nuclear reactions that take place in a fast reactor favour the destruction of Pu and also a fast reactor is more accommodating with respect to the quality of Pu it can operate with.

Assessed as 'Significant Benefit'

27. Plutonium and minor actinide management

Most systems are capable in principle of recycling plutonium and some would also be capable of destroying minor actinides (principally neptunium and americium). This ability to manage plutonium and minor actinides is assessed in this attribute.

27. Plutonium and minor actinide management - references

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3b.4 GDF Disposal Impact – Long Term Radiotoxicity

SM-SFR with full recycle of transuranics would have lower long term radiotoxicity on a per GWy basis than the SM-PWR Reference System, but as the generic SM-SFR uses separated Pu or enriched uranium the advantage is restricted to removal of the U and Pu inventory over the reference case.

Assessed as 'Minor Benefit'

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Description

References

3b.4 GDF Disposal Impact – Long Term Radiotoxicity

For cooling times up to approximately 500 years, it is the fission products that determine the radiotoxicity of spent fuel or immobilised high level waste and only marginal differences are expected between different systems. Beyond 500 years, where there are transuranics present in the spent fuel or immobilised high level waste, it is these that dominate radiotoxicity for up to 10^5 years. Low radiotoxicity on a timeframe of the order of 500 years is sometimes regarded as a desirable attribute of a fuel cycle because it might be feasible to argue that engineering barriers might retain their effectiveness up to that point. Spent uranium or MOX fuel assemblies and immobilised high level waste from uranium or MOX fuels will have high inventories of transuranics and therefore high long term radiotoxicity. Recycling transuranics in fast reactors can reduce the inventory in repository, possibly leading to low long term radiotoxicity. Fuel cycles based on the Th-232/U-233 fuel cycle have low transuranic inventories which give an intermediate level of radiotoxicity for spent thorium assemblies (in the once-through thorium cycle) and a lower level for immobilised waste from a closed Th-232/U-233 fuel cycle. Th-232/U-233 generally have higher radiotoxicities after 1E5 years.

3b.4 GDF Disposal Impact – Long Term Radiotoxicity - references

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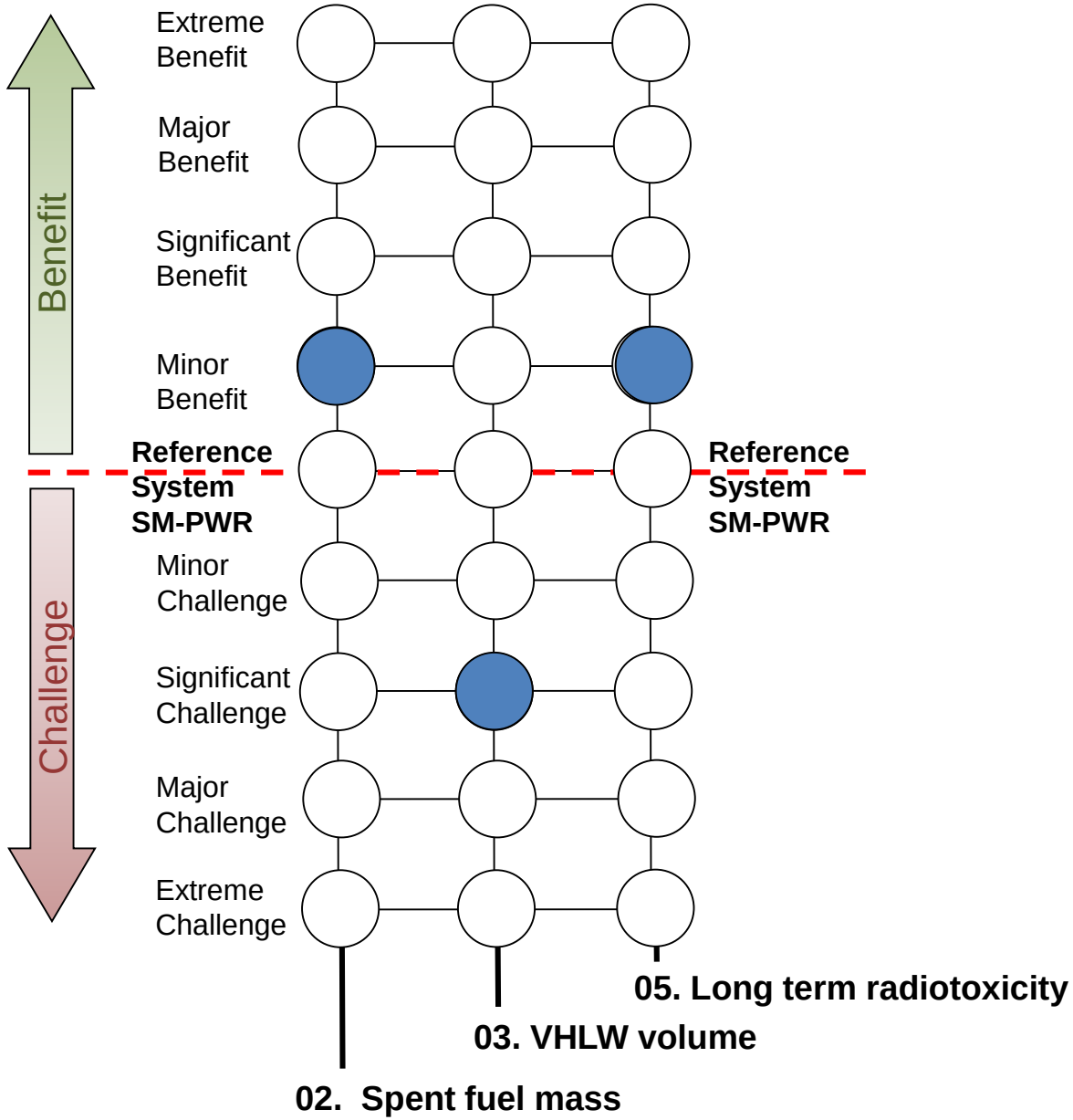
3b.4 GDF disposal impact – long term radiotoxicity



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02. Spent fuel mass

SM-SFR will have lower spent fuel arisings than the SM-PWR Reference System on account of the higher burnup.

Assessed as 'Minor Benefit'

02. Spent fuel mass

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 GWy (tHM/GWyr).

For the recycle options the spent fuel arising is important only in that it determines the throughput and capacity of reprocessing plants,

02. Spent fuel mass - references

Insert

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03. VHLW volume

VLHW arisings from SM-SFR are not known. The mass of fission products is closely equivalent to that of the SM-PWR Reference System (there is some variation depending on the relative thermal efficiencies). A Significant Challenge is posed by the much higher heat load and neutron source of short cooled SFR fuel in comparison with the current fuel cycle, and the effect this will have on VHLW incorporation rates. The UK's vitrification plants are designed to deal with a mix of HLW liquor from MAGNOX reprocessing and mostly long cooled low burnup fuels from THORP.

Assessed as 'Significant Challenge'

03. VHLW volume

This is the volume of high activity (heat generating) waste, expressed in m3 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.

03. VHLW volume - references

Insert

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05. Long term radiotoxicity

SM-SFR with full recycle of transuranics has lower long term radiotoxicity on a per GWye basis than the SM-PWR Reference System, but as the generic SM-SFR case does not yet recycle minor actinides the gain is restricted to removal of U and Pu content.

Assessed as 'Minor Benefit'

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Description

References

05. Long term radiotoxicity

The radiotoxicity is a measure of the hazard potential of radioactive material. Radiotoxicity can be measured as the potential dose from the waste in Sieverts (Sv) per Gwye, or by Toxic Potential, which measures the dilution required to allow dissolved waste to meet dose standards if used for drinking.

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 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.

05. Long term radiotoxicity - references

Insert

3b.5 GDF disposal impact – isotopes driving safety case

SM-SFR is assessed to be essentially equivalent to SM-PWR.
The reason for this is that the isotopes driving the repository safety case are fission and activation products and the fission product spectrum for SM-SFR and SM-PWR are similar.

Assessed as 'Reference'

3b.5 GDF disposal impact – isotopes driving safety case

As GDF safety cases are generally driven by long-lived mobile fission and activation products rather than by radiotoxicity per se, this attribute assesses any material differences in mobile isotope yields on a per GWye basis.

3b.5 GDF disposal impact – isotopes driving safety case - references

Insert

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3c. Siting

Summary

SM-SFR is assessed to be equivalent to the SM-PWR Reference System with respect to siting where reprocessing is carried out in a centralised facility. Co-locating the reprocessing plant at the reactor site complicates time and effort to licensing, environmental authorisation and PRPP acceptability alters the assessment to Significant Challenge.

Assessed as 'Reference'

Attributes
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Description
References

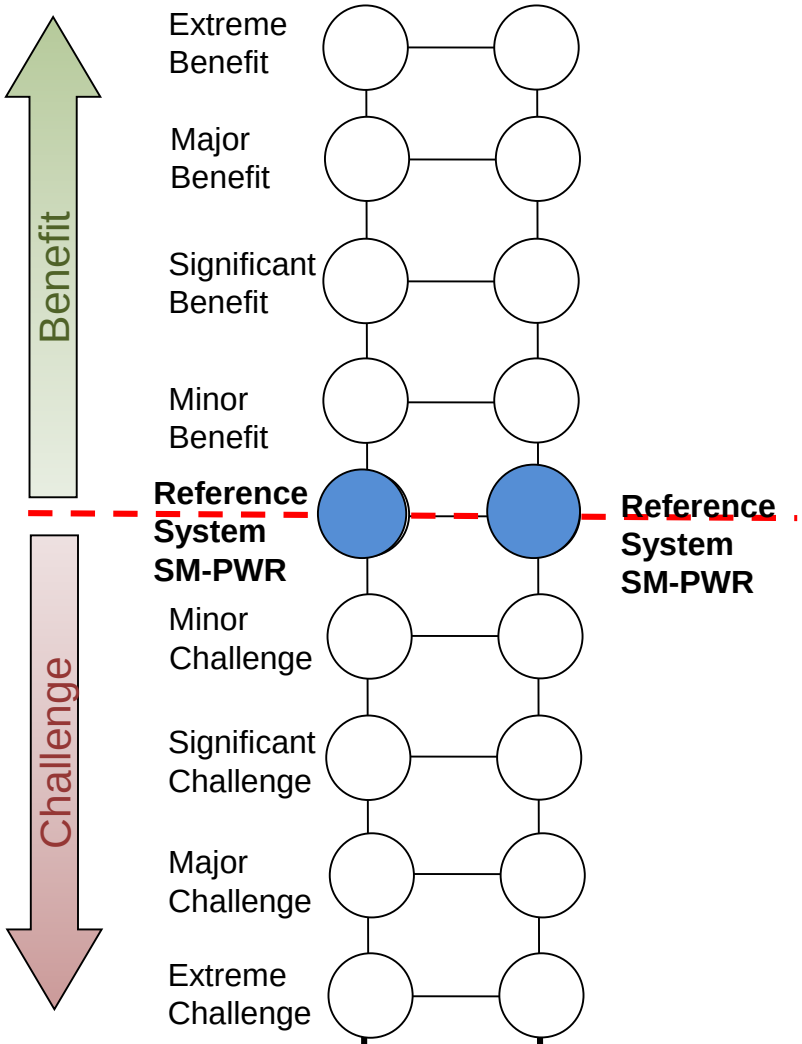
3c. Siting

Reactor systems can be commercially available, competitive, and reliable but all require sites with adequate access to cooling water, power transmission. This Strategic Attribute therefore examines the relative technical suitability of siting reactors and fuel cycle plants across the range of total generation capacity which may be required.

3c Siting - references

Insert

3c. Siting



3c.2 Siting – associated fuel cycle plants

3c.1 Siting - number and size of reactors c/f likely site availability

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Description

3c.1 Siting – number and size of reactors c/f likely site availability

SM-SFR is assessed to be equivalent to the SM-PWR Reference System with respect to siting where reprocessing is carried out in a centralised facility. Co-locating the reprocessing plant at the reactor site complicates time and effort to licensing, environmental authorisation and PRPP acceptability alters the assessment to Significant Challenge.

Assessed 'Reference'

Metrics

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Description

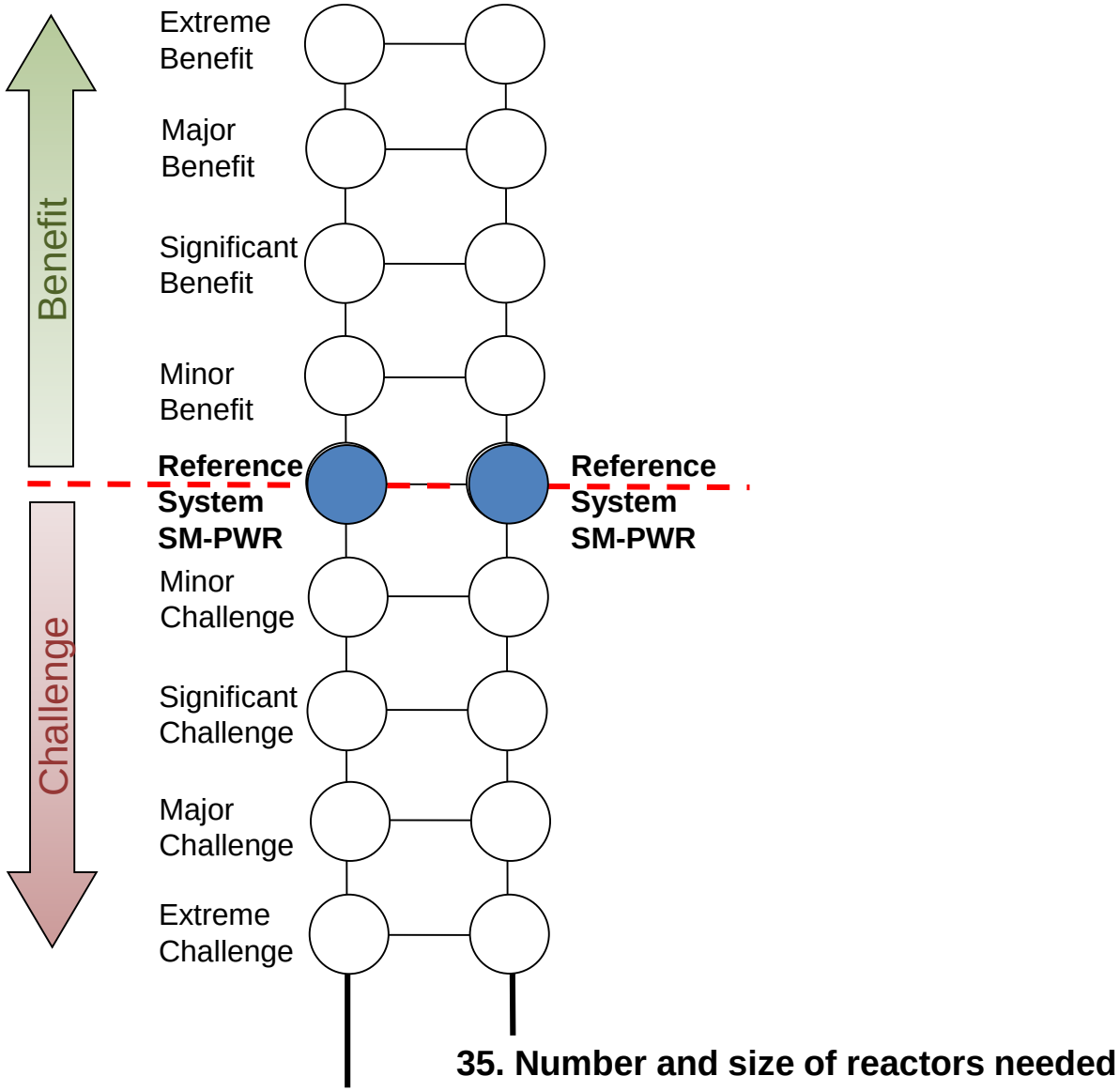
3c.1 Siting – number and size of reactors

3c.1 is intended to measure of how flexible reactor siting would be. It may be possible for small reactors to be sited at locations that would be unsuitable for large reactors on account of reduced land area required and reduced cooling water requirement. It may be possible for a reactor system which, in the event of Design Basis accidents, does not require evacuation outside the site boundary, to be sited more closely to dense concentrations of population.

3c.1 Siting – number and size of reactors - references

Insert

3c.1 Siting - number and size of reactors c/f likely site availability



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32. Flexibility of location

Significant improvement for small power station outputs. Less so for large outputs (>0.5 GWye). Potential benefits for small modular reactors with respect to cooling water availability, ultimate heat sink (for decay heat), grid connections and avoidance of off-site evacuation zone and transmission infrastructure compatibility.

Small modular reactors may offer increased scope for development on alternative locations, such as former coal fired power stations or other former industrial sites.

SM-SFR is equivalent to SM-PWR with respect to flexibility, provided any safety issues are satisfactorily resolved to allow siting distances to conurbations to be the same.

.

Assessed as 'Reference'

32. Flexibility of location

Reactors will have varying siting demands depending on their output and any dependence of co-siting with, for example, fuel cycle plants. Small reactors will make smaller demands on cooling water and grid connections, but will require more sites to reach the same installed output.

32. Flexibility of location - references

Insert

35. Number and size of reactors needed

SM-SFR is equivalent to the SM-PWR Reference System

Assessed as 'Reference'

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Description

References

35. Number and size of reactors needed

The size of individual reactors will directly affect the number of reactors needed per GWe installed. The effects on numbers of sites and on economics are examined elsewhere,

35. Number and size of reactors needed - references

Insert

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3c.2 Siting – associated fuel cycle plants

SM-SFR would be equivalent to the SM-PWR Reference System if the fuel cycle plants are sited at a central location, but potentially different if co-located at the reactor sites. Co-locating the reprocessing plant at the reactor site complicates time and effort to licensing, environmental authorisation and PRPP acceptability and there may be additional cost issues. The assessment is Significant Challenge for co-located reprocessing.

Assessed as 'Reference' for centrally located fuel cycle plants and 'Significant Challenge' for fuel cycle plants co-located with the reactors

Metric - 36. Fuel cycle plants

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Description

References

3c.2 Siting – associated fuel cycle plants

3c.2 covers the need of closed reactor systems for reprocessing, waste processing and fuel refabrication plants. Many outline schemes assume co-location of reactor and fuel cycle plants – but, in nuclear scenarios with large contributions from closed systems, this carries the consequence of either (a) very large generation capacity at one site or (b) multiple sites and fuel cycle plants.

3c.2 Siting – associated fuel cycle plants - references

Insert

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36. Fuel cycle plants

SM-SFR would require new fuel cycle plants designed to the demanding specification of short cooled SFR spent fuel.

Assessed as 'Major Challenge'

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Description

References

36. Fuel cycle plants

The fuel cycle plants needed for the various reactor system options are potentially very different.

36. Fuel cycle plants - references

Insert

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4a. Access to international programmes

SM-SFR offers strong potential for international collaboration, because further development work is required and designs are not fully developed. UK engagement in design, modelling and testing would be a fertile area for maintaining and developing expertise. It would help provide a positive focus for UK nuclear R&D.

Assessed as 'Significant Benefit'

Metric - 4a.1 Re-engagement in international programmes

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Description

References

4a. Access to international programmes

This Strategic Attribute assesses whether access to (or indeed the formation of) international programmes could aid the eventual deployment of a reactor system. The single Attribute assesses the information on the credibility of the route and on its possible timescale for deployment.

4a. Access to international programmes - references

Insert

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4a.1 Re-engagement in international programmes

Strong potential for international collaboration, particularly with aspects of the on-going French ASTRID program. SM-SFR would help provide a positive focus for UK nuclear R&D

Assessed as 'Significant Benefit'

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Description

References

4a.1 Re-engagement in international programmes

This Attribute assesses whether access to (or indeed the formation of) international programmes could aid the eventual deployment of a reactor system. The single Attribute assesses the information on the credibility of the route and on its possible timescale for deployment.

4a.1 Re-engagement in international programmes - references

Insert

4b. Time and Cost to Deployment

Summary

SM-SFR is assessed to be between TRL 3 and TRL 7 depending on the fuel type and energy conversion system and is estimated to have an earliest deployment not before 2040.

This represents a Significant Challenge when compared to the SM-PWR Reference System.

Assessed as 'Significant Challenge'

Attributes

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Description

References

4b. Time and Cost to Deployment

This Strategic Attribute takes in information from the assessment of Strategic Attributes 1a, 1b, 1c and from Attribute 4a above, to assess the overall timescale on which the system could be deployed. This will be placed in the context of the relative economics of the system and its match to the market, which are examined under High Level Discriminator 2 – Competitiveness. The Technology Readiness level will be an assessment, with the grounds for that assessment given, while the Deployment Time should be a time in years, with the reasons and uncertainties stated.

In determining the timescale, funding for R&D activities will be assumed to be available as required, and regulatory effort will also be assumed to be available. Funding for reactor build will also be assumed to be available as required. The estimated time to deployment will be the time from the GFA to the time of power production by the first UK reactor

4b. Time and Cost to Deployment - references

NNL 12415 – Manchester Report on TRL of Gen IV Systems

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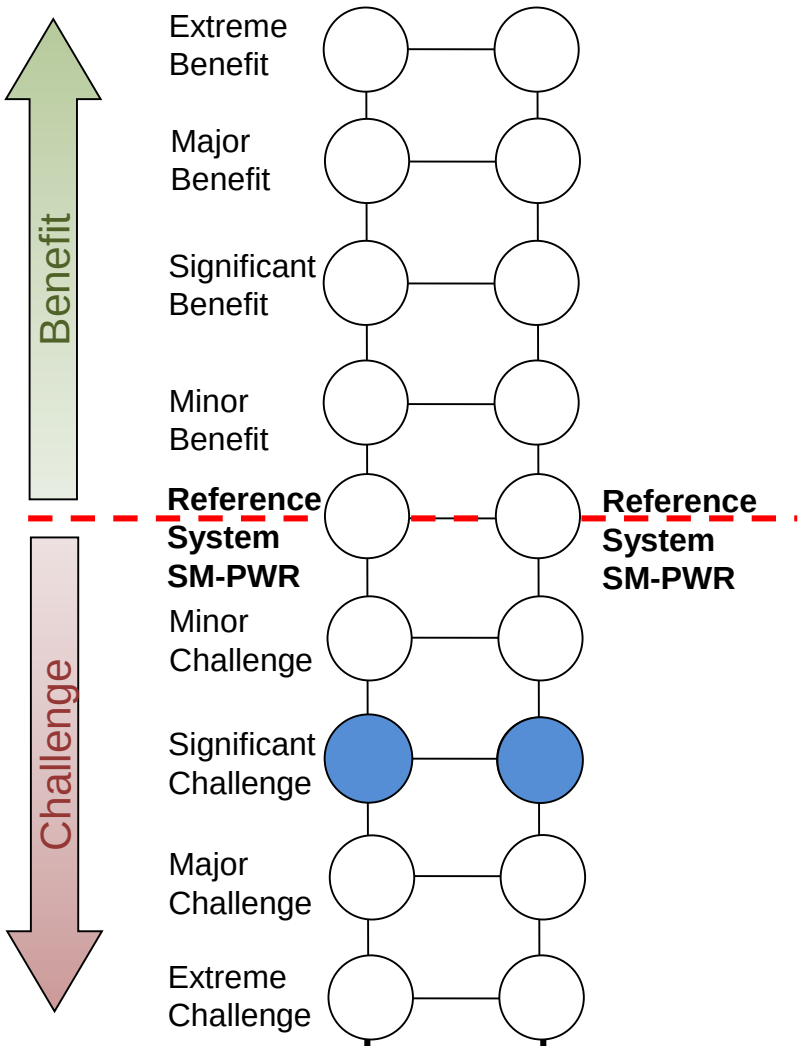
4b. Time and Cost to Deployment



4b.2 Technology Readiness level

4b.1 Commercial availability. Deployment time, plus feed from 1 and 2a

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Description

4b.1 Commercial availability – Deployment Time

Deployment in the UK will involve completing the development and testing of a design to the extent that it can apply for GDA, going through the GDA process, and then building the reactor on a selected UK site. Current designs of SM-SFR are judged to be at least 10 years from being ready for GDA. The GDA process itself has been seen to last around 5 years, so a build time of 5 years after approval would give reactors operational around 2040.

Assessed as 'Significant Challenge'

Metrics

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Description

References

4b.1 Commercial availability – Deployment Time

4b.1 (Deployment time) is the earliest time until the first unit could become operational. It builds on the assessment under in Strategic Attributes 1a, 1b, 1c and 2, and the effect of any international programmes available from 4a.1.

4b.1 Commercial availability – Deployment Time - references

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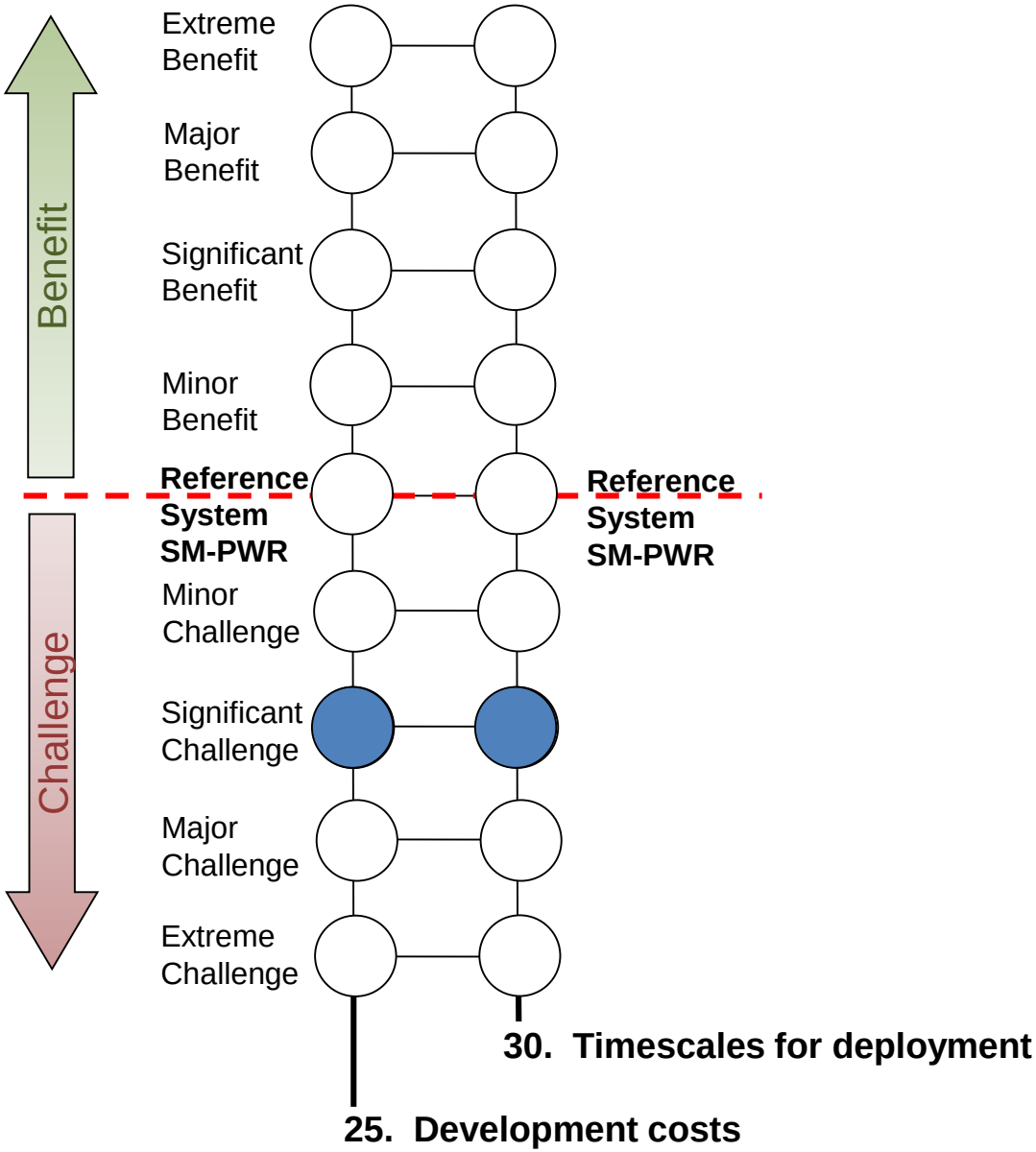
4b.1 Commercial availability



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25. Development costs

SM-SFR will have significant development costs, more onerous than the SM-PWR Reference System. Beyond reach for reactor vendors without help from governments and/or consortia.

Assessed as 'Significant Challenge'

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Description

References

25. Development costs

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.

25. Development costs - references

Insert

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30. Timescales to deployment

SM-SFR will require an estimated minimum 15 years to prepare for licensing and 5 years for GDA. See 1a.2 Timescale required to demonstrate that SAPs can be satisfied.

Allowing a FOAK build time of 5 years would give a current timescale for a reactor 'on the bars' of 2040.

Assessed as 'Significant Challenge'

30. Timescales to deployment

The timescale at which any new system could be deployed would be of high relevance to strategic planning in the UK.

In determining the timescale, funding for R&D activities will be assumed to be available as required, and regulatory effort will also be assumed to be available. Funding for reactor build will also be assumed to be available as required. The estimated time to deployment will be the time from the GFA to the time of power production by the first UK reactor

30. Timescales to deployment - references

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4b.2 Technology Readiness Level

SM-SFR is assessed at various TRL stages, from 5 to 7 (the latter applying to oxide fuel with steam energy conversion system.

Assessed as 'Significant Challenge'

Metric - 31 Technology Readiness Level

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Description

References

4b.2 Technology Readiness Level

4b.1. and 4b.2 combine to give a likely timescale for deployment in the UK. For reactor systems which are already commercially available, this is determined by the lead time for pre-licensing in the UK, the lead time for site approval and the construction time. For systems which are not yet commercially available, an additional lead time would be required for the system to be developed to commercial readiness, with the lead time being longest for systems which are at an early stage of R&D.

This assessment will give an idea of the likely deployment time in the UK. This needs to be compared with the timescales indicated in the Strategic Attributes 1a, 1b and 1c, to come to a consolidated overall view.

4b.2 Technology Readiness Level - references

NNL 12415 – Manchester Report on TRL of Gen IV Systems

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31. Technology Readiness Level

SM-SFR is assessed at various TRL stages, from 5 to 7 (the latter applying to oxide fuel with steam energy conversion system.

Assessed as 'Significant Challenge'

31. Technology Reference Level

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

31. Technology Readiness Level - - references

NNL 12415 – Manchester Report on TRL of Gen IV Systems

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4c. Meet and enable UK supply chain

Summary

SM-SFR presents increased opportunity for UK involvement in the supply chain, but the ability of the UK to realise this potential will be challenging.

The deployment of more mature SMR technology would seem to offer limited potential for UK supply chain involvement, with the UK largely restricted to manufacturing components to a given design/specification.

By contrast, less mature designs may offer increased potential for UK supply chain, with the possibility of UK design expertise being input to develop component designs from the beginning and higher value.

Assessed as 'Significant Benefit'

Attribute - 4c.1 Supply chain opportunities

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Description

References

4c. Meet and enable UK supply chain

Summary

This Strategic Attribute examines the possibility of opportunities for the UK supply chain, providing an additional incentive for UK involvement in any particular reactor system.

4c. Meet and enable UK supply chain - references

Insert here

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4c.2 Supply chain opportunities

On account of its low TRL, SM-SFR presents increased opportunity for UK involvement in the supply chain, but the ability of the UK to realise this potential will be challenging. Some UK companies and research organisation have expertise and know-how on key areas of SFR technology, dating back to the UK Fast Reactor programme, some of which continue to be used in decommissioning work, e.g. sodium handling.

Assessed as 'Significant Benefit'

4c.2 Supply chain opportunities

This Attribute should attempt to assess the level of UK supply chain involvement that could accompany the development and deployment of a given system

4c.2 Supply chain opportunities - references

Insert

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5a Meets Energy Requirements - load follow capability

The impact of power cycling on the SM-SFR systems compared with the SM-PWR Reference case is not clear but oxide fuel systems are likely to suffer pellet-clad interactions (PCI) with cycling in the same way as PWRs . Metal fuel systems will have some PCI but it will not include stress concentrations from pellet cracking. PCI will limit the rate of power change permitted. Both reactor physics and practice has shown that fast reactor systems are more resilient on reactivity effects on power reductions than thermal systems, ie the Xe poisoning effect that places restrictions on low power operation and start-up after trips.

Assessed as 'Minor Benefit'

Attribute - 5a.1 Flexibility – load follow capability

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Description

References

5a Meets Energy Requirements - load follow capability

This Strategic Attribute assesses the ability of systems to respond to particular features of a future energy market. For example, if the percentage of nuclear electricity on the grid is high, and coupled with a significant randomly variable output from renewables, then nuclear systems may be required to load follow. Some systems are much more amenable to this than others.

4c.2 Supply chain opportunities - references

Insert

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5a.1 Flexibility – load follow capability

The impact of power cycling on the SM-SFR systems compared with the SM-PWR Reference case is not clear but oxide fuel systems are likely to suffer pellet-clad interactions (PCI) with cycling in the same way as PWRs but metal fuel systems will have some PCI but it will not include stress concentrations from pellet cracking. PCI will limit the rate of power change permitted. Both reactor physics and practice has shown that fast reactor systems are more resilient on reactivity effects on power reductions than thermal systems, ie the Xe poisoning effect that places restrictions on low power operation and start-up after trips.

Assessed as 'Minor Benefit'

Metric – 28. Load follow capability

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Description

References

5a.1 Flexibility – load follow capability

5a.1 measures the ability of the reactor system to operate in non-baseload or load-follow mode. This is the ability of the reactor to increase or decrease output either in response to short term grid demands or in pre-planned load scheduling. If the total installed capacity of nuclear stations in the UK is only a small or modest fraction of the grid capacity, there is unlikely to be a major requirement for load-follow capability. However, if the nuclear capacity grows sufficiently, with only limited electricity storage capacity, there may come a point at which load-follow will be required, as is the case currently in France. Many current reactors are able to load-follow, but with limitations. Future reactor systems may be able to operate in load-follow mode without such restrictions, hence their ability to load follow will be compared, both from one system to another, and with the current LWR reference systems.

5a.1 Flexibility – load follow capability - references

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28. Load follow capability

The impact of power cycling on the SM-SFR systems compared with the SM-PWR Reference case is not clear but oxide fuel systems are likely to suffer pellet-clad interactions (PCI) with cycling in the same way as PWRs but metal fuel systems will have some PCI but it will not include stress concentrations from pellet cracking. PCI will limit the rate of power change permitted. Both reactor physics and practice has shown that fast reactor systems are more resilient on reactivity effects on power reductions than thermal systems, ie the Xe poisoning effect that places restrictions on low power operation and start-up after trips.

Assessed as 'Minor Benefit'

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Description

References

28. Load follow capability

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.

28. Load follow capability - references

Insert

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Description

5b. Meets energy requirements – Process Heat

SM-SFR is expected to operate at much higher working temperatures than the SM-PWR Reference System, which is capable of supplying only low grade heat. Therefore SM-SFR is assessed as offering Significant Benefit.

Assessed as 'Significant Benefit'

Attribute - 5b.1 Industrial process heat – potential to drive thermal processes

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Description

References

5b. Meets energy requirements – Process Heat

This Strategic Attribute assesses the ability of systems to respond to particular features of a future energy market. For example If sectors such as transport are to be decarbonised, for example by use of hydrogen as an energy vector, then the ability of a reactor system to provide high grade heat (rather than electricity) to power chemical processes could be a significant advantage.

5b. Meets energy requirements – Process Heat - references

Insert

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Description

5b.1 Industrial process heat – potential to drive thermal processes

Not relevant to current UK market, but potential for future market to develop. SM-SFR can potentially supply higher temperature processes than the SM-PWR Reference System

Assessed as 'Significant Benefit'

Metrics

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Description

References

5b. 1 Industrial process heat – potential to drive thermal processes

5b.1 indicates whether the system has the potential to drive thermal processes, such as combined heat and power (CHP), hydrogen production, synthetic fuel production and as a heat source for other industrial processes to displace carbon emitting fossil fuel heating. For thermal applications, a high operating temperature is beneficial, which leads to a simple description based on three levels of temperature:

- LOW TEMPERATURE – Low operating temperatures similar to those of current Light Water Reactors (LWRs) ~300-320°C.
- MEDIUM TEMPERATURE – Medium operating temperatures in range 320-600°C beyond the range accessible with LWRs.
- HIGH TEMPERATURE – High operating temperatures >600°C.

5b. 1 Industrial process heat – potential to drive thermal processes - references

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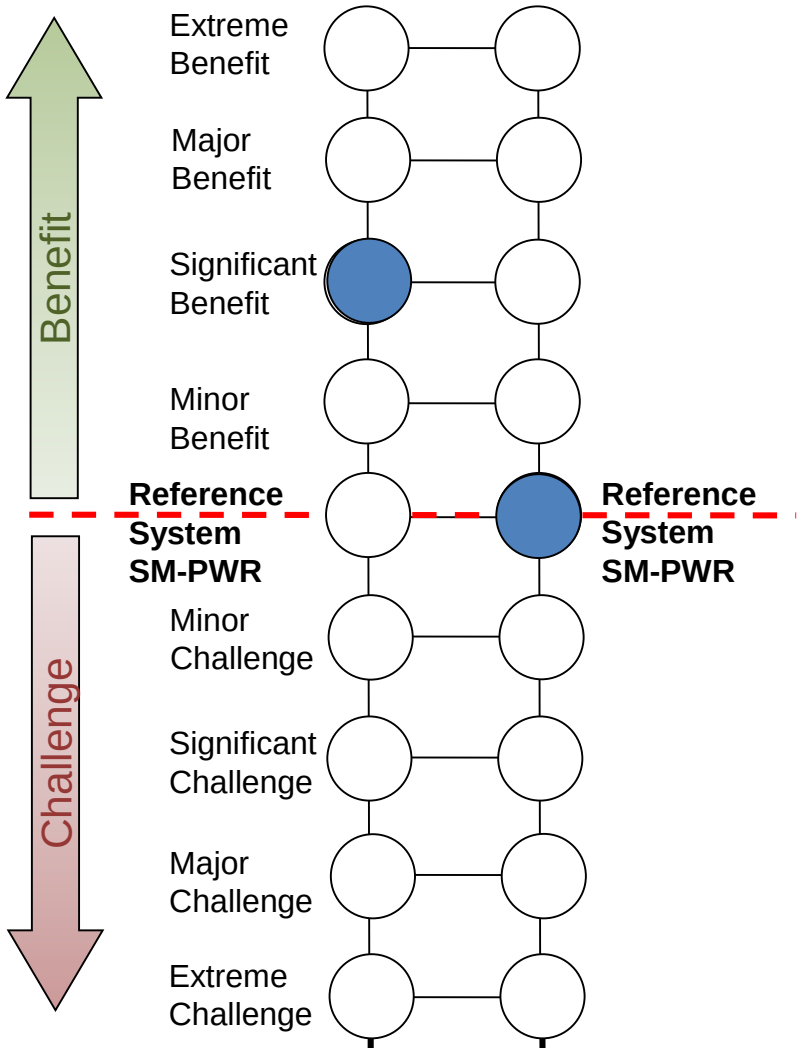
Description

5b.1 Industrial process heat – potential to drive thermal processes



42. Primary purpose

40. Potential to drive thermal processes

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Description

40. Potential to drive thermal processes

Not relevant to current UK market, but potential for future market to develop. SM-SFR can potentially supply higher temperature processes than the SM-PWR Reference System

Assessed as 'Significant Benefit'

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Description

References

40. Potential to drive thermal processes

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 systems (eg GFR, MSR and VHTR) have very primary circuit operating temperatures compatible with high temperature process heat applications.

40. Potential to drive thermal processes - references

Insert

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42. Primary purpose

Not relevant to current UK market, but potential for future market to develop. Widespread adoption of low carbon energy use, such as the adoption of electric cars and the conversion of space heating away from fossil fuel will change grid demand and require bulk energy storage.

Assessed as 'Reference'

42. Primary purpose

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.

42. Primary purpose - references

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MANCHESTER 1824
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Work in Progress

NATIONAL NUCLEAR LABORATORY

The Generic Feasibility Assessment:
An Essential Ingredient in Nuclear Policy making

Assessment Matrix with Descriptions

Subject System: SM-LFR

Reference System: Generic SM-PWR

Template: 13

Date of Assessment: 24th February 2016 Modified to generalise references to Regulators. 20th December 2017

Skip to Assessment

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IDM
integrated decision management

Reference and Subject Systems

Reference System:

Small Modular PWR (SM-PWR)

Subject System:

A Small Modular Lead-cooled Fast Reactor (SM-LFR) with an electric capacity of less than 300 MWe. It should be capable of being deployed in multiple units. SM-LFR is assumed to operate with Lead Bismuth Eutectic or molten lead coolant and use either UO_2 or Uranium Nitride (UN) fuel. The SM-LFR outlet temperature is limited to 550°C.

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Work in Progress

NATIONAL NUCLEAR LABORATORY

Version Development

2015.08.08 Initial GFA of Generic SMR based on 2014 assessment inserted into updated format Template 12

2015.12.08 Aiden Peakman & Kevin Hesketh

2015.12.13 Gregg Butler – removal of spread of Fuel Security assessments

2016.02.01 Reviewed for consistency with SFR GFA

2016.02.08 Minor connection glitches removed – slides 62-82

2016.02.24 Check and mods accepted for Draft Report

2017.12.20 Modified to generalise references to Regulators

References

This Generic Feasibility Assessment draws upon extensive work by NNL on nuclear energy technology assessment, IAEA, OECD/NEA, USDOE and other international literature. Individual references have not been included in the current draft GFA. It is anticipated that as more information becomes available relating to specific Attributes or Metrics, this might either further validate or modify the GFA. This additional information can then be referenced in the appropriate places in the GFA Template.

IDM
integrated decision management

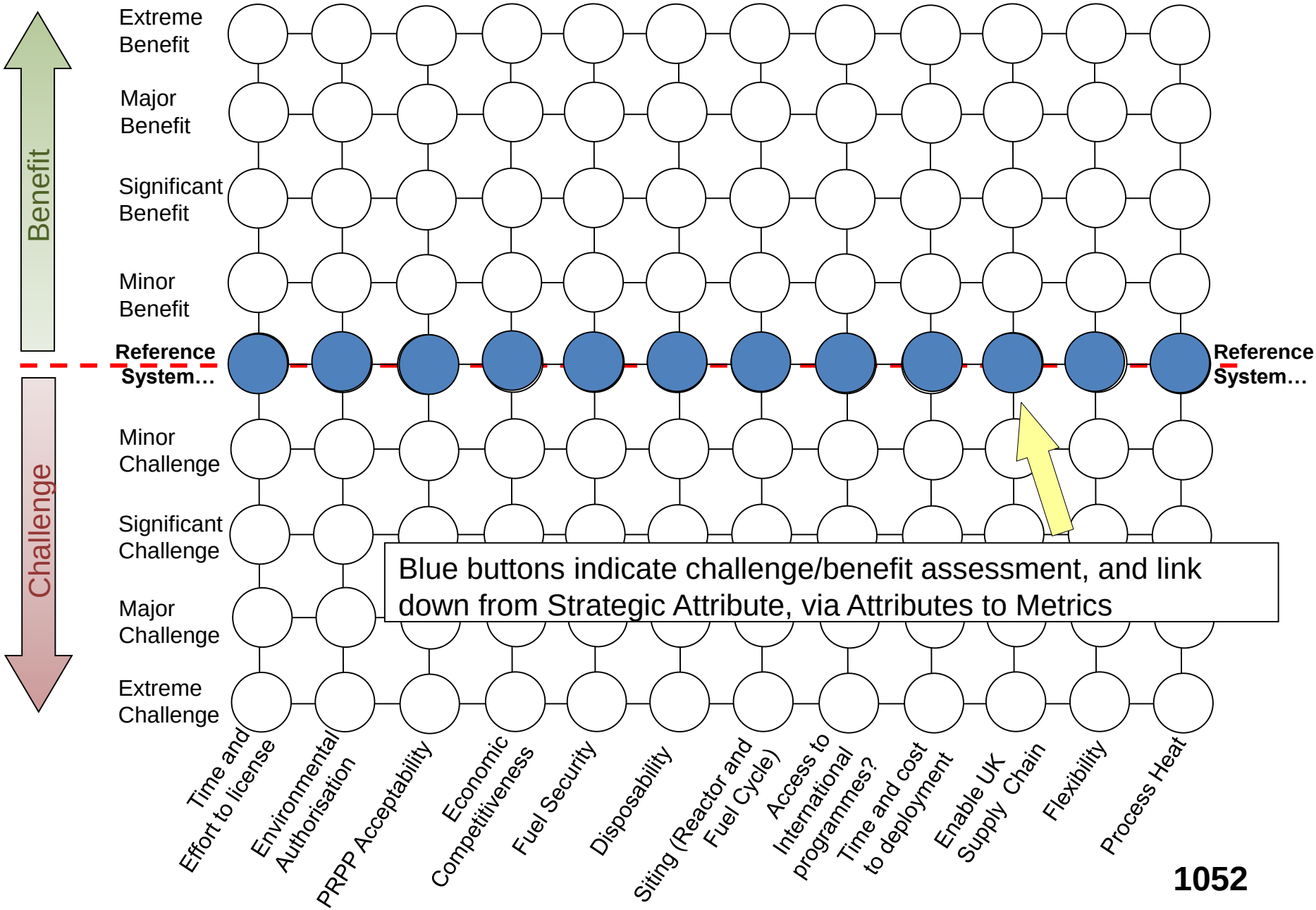
What is Generic Feasibility Assessment?

- GFA was developed for DECC to provide a high level strategic evaluation of nuclear reactor and fuel cycle systems
- It operates by making comparisons between the 'Subject System' and a Reference System, initially 'once-through LWR' as envisaged for new nuclear build in the UK
- The analysis uses 12 Strategic Attributes, using public domain information and informed professional judgement to assess the relative degree of benefit or challenge offered by the Candidate System.

What is Generic Feasibility Assessment?

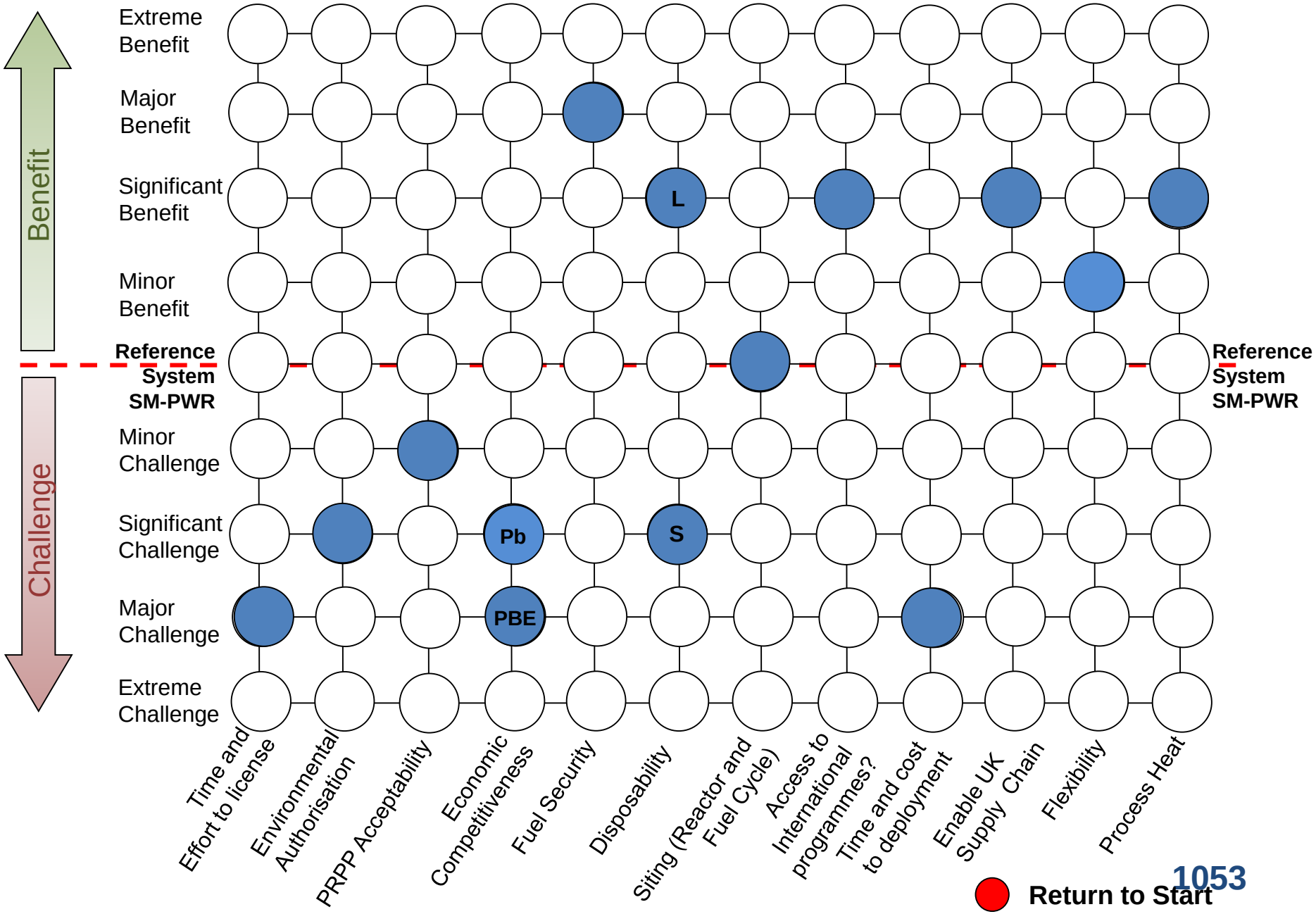
- GFA presents a high level, accessible visual representation of benefits and challenges, while allowing more detailed interrogation of the underpinning rationale and data
- As all information is public domain, any additional evidence can, and will, lead to modification of the assessment: GFA assessments are always 'Work in Progress'
- A full description of how GFA was derived and developed is available at: www.dalton.manchester.ac.uk/gfa
- This Visualisation provides a guide to how GFA is built up, the definitions of Strategic Attributes, Attributes and Metrics, and demonstrates how the information and logic tree can be navigated.

GFA Assessment Subject System: SM-LFR **Reference System: Generic SM-PWR** ***– Work in Progress***



Blue buttons indicate challenge/benefit assessment, and link down from Strategic Attribute, via Attributes to Metrics

GFA Assessment Subject System: SM-LFR **Reference System: Generic SM-PWR** ***– Work in Progress***



1a. Time and Effort to License

Summary

The overall assessment is that SM-LFR will require considerably more design and development effort than the SM-PWR Reference System and the timescales for commercial readiness will be correspondingly longer.

Assessed as 'Major Challenge'

Attributes

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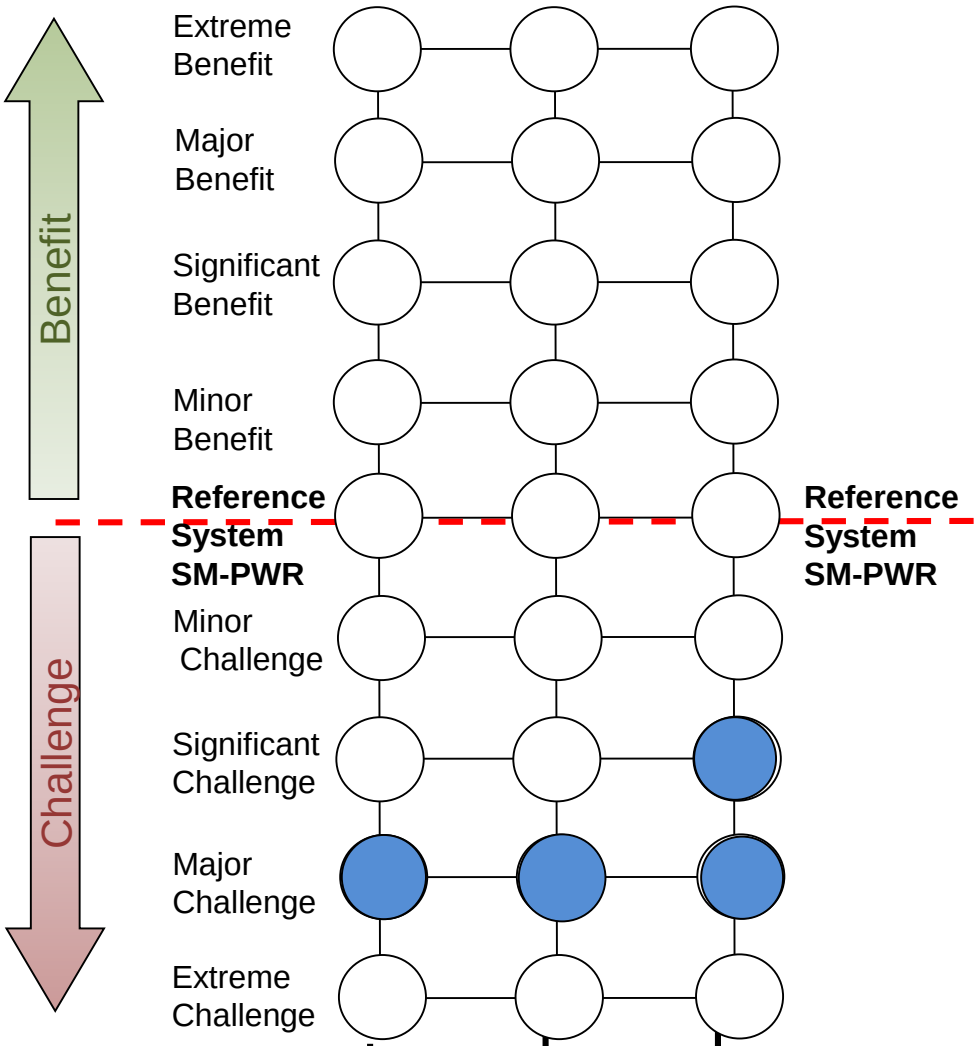
Description

1a. Time and Effort to License



1a.3 Effort to meet radiological regulations

1a.2 Timescale required to demonstrate that Safety Regulation Requirements can be satisfied

1a.1 Effort to satisfy Safety Regulation Requirements

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Description

1a. Time and Effort to License

Nuclear facilities in the UK are required to comply with the requirements set down by the appropriate regulatory bodies. Safety and licensing requirements are the responsibility of the Office of Nuclear Regulation (ONR), which also sets the radiological protection requirements for occupational exposure and members of the public.

Any reactor system to be deployed in the UK must be demonstrated to be safe, and to do so the reactor system must adhere to the fundamental safety principles as laid down by the licensing regulator. ONR has defined a series of Safety Assessment Principles known by the acronym 'SAPs'. These SAPs are seen as the top level goals which any system for deployment in the UK must be able to meet. The SAPs framework provides ONR with a set of guidelines by which ONR inspectors can make consistent judgements on nuclear safety assessment.

The top level safety criterion can be posed as: ***How much time and effort will be involved to allow the reactor system to meet the various UK safety regulatory requirements?***

From this top level criterion, the following attributes are obtained:

- ***Nuclear safety and regulation. What challenges must be met to enable the reactor system to meet well developed*** **Safety Regulation Requirements** ***(Button 1a.1)and on what timescale can such compliance be demonstrated? (Button 1a.2)***
- ***Radiological regulation. What challenges must be met to enable the reactor system to comply with the radiological dose limits defined by regulators for workers and members of the public? (Button 1a.3)***

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1a.1 Effort to satisfy ONR Safety Regulation Requirements

Summary

SM-LFR have a number of attractive safety performance characteristics such as high thermal inertia and the coolant exhibiting no strongly exothermic reactions with water or air. However, SM-LFRs will require a long term design and development programme before they are for ready licensing. There is no experience operating near-commercial LFRs. Moreover, considerable test programmes will need to demonstrate key reactor technologies. In terms of effort to licensing, this implies a Major Challenge relative to the SM-PWR Reference System

Assessed as 'Major Challenge'

Metrics

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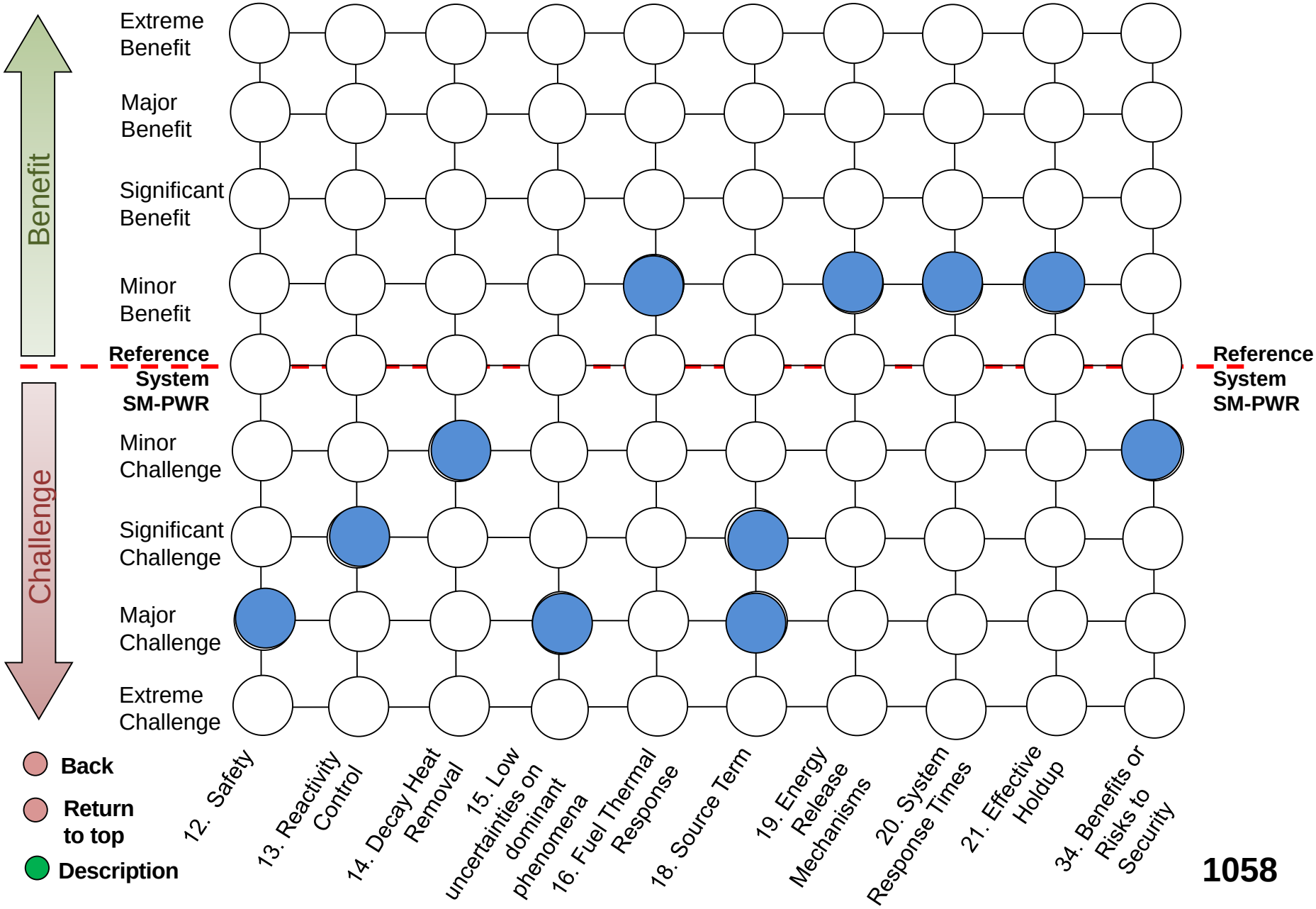
Description

References

1a.1 Effort to satisfy Safety Regulation Requirements



1a.1 Effort to satisfy Safety Regulation Requirements

1a.1 assesses the challenge faced by a reactor system in meeting the goals defined by the Safety Regulation Requirements. Levels of challenge would be expected to increase as the system examined moves further away from current experience, for example:

- Systems which are already deployed commercially or whose designs are already licensed in other countries.
- Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.
- Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.
- Systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

Assessments will assume that regulatory effort is available when and as required

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12. Safety

SM-LFR requires far more design and development effort to license than the SM-PWR Reference System. Candidates for structural materials have been identified but require large amounts of material testing to be performed for prolonged time periods. Moreover, structural materials currently under consideration necessitate careful oxygen control, which is yet to be demonstrated under prototypic LFR conditions. The phenomenology of core meltdown accidents in LFRs is also poorly understood.

Assessed as 'Major Challenge'

12. Safety

Any new reactor system deployed in the UK would need to meet very stringent safety standards. Some of the systems considered will rely on passive safety and this might distinguish them from other systems that rely on conventional active safety systems.

12. Safety - references

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13. Reactivity Control

Reactivity control in fast reactors necessitates careful consideration due, in part, to faster reactor kinetics. The heavy liquid metals in LFRs significantly increases the time it takes to insert control rods relative to both PWRs and SFRs due to the buoyancy forces that must be overcome.

Assessed as 'Significant Challenge'

13. Reactivity Control

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. Shutdown means that the reactor must be demonstrated to be sub-critical (k-eff < 0.95), taking account of calculation uncertainties and one stuck control/shutdown rod with the reactor cooled to ambient temperature.

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.

13. Reactivity Control - references

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14. Decay Heat Removal

The generic SM-LFR is assumed to have passive decay heat removal, as does the Reference System. It is assumed that additional design and development effort, including test data will be needed to support the safety case for decay heat removal in SM-LFR than SM-PWR.

Assessed as 'Minor Challenge'

14. Decay Heat Removal

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. SM-LFR would typically rely on passive decay heat removal, which is the same as the Reference System.

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.

14. Decay Heat Removal - references

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15. Low uncertainties on dominant phenomena

Considerable uncertainties regarding material performance under normal and transient conditions. Phenomenology during core melt accidents is poorly understood.

Assessed as 'Major Challenge'

15. Low uncertainties on dominant phenomena

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.

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15. Low uncertainties on dominant phenomena - references

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16. Fuel Thermal Response

SM-LFR would be expected to have a large thermal inertia on account of the mass and specific heat capacity of the sodium coolant and the large coolant mass in pool-type core designs, though possibly countered to an extent by a high power density. Compared with the Reference System, fuel thermal response times would be slower, which is beneficial.

Assessed as 'Minor Benefit'

16. Fuel Thermal Response

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.

16. Fuel Thermal Response - references

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18. Source Term

The source term for SM-LFR requires significant design and development work. There is limited LFR experience in the public to draw on.

For SM-LFRs using LBE as the coolant the considerable production of Po-210 will have a negative impact on the radiological inventory.

Assessed as 'Significant Challenge' for molten lead-cooled LFR and 'Major Challenge' for LBE-cooled LFR

18. Source Term

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.

18. Source Term - references

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19. Energy Release Mechanisms

SM-LFRs operate at low pressure and the coolant does not undergo strongly exothermic reactions with air or water. However, there is the risk of water coming into contact with the molten lead and becoming superheated. The corresponding increase in pressure could damage structural materials.

Assessed as 'Minor Benefit'

19. Energy Release Mechanisms

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.

19. Energy Release Mechanisms - references

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20. System response times

The system response for SM-LFR depends on the specific rating, which in some designs may be higher than SM-LWRs. LFR exhibit increased thermal inertia thanks to the high volumetric heat capacity of the coolant and high boiling point. This suggests fuel thermal response times somewhat larger than SM-LWRs.

Assessed as 'Minor Benefit'

20. System response times

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.

20. System response times - references

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21. Effective Holdup

Lead is capable of retaining the hazardous fission products caesium and iodine at least up to temperatures of 600°C.

Assessed as 'Minor Benefit'

21. Effective Holdup

Effective hold-up refers to mechanisms in the design of a plant for containing radioactive material following an accident condition. The hold-up of volatile fission product will impact the containment design will affect whether there is a requirement for off-site evacuation procedures to be in place.

21. Effective Holdup - references

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34. Benefits or challenges for security

Compared with the once-through fuel cycle used by SM-PWR (where no reprocessing occurs), the level of intrinsic protection of nuclear materials is reduced, leading to it being assessed as a Minor Challenge.

Assessed as 'Minor Challenge'

34. Benefits or challenges for security

Inherent Proliferation Resistance and Proliferation Protection PRPP is an area which needs to be assessed for new reactor systems according with best practice set out by IAEA INPRO and GIF. The threats considered are diversion of fissile material by a state and acquisition of radioactive materials by an illegal sub-national group. Both threats are considered by OCNS as part of defining the security and safeguards requirements and these requirements are not affected in inherent PRPP. Inherent PRPP is simply to be regarded as a fall-back protective feature that would apply in the hypothetical case of a nuclear system falling outside national controls.

34. Benefits or challenges for security - references

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1a.2 Timescale required to demonstrate that Safety Regulation Requirements can be satisfied

In the UK the Generic Design Approval (GDA) process is new and only EPR has been through it in its entirety. The process for EPR took almost 6 years, but the experience gained should allow future LWRs to gain approval within 4 years or so. ONR already had expertise in PWR safety assessment and this must have been helpful for the GDA. For LFR there is currently no expertise within ONR. ONR would require an application for a GDA from an LFR designer before building up an assessment team. It is unlikely that the GDA process would be as straightforward as EPR because the safety case approach will be substantially different to conventional reactors and may require a reinterpretation of the Safety Assessment Principles.

The lack of experience operating near-commercial prototype LFRs and the very limited material performance data suggest that the timescales to demonstrate SAPs will likely be very long.

Assessed as 'Major Challenge'

1a.2 Timescale required to demonstrate that Safety Regulation Requirements can be satisfied

1a.2 assesses how long it might reasonably be expected to take to demonstrate that the system can satisfy stringent Safety Regulation Requirements**.** Levels of challenge would be expected to increase as the system examined moves further away from current experience, for example:

- Systems which are already deployed commercially or whose designs are already licensed in other countries.
- Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.
- Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.
- Systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

Assessments will assume that regulatory effort is available when and as required

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1a.2 Timescale required to demonstrate that SAPs can be satisfied - references

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1a.3 Effort to meet radiological regulations

In the absence of engineered designs, it is not possible at this stage to assess the ability of SM-LFR to meet radiological regulations. The requirement for further design work puts the assessment at Significant Challenge relative to the SM-PWR Reference System.

For reactors employing LBE coolant, the inventory of Po-210 is likely to make meeting radiological regulations very difficult without systems in place to immobilise the inventory of Po-210. Systems to immobilise Po-210 present in the coolant inventory are very immature.

Assessed as 'Significant Challenge' for Pb cooled reactors and 'Major Challenge' for LBE cooled reactors

Metric - 11. Worker Exposures

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Description

References

1a.3 Effort to meet radiological regulations

1a.3 assesses the difficulty likely to be experienced in meeting the worker radiological protection requirements defined by regulators, noting that this includes the reactor and its fuel cycle. Levels of challenge would be expected to increase as the system examined moves further away from current experience, for example:

- Systems which are already deployed commercially or whose designs are already licensed in other countries.
- Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.
- Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.
- Systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

Assessments will assume that regulatory effort is available when and as required

1a.3 Effort to meet radiological regulations - references

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11. Worker Exposures

It is difficult to assess worker exposures for SM-LFR because none of the proposed designs have yet been developed to the stage where detailed understanding of the maintenance requirements and dose uptake is available. This is assessed as a Significant Challenge relative to the SM-PWR Reference System.

For reactors employing LBE coolant, the inventory of Po-210 is likely to make meeting radiological regulations very difficult without systems in place to immobilise the inventory of Po-210. Systems to immobilise Po-210 present in the coolant inventory are very immature.

Assessed as 'Significant Challenge' for Pb cooled reactors and 'Major Challenge' for LBE cooled reactors

11. Worker Exposures

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.

11. Worker Exposures - references

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1b. Time and Effort for Environmental Permitting

Summary

SM-LFR is assessed to require considerable further design and development in order to be able to satisfy environmental permitting requirements.

Assessed as 'Significant Challenge'

Attribute – 1b.1 Effort to meet environmental regulations

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Description

References

1b. Time and Effort for Environmental Permitting

Nuclear facilities in the UK are required to comply with the requirements set down by the appropriate regulatory bodies. Environmental regulations are the responsibility of the Environment Agencies (EA, NRW , SEPA) and are implemented through the granting of site aerial and liquid Discharge Authorisations. The Environment Agencies are also responsible for the authorisation of solid waste disposal.

1b. Time and Effort for Environmental Permitting - References

Insert

1b.1 Effort to meet environmental regulations

It is too soon to judge whether SM-LFR and its associated fuel cycle will be able to meet environmental regulatory requirements. With respect to doses to the workforce, the details will be design specific and currently none of the proposed SM-LFR designs are likely to be mature enough for this requirement to be addressed. The need for design and development effort leads this attribute being assessed as a Significant Challenge.

Assessed as 'Significant Challenge'

Metric – 06 Environmental Impact

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Description

References

1b.1 Effort to meet environmental regulations

1b.1 assesses the challenge faced by a reactor system in meeting the environmental impact requirements defined by the regulators, noting that this includes the reactor and its fuel cycle. This parameter is assumed to refer to routine operational environmental discharges. Levels of challenge would be expected to increase as the system examined moves further away from current experience, for example:

- Systems which are already deployed commercially or whose designs are already licensed in other countries.
- Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.
- Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.
- Systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

Assessments will assume that regulatory effort is available when and as required

1b.1 Effort to meet environmental regulations - references

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06. Environmental Impact

It is too soon to know if SM-LFR and its associated fuel cycle plants are capable of meeting modern environmental regulations. In terms of discharges to the environment and doses to members of the public, the proposed are not yet developed to the point where discharges can be reliably estimated.

Assessed as 'Significant Challenge'

06. Environmental Impact

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.

06. Environmental Impact - references

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1c. Proliferation Resistance and Physical Protection (PRPP) Acceptability

Summary

The once-through LWR fuel cycle is internationally recognised as the reference system for inherent PRPP assessments. Given that the spent fuel from SM-LFR will be reprocessed, there is the potential for the inherent PRPP performance to be less favourable (this applies even if the reprocessing flowsheet avoids the separation of pure plutonium). Overall, the security and safeguards will be designed to offer adequate protection and inherent PRPP is seen as posing a Minor Challenge.

PRPP is taken to have a dual meaning, with Proliferation Resistance referring to state involvement in diversion of fissile materials and Physical Protection concerned with the threat of acquisition of nuclear materials by a sub-national group. The assessments are potentially different for the two aspects.

Assessed as 'Minor Challenge'

Attributes

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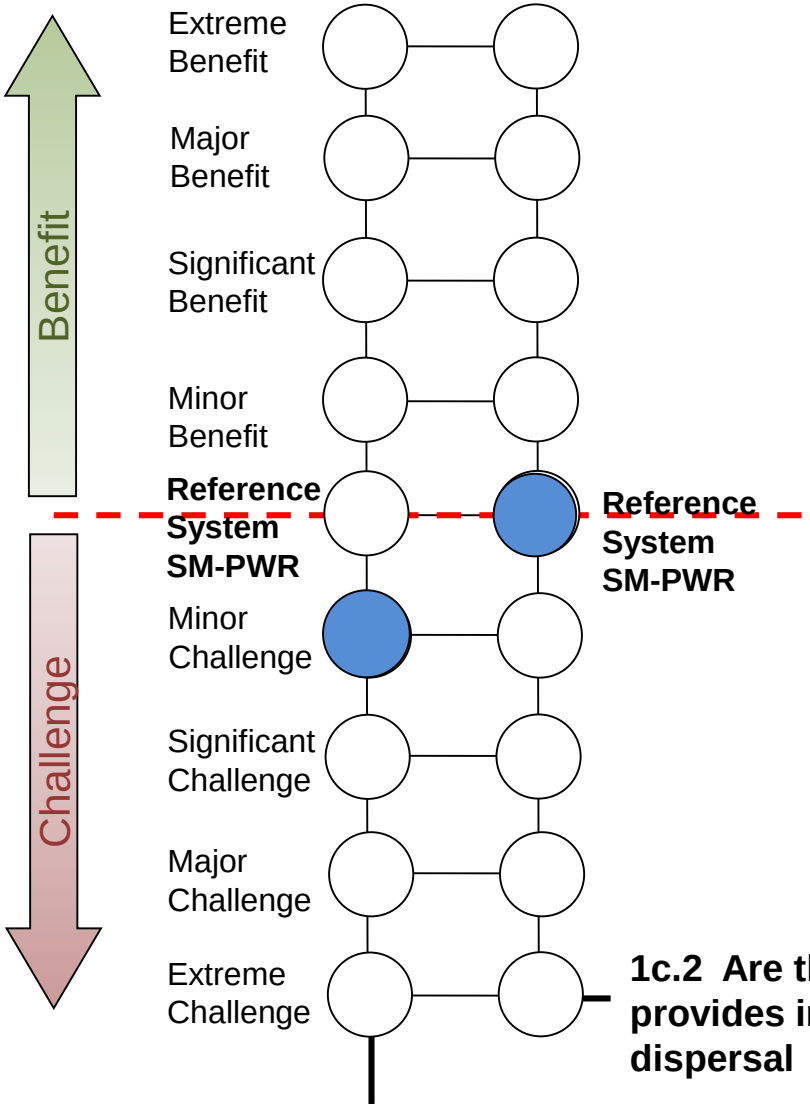
1c. Proliferation Resistance and Physical Protection (PRPP) Acceptability



1c.2 Are the nuclear materials in a form that provides inherent self-protection against theft or dispersal

1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage

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1c. Proliferation Resistance and Physical Protection (PRPP) Acceptability

Any new system deployed in the UK will be required to satisfy the Nuclear Industries Security Regulations 2003. This is a system which responds to the nuclear processes being carried out and the amount and form of nuclear materials being used, and ensures that a system is in place which will “prevent the theft or sabotage of nuclear material or the sabotage of nuclear facilities”. The Office of Civil Nuclear Security (OCNS) is the responsible regulator.

UK situation is that, while systems may not accord with the ideals of PRPP, yet there are systems, monitored and enforced by OCNS, which ensure risks of theft or sabotage are maintained at acceptably low levels. Thus while it is highly relevant to monitor the PRPP characteristics of nuclear reactor systems, the value of this Attribute in the UK context is predominantly to be judged by policy makers. The assessment will, however, give an indication of the challenges to be met in order to generate an approved Security Plan for the candidate system.

The top level PRPP criterion can be posed as: *“Are the nuclear materials produced in the fuel cycle difficult to access?”*

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1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage

Depending on the specific fuel cycle SM-LFR may produce separated fissile material by irradiation of fertile material, which is unfavourable relative to the once-through LWR fuel cycle.

Assessed as 'Minor Challenge'

Metrics

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Description

References

1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage

This attribute accounts for the physical forms of fissile materials in the fuel cycle. The levels of challenge will vary between:

Fuel cycles in which high grade fissile materials are present at any stage, for example high enriched uranium (HEU) or plutonium, which will be considered to present considerable PRPP challenges. Examples would include a fuel cycle based on HEU fuel or the separation of pure plutonium for recycle (as in conventional PUREX reprocessing).

A LWR fuel cycle with low enriched uranium (LEU) and a once-through fuel cycle will present a lower level of PRPP challenge.

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1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage - references

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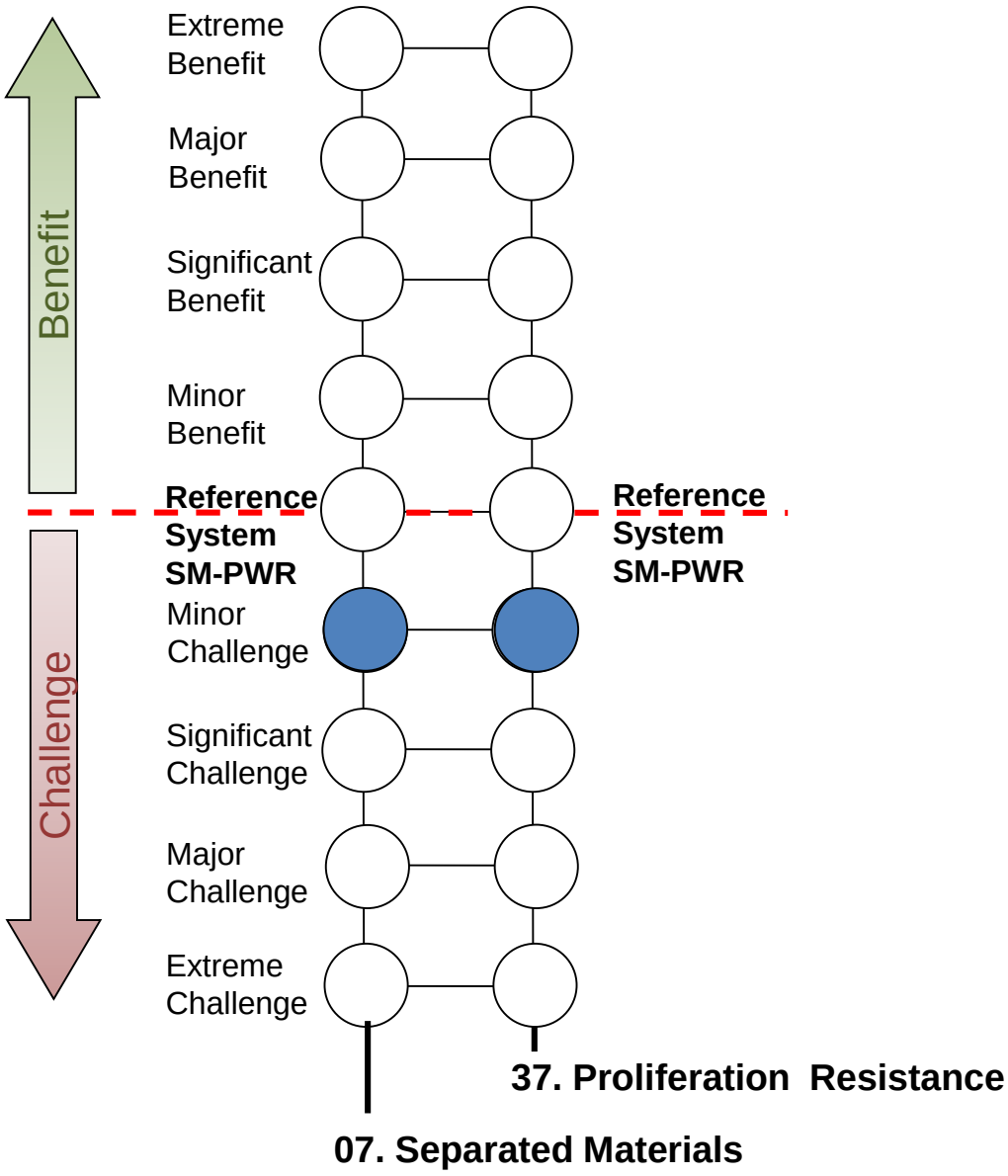
1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage



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07. Separated Materials

Depending on the specific fuel cycle SM-LFR will involve reprocessing which is unfavourable relative to the once-through LWR fuel cycle, as the production of fissile material even as a co-product reduces the level of inherent protection relative to irradiated fuel.

Assessed as 'Minor Challenge'

07. Separated Materials

One of the PRPP goals of advanced systems is that they 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.

07. Separated Materials - references

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37. Proliferation Resistance

The once-through LWR fuel cycle is internationally recognised as the reference system for inherent PRPP assessments. Depending on the specific fuel cycle SM-LFR will involve reprocessing which is unfavourable relative to the once-through LWR fuel cycle, as the production of fissile material even as a co-product makes potential diversion scenarios simpler to enact.

Assessed as 'Minor Challenge'

37. Proliferation Resistance

There is increasing interest in international reactor systems development to be able to demonstrate increased proliferation resistance by design, and different reactor systems may be considerably differentiated by inherent proliferation resistance. 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.

37. Proliferation Resistance – references

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1c.2 Are the nuclear materials in the fuel cycle in a form which provides inherent self-protection against theft or dispersal

SM-LFR reprocessing will generate fissile material in a form which offers less self-protection than the LWR once-through fuel cycle. Even if an advanced separation process is deployed that avoids the production of pure fissile material, the degree of self-protection is less than that of irradiated fuel.

Assessed as 'Minor Challenge'

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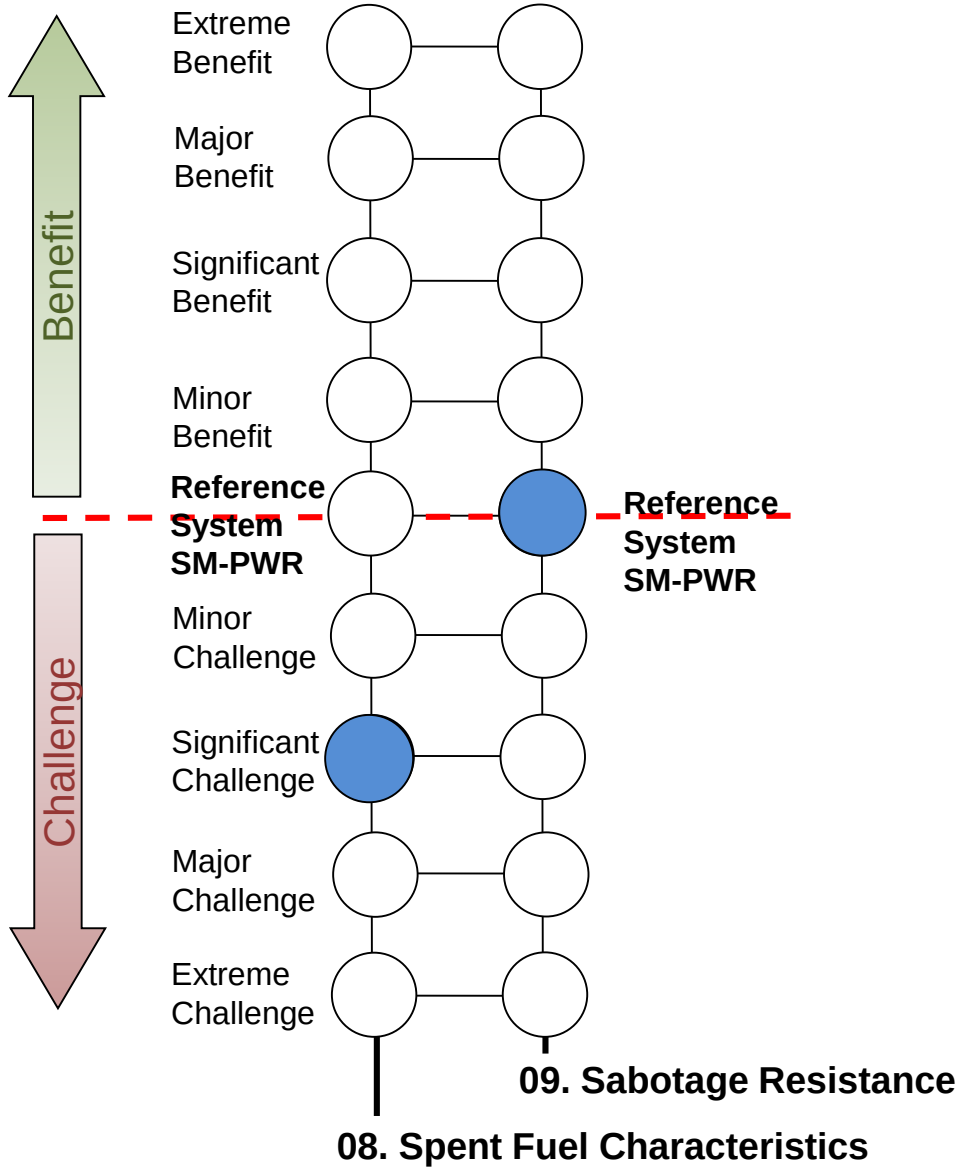
Description

References

1c.2 Are the nuclear materials in the fuel cycle in a form which provides inherent self-protection against theft or dispersal



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Description

1c.2 Are the nuclear materials in the fuel cycle in a form which provides inherent self-protection against theft or dispersal

1c.2 (Inherent PRPP). This attribute tests whether nuclear material is inherently protected by physical or chemical form, or by a strong self-protective radiation field. It is also intended to test whether the material is in a form that could be readily dispersed. Illustrations of levels of challenge are:

- a once-through fuel cycle with uranium oxide fuel in which there are multiple inherent barriers to accessing fissile material.
- fuel cycles which involve the production at some stage of unirradiated HEU fuel or plutonium oxide powder which present no inherent barriers.

1c.2 Are the nuclear materials in the fuel cycle in a form which provides inherent self-protection against theft or dispersal - references

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08. Spent fuel characteristics

The spent fuel from SM-LFR may pose challenges for transport and reprocessing, especially if there is a requirement for it to be reprocessed after a short cooling time, on account of the decay heat load.

Assessed as 'Significant Challenge'

08. Spent fuel characteristics

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.

08. Spent fuel characteristics - references

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09. Sabotage resistance

A detailed design assessment of the vulnerability of SM-LFR to sabotage/missile attack will need to be made. However, it is believed that SM-LFRs will offer comparable sabotage resistance properties to SM-LWRs.

Assessed as 'Reference'

09. Sabotage resistance

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 but in some of the systems, for example small modular PWRs, the nuclear island is largely sited underground and therefore exceptionally well protected.

09. Sabotage resistance - references

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2a. Economic Competitiveness

Summary

There are Major Challenges that must be overcome to demonstrate the economic competitiveness of SM-LFRs. R&D costs and operation and maintenance costs are likely to be considerably higher than those associated with SM-PWRs.

Assessed as 'Significant Challenge' for Pb cooled system and 'Major Challenge' for LBE cooled system

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Description

2a. Economic Competitiveness

The electrical generation cost is one of the principal criteria against which a nuclear system will be assessed – without a demonstrably economically competitive system, utilities are unlikely to invest.

The top level economics Attribute can be posed as: *Will the reactor system be economically competitive in the electricity generation market or in possible future heat generation markets?*

From this Strategic Attribute, the following Criteria are obtained:

Overnight construction cost. The cost of building and financing the nuclear system, usually expressed as £/MWe.

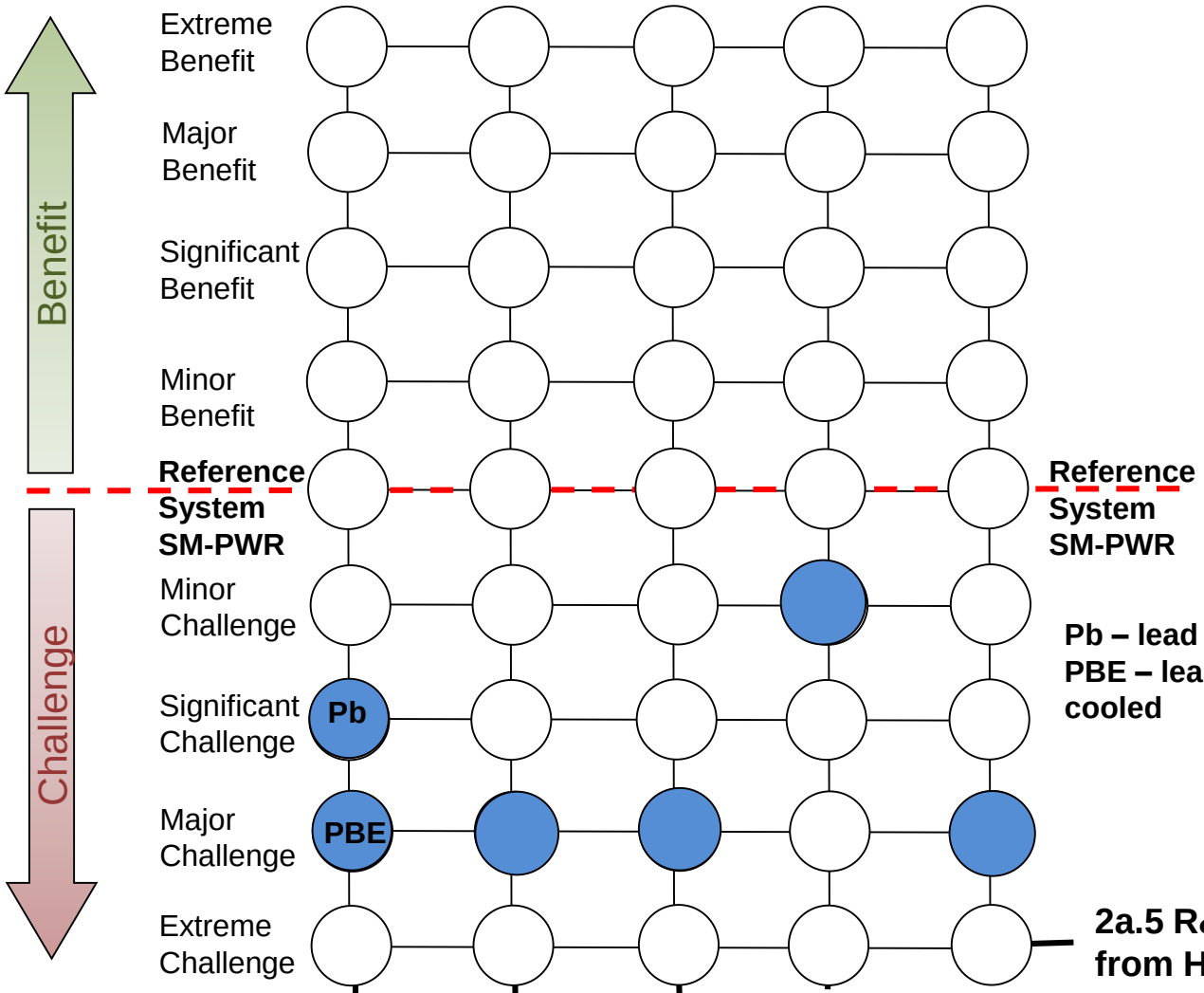
Operating and maintenance cost: This is the cost of operating and maintenance (O&M), taken to include staffing costs, operating costs (excluding fuel), the cost of routine maintenance and other related costs, usually expressed as a levelised cost in £/MWh.

Fuel cycle cost: This criterion is intended to capture the cost of operating the fuel cycle, both procuring new fuel and all the back-end costs associated with spent fuel management or reprocessing/recycle, usually expressed as a levelised cost in £/MWh.

Decommissioning cost: This is the actual cost of decommissioning *without* applying financial discounting, expressed as £/MWe.

R&D cost: This is the cost of the research and development programme needed to bring a system to commercial readiness. This will generally be an infeed into this attribute from High Level Discriminator 1 – Regulatory Challenges and Timescales.

2a. Economic Competitiveness



Pb – lead cooled
PBE – lead – bismuth eutectic cooled

2a.5 R&D cost – feed from HLD1

2a.4 Decommissioning cost

2a.3 Fuel cycle cost – front and back end combined

2a.2 Operating and Maintenance cost

2a.1 Overnight construction cost

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Description

2a1. Overnight construction cost

For SMR generally there is an economy of scale penalty (for which there is a consensus), but with potential for savings from replication, factory build and increased modularisation. There is also the potential for first module to finance later modules but note need for common infrastructure to be in place for the first module.

SM-LFR is considered equivalent to the SM-PWR Reference System in respect of scaling, but penalised because of the likely increased complexity of instrumentation, control and chemical systems; in addition the need for sufficient redundancy to reduce the likelihood of coolant freezing. Many SM-LFRs do not include an intermediate circuit (which is economically favourable); however, there is uncertainty regarding the licensability of such designs.

For LBE-cooled reactors the expense of bismuth considerably degrades the economic performance of the reactor system.

Assessed as 'Significant Challenge' for Pb-cooled reactors and 'Major Challenge' for LBE-cooled reactors

2a.1 Overnight construction cost

2a.1 (Overnight construction cost). The cost of building and financing the nuclear system, usually expressed as £/MWe. This attribute is the cost of construction and of financing construction, usually taken as the overnight construction cost with all financing costs discounted to the date at which the plant becomes operational. Included in this context, is the construction cost of any fuel cycle plants needed for fuel reprocessing, recycle or waste management. Illustrations of levels of challenge are:

- Plants with a high degree of modularisation and short construction times.
- Plants with a limited degree of modularisation and moderate construction times. This might apply to current large PWRs operating a once-through fuel cycle, for example.
- Complex plants with long and difficult construction demands. This might apply to systems involving extensive reprocessing and recycle.

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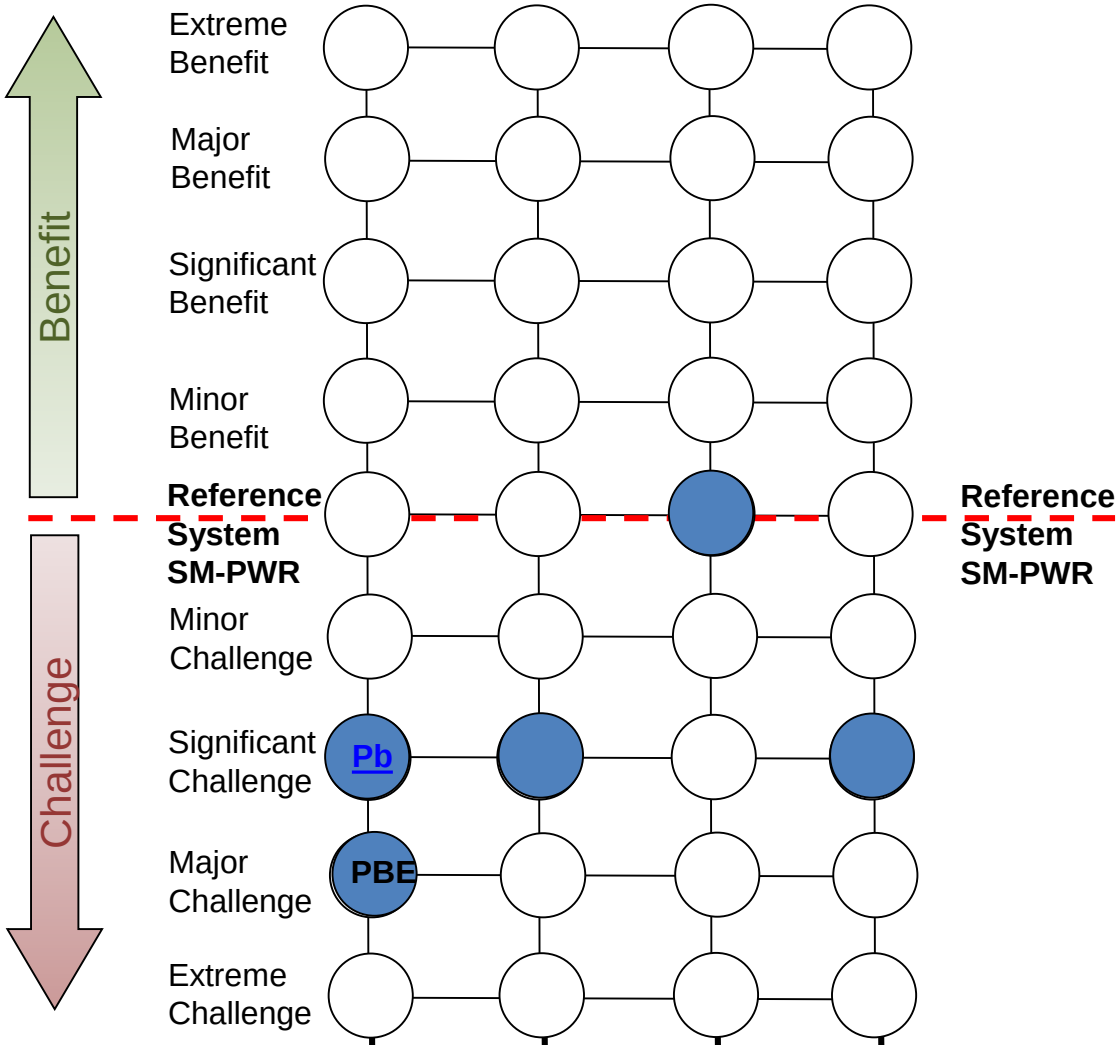
2a.1 Overnight construction cost



Pb – lead cooled
PBE – lead – bismuth eutectic cooled

34. Ease of Construction

29. Scaleability

24. Construction Duration

22. Overnight construction cost

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Description

22. Overnight construction cost

For SMR generally there is an economy of scale penalty (for which there is a consensus), but with potential for savings from replication, factory build and increased modularisation. There is also the potential for first module to finance later modules but note need for common infrastructure to be in place for the first module.

SM-LFR is considered equivalent to the SM-PWR Reference System in respect of scaling, but penalised because of the likely requirement for reactor internals requiring increased replacement due to the corrosiveness of lead-based coolants. Many SM-LFRs do not include an intermediate circuit (which is economically favourable); however, there is uncertainty regarding the licensability of such designs.

For LBE-cooled reactors the expense of bismuth considerably degrades the economic performance of the reactor system.

Assessed as 'Significant Challenge' for Pb-cooled reactors and 'Major Challenge' for LBE-cooled reactors

22 Overnight construction cost

22 (Overnight construction cost). The cost of building and financing the nuclear system, usually expressed as £/MWe. This attribute is the cost of construction and of financing construction, usually taken as the overnight construction cost with all financing costs discounted to the date at which the plant becomes operational. Included in this context, is the construction cost of any fuel cycle plants needed for fuel reprocessing, recycle or waste management. Illustrations of levels of challenge are:

- Plants with a high degree of modularisation and short construction times.
- Plants with a limited degree of modularisation and moderate construction times. This might apply to current large PWRs operating a once-through fuel cycle, for example.
- Complex plants with long and difficult construction demands. This might apply to systems involving extensive reprocessing and recycle.

22. Overnight construction costs - references

None of the SM-LFR designs currently being developed have reached the stage where there is a detailed breakdown of construction costs.

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24. Construction duration

Short construction times reduces finance cost and risk with theoretically lower £/kWe. SM-LFR designs currently being developed are not yet at the stage where short construction times can be considered demonstrated. The relatively large size of LFR Reactor Pressure Vessels does not fit as well with modular installation as the SM-PWR Reference System. Assessed as a Significant Challenge relative to SM-PWR.

Assessed as 'Significant Challenge'

24. Construction duration

The duration of plant construction has already been discussed under Item 22 (overnight construction cost) and the same assessment applies.

24. Construction duration - references

Insert here

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29. Scaleability

Better fit to small grid systems. Not applicable to current UK grid. SM-LFR is regarded equivalent to the SM-PWR Reference System in this respect.

Assessed as 'Reference'

29. Scaleability

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.

29. Scaleability - references

Insert

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34. Ease of Construction

The relatively large size of LFR Reactor Pressure Vessels does not fit as well with modular installation as the SM-PWR Reference System. Assessed as a Significant Challenge relative to SM-PWR.

Assessed as 'Significant Challenge'

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References

34. Ease of Construction

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.

34. Ease of Construction - references

Insert here

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2a.2 Operating and maintenance cost

The relatively high melting points of lead-based coolants and the corrosiveness are likely to detrimentally impact LFR reliability. Furthermore, performing in-service inspection and repair will be very difficult due to the opaqueness of the coolant and its high density.

Assessed as 'Major Challenge'

Metrics

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Description

References

2a.2 Operating and maintenance cost

This Attribute covers the cost of operating and maintenance, taken to include staffing costs, operating costs (excluding fuel), the cost of routine maintenance and other related costs. Illustrations of levels of O&M costs are:

- Plants such as LWRs with long operating lives and no requirement for mid-life refurbishment of major plant items
- Plants with a requirement for through-life replacement of major components
- Complex plants with difficult operational requirements

2a.2 Operating and maintenance cost - references

None of the SM-LFR designs currently being developed have reached the stage where there is a detailed breakdown of O&M costs.

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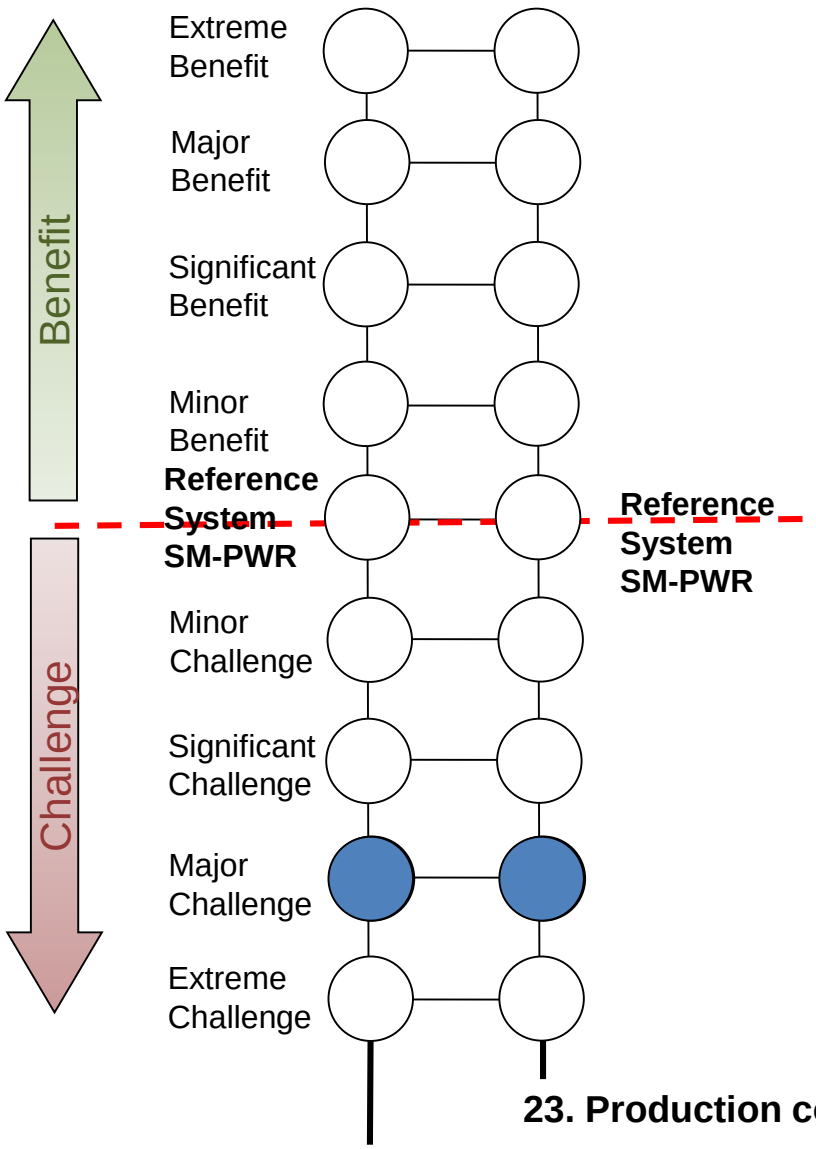
2a.2 Operating and maintenance cost



23. Production costs (O&M)

10. Reliability

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10. Reliability

There is limited publicly available information on the operational performance of LFRs. The high melting point for Pb-coolants (and to some extent LBE-coolants) and the corrosiveness of lead-based coolants are likely to detrimentally impact the reliability of SM-LFR systems.

Assessed as 'Major Challenge'

10. Reliability

This is the forced outage rate, which should be very low. It is an operational safety and reliability issue, but it is also important for economics. Best operational practice at modern PWRs 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.

10. Reliability - references

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23. Production costs (O&M)

There are considerable difficulties associated with performing maintenance in lead-coolants due to the opaqueness of the coolant, its high density, high melting point and corrosiveness. All of these attributes makes performing in-service inspection and repair very difficult.

Assessed as 'Major Challenge'

23. Production costs (O&M)

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.

23. Production costs (O&M) - references

None of the SM-LFR designs currently being developed have reached the stage where there is a detailed breakdown of O&M costs.

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2a.3 Fuel cycle costs (front and back-end combined)

SM-LFR will operate a closed fuel cycle. This is a disadvantage over the SM-PWR Reference System, which uses the once-through fuel cycle. It is expected that the LFR fuel cycle will be prove more expensive than SM-PWR due to the extra complexity and the technically demanding fuel cycle.

Assessed as 'Major Challenge'

2a.3 Fuel cycle costs (front and back-end combined)

2a.3 (Fuel cycle cost). This attribute is intended to capture the cost of operating the fuel cycle, both procuring new fuel and all the back-end costs associated with spent fuel management or reprocessing/recycle. Illustrations of varying levels of challenge with choice of fuel cycle are:

- the once-through LWR fuel cycle
- the closed LWR fuel, cycle (i.e. thermal recycle)
- a fast reactor system with recycle, especially if there was recycle of minor actinides.

2a.3 Fuel cycle costs (front and back-end combined) - references

Insert

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2a.4 Decommissioning costs

41. Decommissioning costs

The reactor pressure vessel is relatively large, which complicates decommissioning. Also the processing of the remaining coolant is likely to be more difficult than the light water.

Assessed as 'Minor Challenge'

2a.4 Decommissioning costs

41. Decommissioning costs

2a.4 (Decommissioning cost). This attribute is intended to represent the actual cost of decommissioning without applying financial discounting. The decommissioning cost represents a significant risk element in financial analysis, even though the discounted cost is usually very low. Levels of challenge are illustrated by:

- A nuclear system with small, modular components compatible with disposal as self-contained units.
- Current LWRs where, after defueling, there are only medium active components that need to be decommissioned in the core.
- Systems with graphite moderation, such as the UK's legacy gas cooled reactors, due to the need to deal with large masses of material.

2a.4 Decommissioning costs - references

41. Decommissioning costs

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2a.5 R&D cost

Candidate structural materials for use in LFRs have undergone relatively limited material performance tests. Materials will need to demonstrate adequate corrosion characteristics and mechanical properties for extended periods of time under prototypic LFR conditions. Chemistry control in and of itself is considered a major challenge as oxygen concentrations will have to be monitored and potentially adjusted throughout the primary circuit. Systems to perform oxygen control and adjustment are at low technology readiness levels.

Assessed as 'Major Challenge'

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Description

References

2a.5 R&D cost

This Attribute covers the cost of the research and development programme needed to bring a system to commercial readiness. Illustrations of levels of R&D cost are:

- Those associated with an existing system or a minor development of an existing system
- Those associated with the evolution of a current system
- Those associated with novel systems involving significant innovations and long and extensive R&D

2a.5 R&D cost - references

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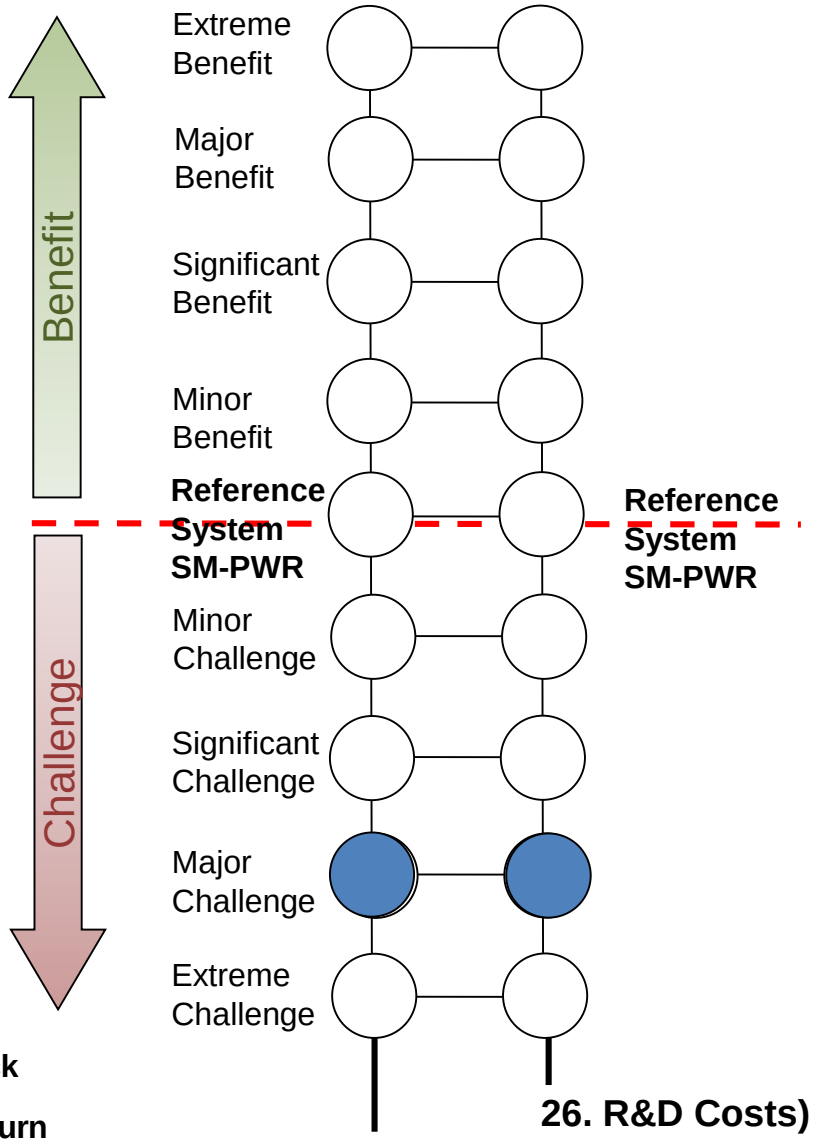
2a.5 R&D cost



26. R&D Costs)

17. Integral experiment scaleability

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17. Integral experiment scaleability

Public information regarding integral experimental results are not readily available.
Historical experience with LFRs is very limited relative to PWR systems.

Assessed as 'Major Challenge'

17. Integral experiment scaleability

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.

17. Integral experiment scaleability - references

Insert

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26. R&D costs

Significant R&D is required in a number of areas including material performance, chemistry control and validation of computer models.

Assessed as 'Major Challenge'

26. R&D costs

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. However, if the UK was to buy into technology that was not being developed elsewhere, the UK could incur the R&D costs and risks.

26. R&D costs - references

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3a. Fuel Security

Summary

With a closed fuel cycle SM-LFR could in principle operate with a high conversion ratio or breeding cycle. In this instance, the system could operate independently of the world uranium market, which is beneficial for fuel security. Assessed as a Major Benefit

Assessed as 'Major Benefit'

Attributes

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Description

References

3a. Fuel Security

Summary

This Strategic Attribute assesses whether fissile materials are available to start up a reactor system, and whether the supplies are sufficient and secure enough to fuel the reactor(s) over their projected lifetime

3a. Fuel Security - references

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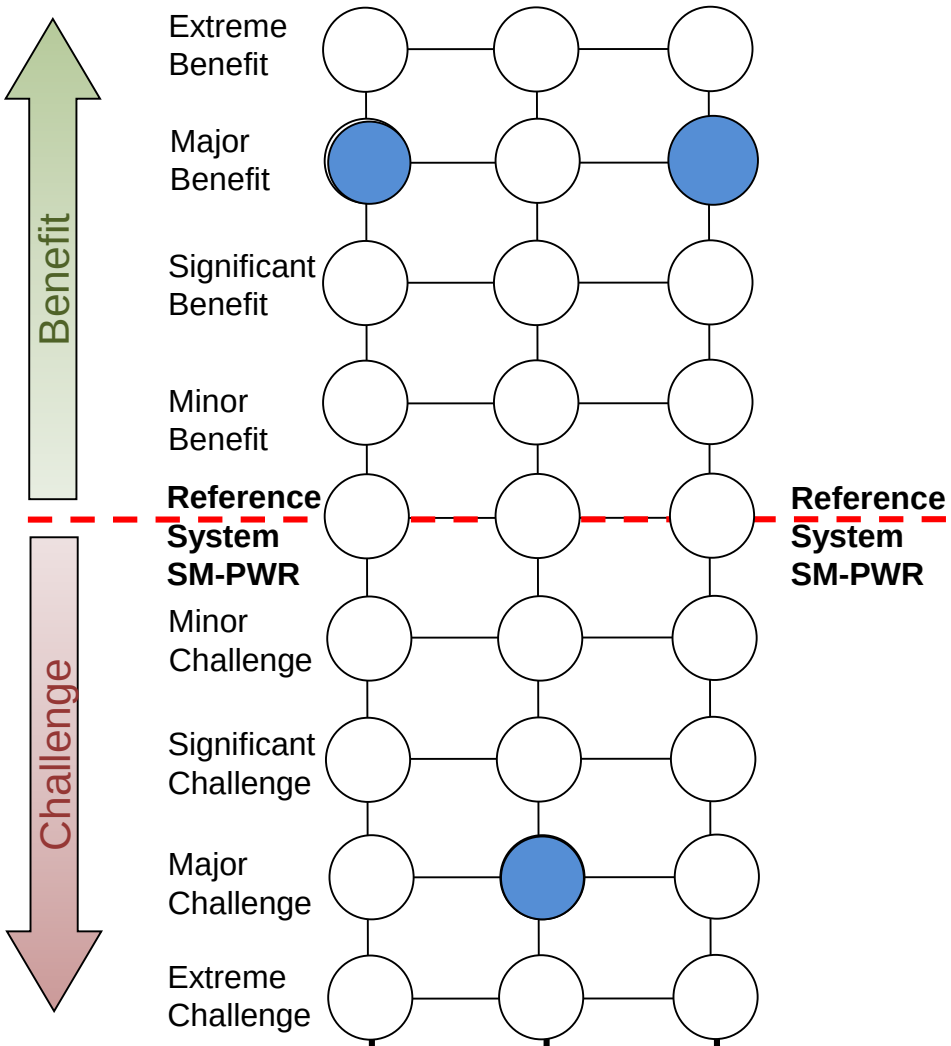
3a. Fuel Security



3a.3 Uranium dependence

3a.2 Spent fuel characteristics – compatible with existing reprocessing technology?

3a.1 Ability to deploy – fissile material availability

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Description

3a.1 Ability to deploy – fissile material availability

With a closed fuel cycle SM-LFR could in principle operate with a high conversion ratio or breeding cycle. In this instance, the system could operate independent of the world uranium market, which is beneficial for fuel security. Assessed as a Major Benefit

Assessed as 'Major Benefit'

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Description

References

3a.1 Ability to deploy – fissile material availability

3a.1 (Fissile material availability) applies specifically to closed fuel cycle systems which may have limitations on the rate at which new reactors could be deployed because of the need to acquire and/or build up the necessary fissile material. The levels of challenge vary between open and closed fuel cycle systems:

OPEN - this designates an open fuel cycle in which reactors are fuelled by LEU, which as natural uranium or LEU is available on the world market. In this instance the deployment rate would not be restricted, provided that world market supplies are sufficient and sufficient reactor build capacity was available.

CLOSED – this designates a closed fuel cycle which will eventually operate virtually independently of uranium availability, but which may be subject to constraints on the initial rate of deployment depending on the availability of fissile material. Limitations to closed cycle deployment can be calculated for any assumed future nuclear generation scenario.

3a.1 Ability to deploy – fissile material availability - references

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3a.2 Spent fuel characteristics – compatible with existing reprocessing technology?

The spent fuel form for SM-LFR (using UN or UO_2 fuel) is essentially compatible with current reprocessing technology. However, LFR spent fuel is more challenging to reprocess on account of its high initial fissile content, high burnup and associated decay heat output. Current reprocessing plants are incompatible with such fuels and new designs will need to be developed, although there is a body of experience from various project to demonstrate the closed fast reactor fuel cycle at Dounreay, Idaho National Laboratory, Marcoule and in Russia.

Assessed as 'Major Challenge'

3a.2 Spent fuel characteristics – compatible with existing reprocessing technology?

3a.2 (Spent fuel characteristics).
Spent fuel characteristics: Is the spent fuel of a form that is compatible with established reprocessing methods, or are there features that would preclude its reprocessing using current reprocessing methods? This Attribute tests whether or not the spent fuel form is compatible with established reprocessing technologies and gives a measure of the accessibility of the contained fissile material and hence the ability to affect any closed cycle deployment limitations in 3a.1.

Conventional spent oxide or metallic fuel, irrespective of whether the main fissile material is uranium or plutonium, are compatible with existing reprocessing technologies.

Unconventional fuels, such as fuels based on thorium matrix or coated particle TRISO fuels (used in high temperature gas reactors) are incompatible with established reprocessing methods. Fuel which is not straightforward to reprocess represents an intrinsic barrier to accessing fissile material.

3a.2 Spent fuel characteristics – compatible with existing reprocessing technology?

References

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3a.3 Uranium dependence

SM-LFR is in principle capable of operating a breeder cycle or a high conversion cycle. In this case, its dependence on uranium available on the international market would be eliminated or considerably reduced in the very long term. Assessed as a Major Benefit.

Assessed as 'Major Benefit'

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3a.3 Uranium dependence

The uranium usage Attribute poses the questions: "*Will there be sufficient uranium available on the world market to meet the requirements of the reactor system over its operational lifetime?"* and therefore *"Is the system more or less dependent on uranium ore availability/supply on the world market?*"

3a.3 therefore categorises the dependence of the nuclear system on uranium obtained from the world market. Illustrations of levels of uranium usage are:

LWRs have a specific uranium requirement of approximately 200 tU/GWye. CANDU reactors have a lower specific uranium requirement of approximately 160 tU/GWye.

Systems with high conversion ratios or with partial recycle of fissile materials are less dependent on uranium ore, defined as specific uranium requirements in the range 20 to 160 tU/GWye.

The lower range is set arbitrarily to 20 tU/GWye to allow for systems with high conversion ratios that are not quite self-sustained. Systems which have full recycle of fissile materials and operate a breeding cycle totally independent of external uranium supplies.

3a.3 Uranium dependence - References

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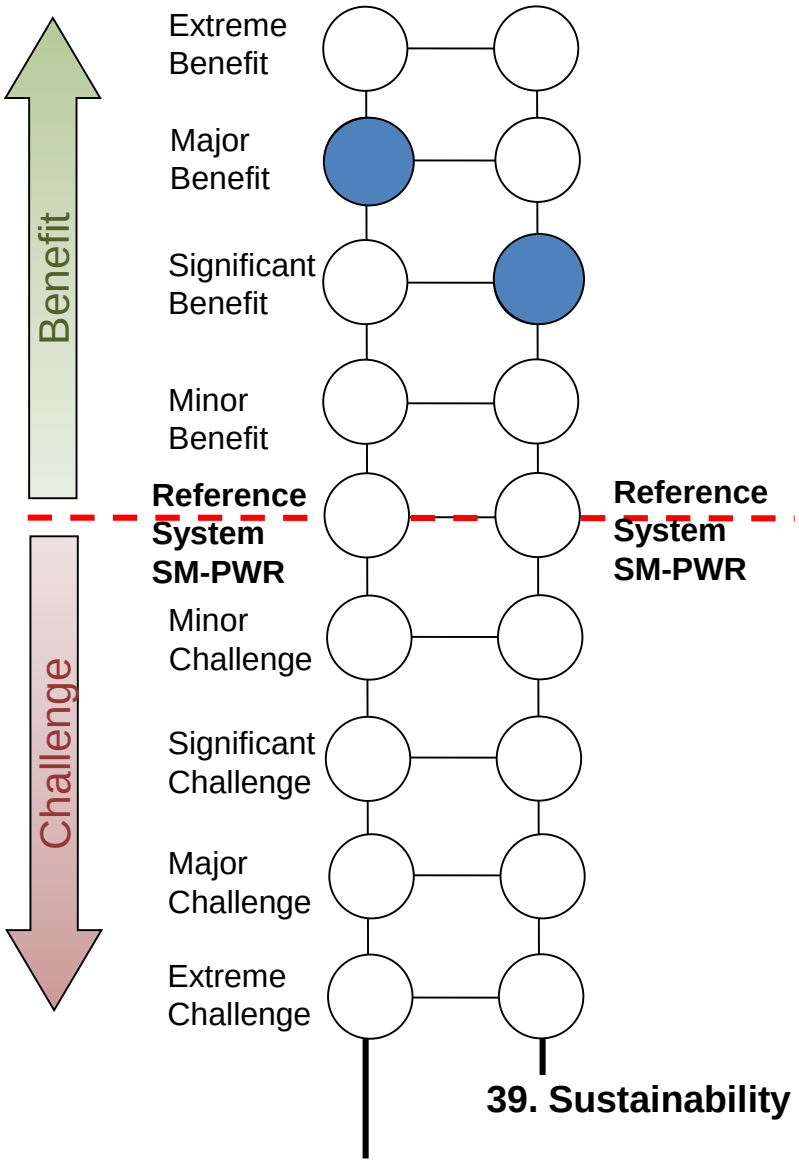
3a.3 Uranium dependence



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Description

01. Fuel utilisation

SM-LFR is in principle capable of operating a breeder cycle or a high conversion cycle. In this case, its dependence on uranium available on the international market would be eliminated or considerably reduced in the very long term. Assessed as a Major Benefit.

Assessed as 'Major Benefit'

01. Fuel utilisation

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.

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.

01. Fuel utilisation - references

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39. Sustainability

This is potentially a broad area encompassing the uranium ore requirement, environmental impact, waste arisings and others. SM-LFR operating a closed fuel cycle is assessed as 'Major Benefit' with respect to uranium ore demand. While it is too soon to assess other areas such as environmental impact, detailed assessment of waste arisings has shown considerable benefits in terms of decay heat load of waste for geological disposal. For this reason, SM-LFR is assessed as Significant Benefit against sustainability.

Assessed as 'Significant Benefit'

39. Sustainability

Sustainability is potentially a broad area encompassing the uranium ore requirement, environmental impact, waste arisings and others.

39. Sustainability - references

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3b. Waste storage and disposability

Summary

The spent fuel characteristics of SM-LFR are considerably more challenging than for the SM-PWR Reference Systems, especially if the fuel is reprocessed at short cooling times. Furthermore, there are complications associated with elevated C-14 concentrations for the waste from a uranium nitride fuelled LFR.

Overall assessment ranging from Significant Challenge, for short cooling time requirement using UN fuel, to Significant Benefit if long cooling times are allowed and UO_2 fuel is utilised.

Assessed as range from 'Significant Challenge' to 'Significant Benefit

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References

3b. Waste storage and disposability

Summary

All nuclear reactors generate nuclear waste that needs to be managed as part of the fuel cycle. The management and disposability of nuclear waste is one of the key long term considerations for the nuclear power industry. The current solution sought for long term disposability is to encapsulate waste into solid forms which are then protectively packaged and placed into a geological disposal facility (GDF). It is therefore required that any spent fuel, high level or intermediate level waste arising must be suitable for encapsulation and safe long term disposal in a GDF.

The waste management Strategic Attribute can be posed as: *Can the waste arisings from reactor systems be managed and eventually disposed of in a safe manner that is compatible with the acceptance criteria for existing or anticipated waste treatment plants and disposal facilities?*

From this top level Strategic Attribute, the following attributes are obtained:

Compatibility of waste forms: The masses and volumes of waste forms for disposal.

Suitability for disposal in GDF: Waste incorporation rate, long term decay heat and radiotoxicity.

3b. Waste storage and disposability - References

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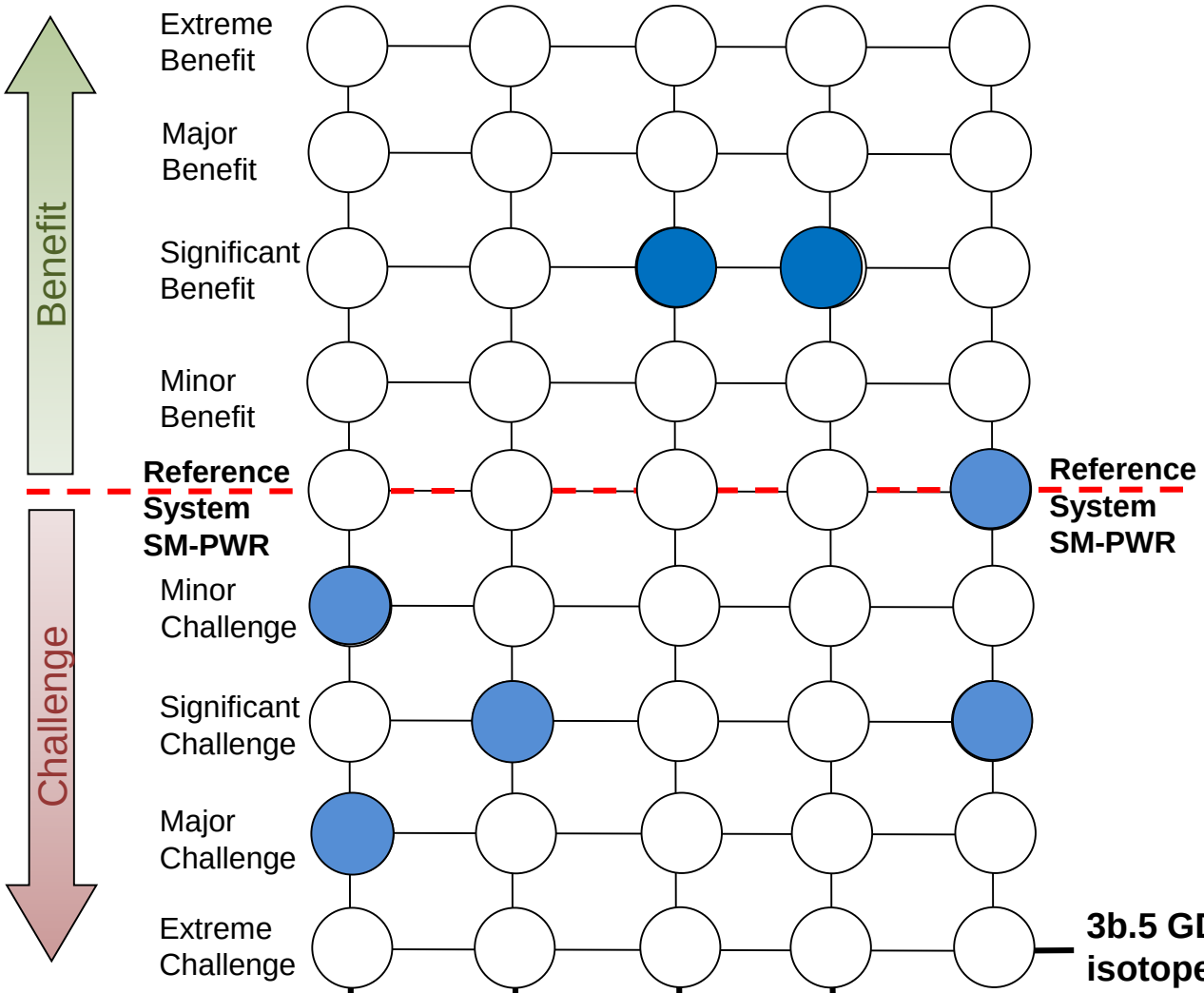
3b. Waste storage and disposability



3b.5 GDF disposal impact – isotopes driving safety case

3b.4 GDF disposal impact – long term radiotoxicity

3b.3 GDF disposal impact – long term decay heat

3b.2 GDF disposal impact – waste incorporation rate

3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology?

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3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology?

For oxide fuels with wet reprocessing the waste forms for SM-LFR would be largely compatible. However, there are some characteristics that makes reprocessing more difficult due to the higher decay heats and greater fissile concentrations than spent SM-PWR fuel. This is particularly true for spent fuel with short cooling times.

Nitride fuel is in principle compatible with the PUREX process however there is limited experience with reprocessing nitride fuel on a large scale. Furthermore, unless nitrogen enrichment is employed, the spent fuel will contain elevated concentrations of C-14. C-14 is a problematic nuclide due to its high mobility, bio-compatibility and relatively long half life. Therefore, the waste forms arising from spent nitride fuel are considered a Major Challenge relative to the reference system.

Assessed as 'Minor Challenge' for spent fuel with long cooling times from UO_2 fuelled LFRs and 'Major Challenge' for UN fuelled LFRs with short cooling times

3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology?

3b.1 (Number and type of waste forms). This attribute accounts for the number of different waste forms produced. It is intended to take account of waste forms that are incompatible with existing or expected future waste packaging and disposal facilities. Any incompatible waste forms produced will require the construction and operation of new facilities to deal with them, and this will be noted..

3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology? References

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3b.2 GDF disposal impact – waste incorporation rate

SM-LFR spent fuel will pose challenges for waste incorporation if processed in plants designed to current specifications.

Assessed as 'Significant Challenge'

Metric - 33. Waste arisings – volumes of HLW, ILW, LLW

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Description

References

3b.2 GDF disposal impact – waste incorporation rate

3b.2 (Waste Incorporation rate). Waste packages for disposal in the GDF mass may consist of spent fuel assemblies or immobilised high level waste forms (such as glass blocks) depending upon the fuel cycle. For the disposal of spent fuel assemblies, disposal canisters would normally be designed to accommodate uranium fuel assemblies with a relatively low long term decay heat output. Other types of fuel assemblies, for example MOX assemblies, would have a higher long term decay heat output and the disposal canister might be able to accommodate fewer of them, giving a low incorporation rate. Immobilised high level waste from reprocessing of low burnup fuels contains relatively low amounts of transuranics contributing to heat and neutron output and therefore can give a high incorporation rate. High burnup fuels are characterised by high transuranic content, with high heat and neutron outputs that may results in reduced incorporation rates. Illustrations of levels of waste incorporation rate are:

HIGH – Applies to reactor systems producing waste forms with relatively low heat and neutron outputs compatible with current waste forms.

LOW – Applies to reactor systems producing waste forms with relatively high heat and neutron outputs that are incompatible with current waste forms.

3b.2 GDF disposal impact – waste incorporation rate - references

Insert

33. Waste arisings – volumes of HLW, ILW, LLW

SM-LFR will require effort to understand the HLW, ILW and LLW waste volumes. This leads to it being assigned as 'Significant Challenge' in recognition of the effort that will be required to underpin its performance against this attribute.

Assessed as 'Significant Challenge'

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References

33. Waste arisings – volumes of HLW, ILW, LLW

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.

33. Waste arisings – volumes of HLW, ILW, LLW - references

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3b.3 GDF disposal impact – long term decay heat

An SM-LFR operated with recycle of plutonium would produce significantly lower decay heat once equilibrium was established.

Assessed as 'Significant Benefit'

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References

3b.3 GDF disposal impact – long term decay heat

This is a measure of the long term decay heat of spent fuel or high level waste in interim storage pending disposal and in the GDF. Decay heat is important, because it determines how long spent fuel or immobilised high level waste will need to be held in interim storage prior to final disposal. Also, decay heat loading is the principal determinant of repository footprint. Spent uranium fuel or immobilised high level waste derived from uranium fuels sets the baseline for low long term decay heat. Spent fuel containing higher inventories of transuranics (such as MOX fuels) or immobilised high level waste originating from such fuels will have elevated decay heat output. Immobilised high level waste from fast spectrum systems with recycle of transuranics and from thorium systems would be expected to have a low inventory of transuranics and therefore low decay heat.
Illustrations of levels of long term decay heat are:

LOW – Applies to reactor systems producing waste forms with relatively low long term decay heat output consistent with long, but manageable interim storage times.

HIGH – Applies to reactor systems producing waste forms with relatively high long term decay heat output that would lead to unfeasibly long interim storage times.

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3b.3 GDF disposal impact – long term decay heat - references

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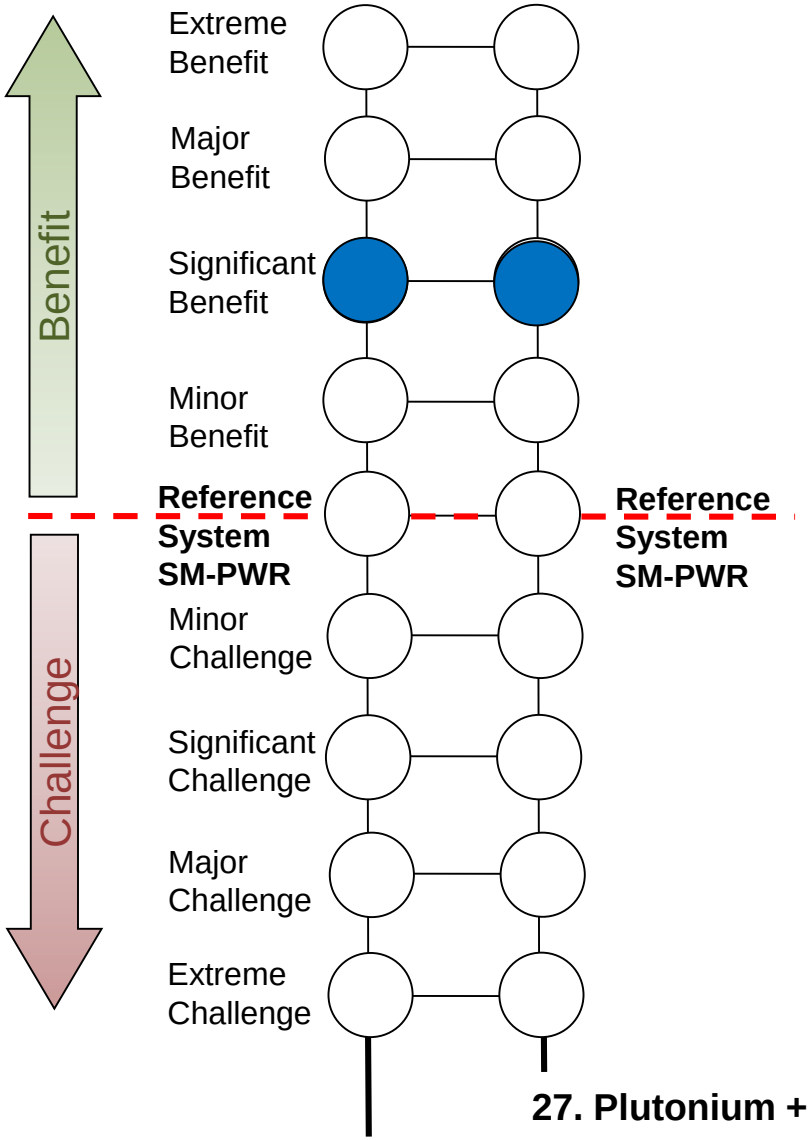
3b.3 GDF disposal impact – long term decay heat



27. Plutonium + minor actinide management

04. Long term heat output

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04. Long term heat output

An SM-LFR operated with recycle of plutonium would produce significantly lower decay heat once equilibrium was established.

Assessed as 'Significant Benefit'

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Description

References

04. Long term heat output

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.

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

04. Long term heat output - references

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27. Plutonium and minor actinide management

SM-LFR is more flexible at plutonium and minor actinide management than the SM-PWR Reference System. Even when only operating the SM-LFR with U-Pu fuel, the nuclear reactions that take place in a fast reactor favour the destruction of Pu and also a fast reactor is more accommodating with respect to the quality of Pu it can operate with.

Assessed as 'Significant Benefit'

27. Plutonium and minor actinide management

Most systems are capable in principle of recycling plutonium and some would also be capable of destroying minor actinides (principally neptunium and americium). This ability to manage plutonium and minor actinides is assessed in this attribute.

27. Plutonium and minor actinide management - references

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3b.4 GDF Disposal Impact – Long Term Radiotoxicity

SM-LFR with recycle of uranium and plutonium has lower long term radiotoxicity on a per GWye basis than the SM-PWR Reference System.

Assessed as 'Significant Benefit'

Metrics

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Description

References

3b.4 GDF Disposal Impact – Long Term Radiotoxicity

For cooling times up to approximately 500 years, it is the fission products that determine the radiotoxicity of spent fuel or immobilised high level waste and only marginal differences are expected between different systems. Beyond 500 years, where there are transuranics present in the spent fuel or immobilised high level waste, it is these that dominate radiotoxicity for up to 10^5 years. Low radiotoxicity on a timeframe of the order of 500 years is sometimes regarded as a desirable attribute of a fuel cycle because it might be feasible to argue that engineering barriers might retain their effectiveness up to that point. Spent uranium or MOX fuel assemblies and immobilised high level waste from uranium or MOX fuels will have high inventories of transuranics and therefore high long term radiotoxicity. Recycling transuranics in fast reactors can reduce the inventory in repository, possibly leading to low long term radiotoxicity. Fuel cycles based on the Th-232/U-233 fuel cycle have low transuranic inventories which give an intermediate level of radiotoxicity for spent thorium assemblies (in the once-through thorium cycle) and a lower level for immobilised waste from a closed Th-232/U-233 fuel cycle. Th-232/U-233 generally have higher radiotoxicities after 1E5 years.

3b.4 GDF Disposal Impact – Long Term Radiotoxicity - references

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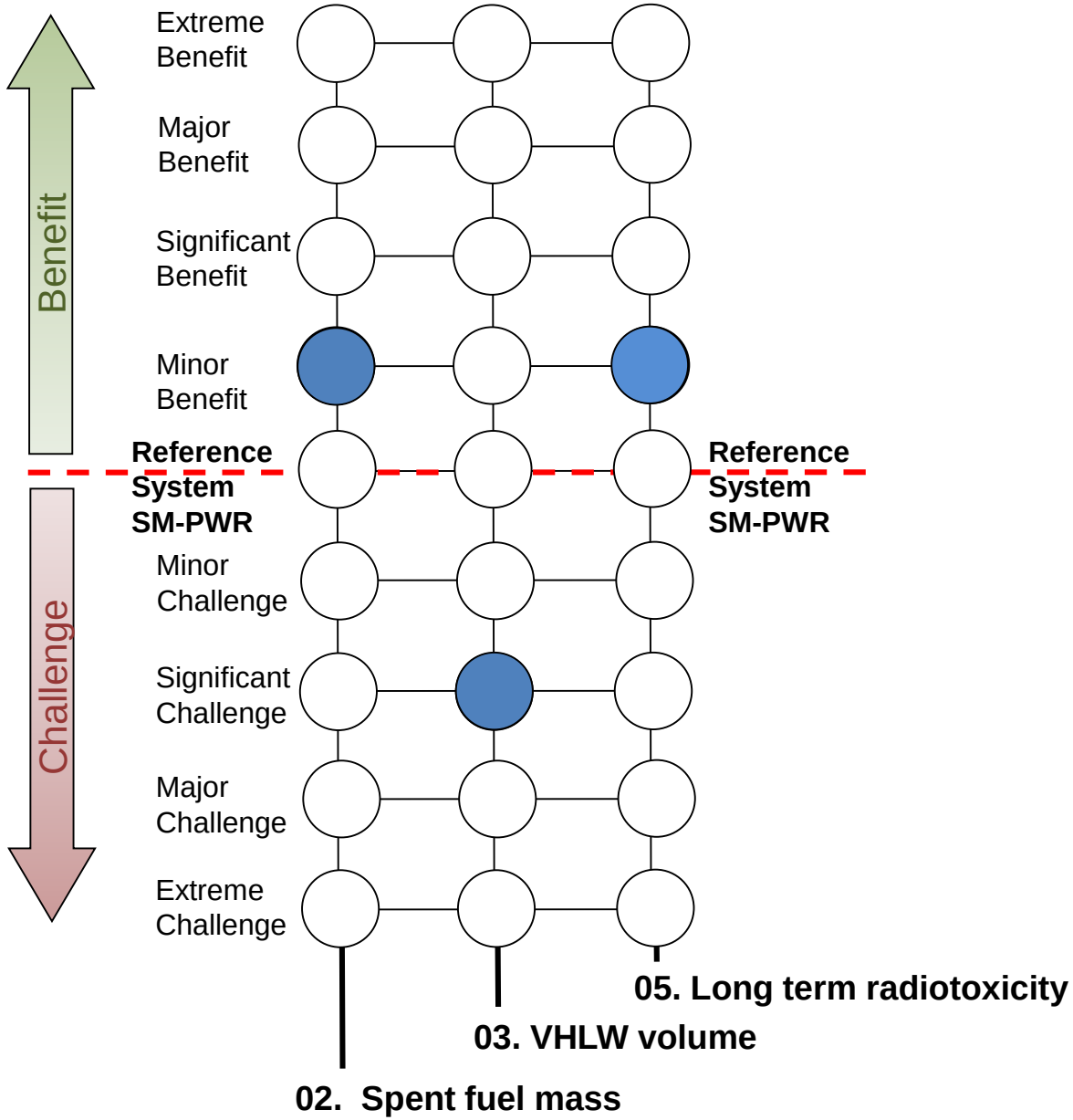
3b.4 GDF disposal impact – long term radiotoxicity



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02. Spent fuel mass

SM-LFR will have lower spent fuel arisings than the SM-PWR Reference System on account of the higher burnup.

Assessed as 'Minor Benefit'

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Description

References

02. Spent fuel mass

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).

For the recycle options the spent fuel arising is important only in that it determines the throughput and capacity of reprocessing plants,

02. Spent fuel mass - references

Insert

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03. VHLW volume

VLHW arisings from SM-LFR are not known. The mass of fission products is closely equivalent to that of the SM-PWR Reference System (there is some variation depending on the relative thermal efficiencies). A Significant Challenge is posed by the much higher heat load and neutron source of short cooled LFR fuel in comparison with the current fuel cycle, and the effect this will have on VHLW incorporation rates. The UK's vitrification plants are designed to deal with a mix of HLW liquor from MAGNOX reprocessing and mostly long cooled low burnup fuels from THORP.

Assessed as 'Significant Challenge'

03. VHLW volume

This is the volume of high activity (heat generating) waste, expressed in m3 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.

03. VHLW volume - references

Insert

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05. Long term radiotoxicity

SM-LFR with recycle of uranium and plutonium has lower long term radiotoxicity on a per GWye basis than the SM-PWR Reference System, but as the generic SM-LFR case does not yet recycle minor actinides the gain is restricted to removal of U and Pu content.

Assessed as 'Minor Benefit'

05. Long term radiotoxicity

The radiotoxicity is a measure of the hazard potential of radioactive material. Radiotoxicity can be measured as the potential dose from the waste in Sieverts (Sv) per Gwye, or by Toxic Potential, which measures the dilution required to allow dissolved waste to meet dose standards if used for drinking.

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 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.

05. Long term radiotoxicity - references

Insert

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3b.5 GDF disposal impact – isotopes driving safety case

SM-LFR with uranium oxide fuel is assessed to be essentially equivalent to SM-PWR. However, for SM-LFRs with uranium nitride fuel the elevated concentrations of C-14 will pose a significant challenge with respect to disposability.

Assessed as 'Reference' for UO_2 fuelled LFRs and 'Significant Challenge' for UN fuelled LFRs

3b.5 GDF disposal impact – isotopes driving safety case

As GDF safety cases are generally driven by long-lived mobile fission and activation products rather than by radiotoxicity per se, this attribute assesses any material differences in mobile isotope yields on a per GWye basis.

3b.5 GDF disposal impact – isotopes driving safety case - references

Insert

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3c. Siting

Summary

SM-LFR is assessed to be equivalent to the SM-PWR Reference System with respect to siting, assuming reprocessing is performed at a central facility.

Assessed as 'Reference'

Attributes
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Description
References

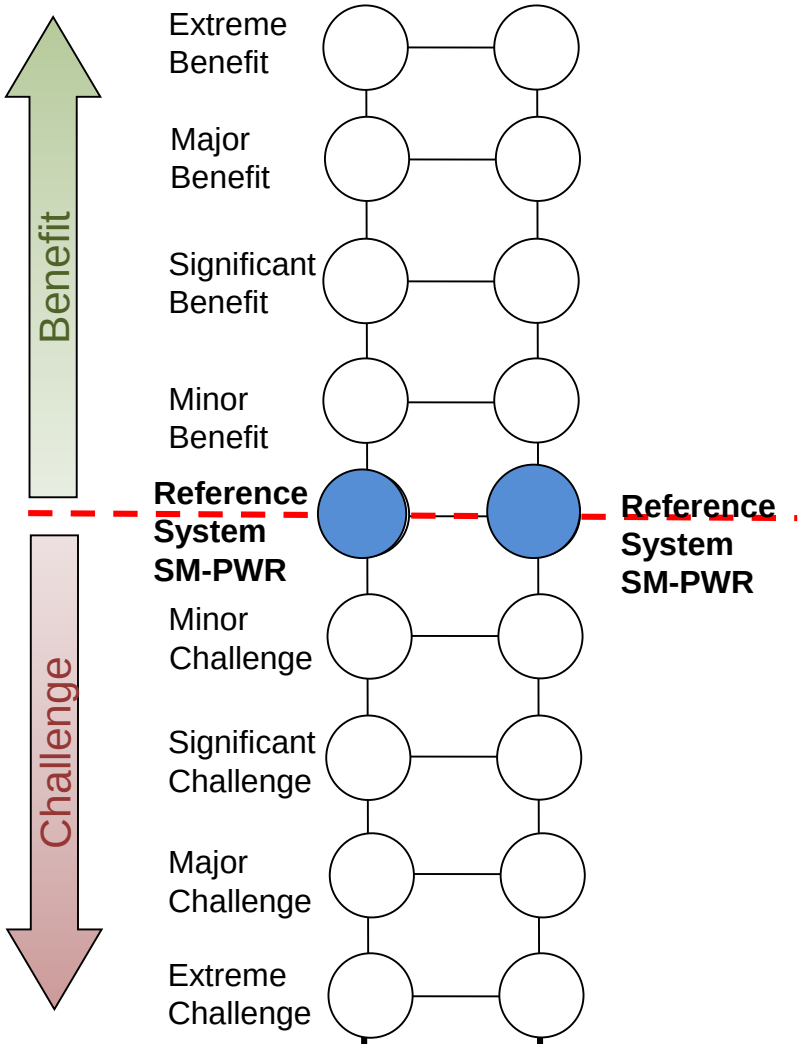
3c. Siting

Reactor systems can be commercially available, competitive, and reliable but all require sites with adequate access to cooling water, power transmission. This Strategic Attribute therefore examines the relative technical suitability of siting reactors and fuel cycle plants across the range of total generation capacity which may be required.

3c Siting - references

Insert

3c. Siting



3c.2 Siting – associated fuel cycle plants

3c.1 Siting - number and size of reactors c/f likely site availability

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Description

3c.1 Siting – number and size of reactors c/f likely site availability

SM-LFR is equivalent to SM-PWR with respect to siting.

Assessed 'Reference'

Metrics

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Description

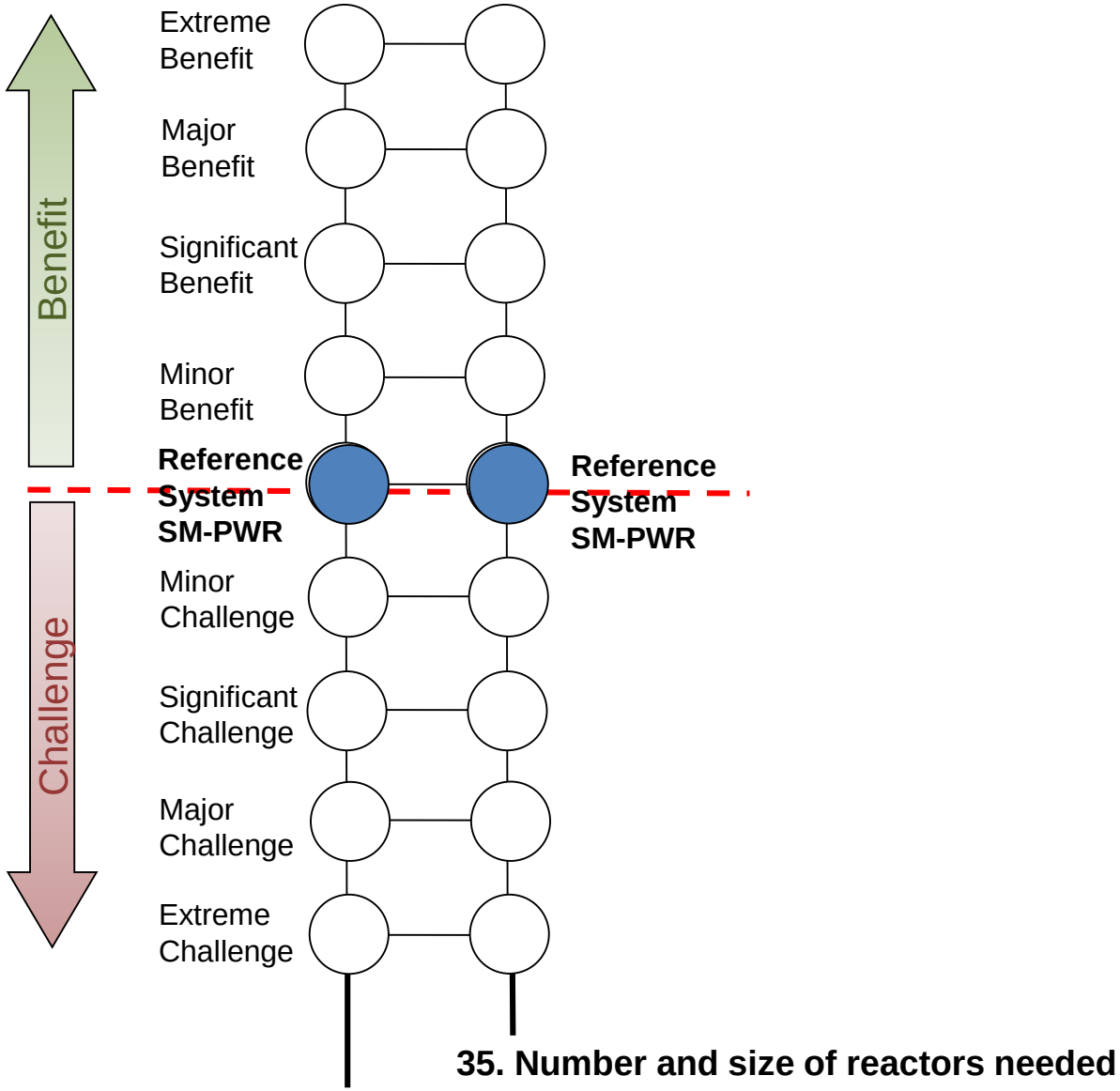
3c.1 Siting – number and size of reactors

3c.1 is intended to measure of how flexible reactor siting would be. It may be possible for small reactors to be sited at locations that would be unsuitable for large reactors on account of reduced land area required and reduced cooling water requirement. It may be possible for a reactor system which, in the event of Design Basis accidents, does not require evacuation outside the site boundary, to be sited more closely to dense concentrations of population.

3c.1 Siting – number and size of reactors - references

Insert

3c.1 Siting - number and size of reactors c/f likely site availability



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32. Flexibility of location

Significant improvement for small power station outputs. Less so for large outputs (>0.5 GWye). Potential benefits for small modular reactors with respect to cooling water availability, ultimate heat sink (for decay heat), grid connections and avoidance of off-site evacuation zone and transmission infrastructure compatibility.

Small modular reactors may offer increased scope for development on alternative locations, such as former coal fired power stations or other former industrial sites.

SM-LFR is equivalent to SM-PWR with respect to flexibility.

Assessed as 'Reference'

32. Flexibility of location

Reactors will have varying siting demands depending on their output and any dependence of co-siting with, for example, fuel cycle plants. Small reactors will make smaller demands on cooling water and grid connections, but will require more sites to reach the same installed output.

32. Flexibility of location - references

Insert

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35. Number and size of reactors needed

SM-LFR is equivalent to the SM-PWR Reference System

Assessed as 'Reference'

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Description

References

35. Number and size of reactors needed

The size of individual reactors will directly affect the number of reactors needed per GWe installed. The effects on numbers of sites and on economics are examined elsewhere,

35. Number and size of reactors needed - references

Insert

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Return to top

3c.2 Siting – associated fuel cycle plants

SM-LFR would be equivalent to the SM-PWR Reference System if the fuel cycle plants are sited at a central location.

Assessed as 'Reference'

Metric - 36. Fuel cycle plants

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Description

References

3c.2 Siting – associated fuel cycle plants

3c.2 covers the need of closed reactor systems for reprocessing, waste processing and fuel refabrication plants. Many outline schemes assume co-location of reactor and fuel cycle plants – but, in nuclear scenarios with large contributions from closed systems, this carries the consequence of either (a) very large generation capacity at one site or (b) multiple sites and fuel cycle plants.

3c.2 Siting – associated fuel cycle plants - references

Insert

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36. Fuel cycle plants

SM-LFR would require new fuel cycle plants designed to cope with the demands of high burnup LFR fuel (high decay heat and high fissile concentrations).

Assessed as 'Significant Challenge'

36. Fuel cycle plants

The fuel cycle plants needed for the various reactor system options are potentially very different.

36. Fuel cycle plants - references

Insert

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4a. Access to international programmes

SM-LFR offers strong potential for international collaboration due to the significant cross-over with Sodium Fast Reactor technology (for which there is significant research ongoing in a number of countries) and currently there is significant R&D investigating advanced material options for LFR systems. UK engagement in design, modelling and testing would be a fertile area for maintaining and developing expertise. It would help provide a positive focus for UK nuclear R&D.

Assessed as 'Significant Benefit'

Metric - 4a.1 Re-engagement in international programmes

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Description

References

4a. Access to international programmes

This Strategic Attribute assesses whether access to (or indeed the formation of) international programmes could aid the eventual deployment of a reactor system. The single Attribute assesses the information on the credibility of the route and on its possible timescale for deployment.

4a. Access to international programmes - references

Insert

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4a.1 Re-engagement in international programmes

Strong potential for international collaboration. SM-LFR would help provide a positive focus for UK nuclear R&D.

Assessed as 'Significant Benefit'

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Description

References

4a.1 Re-engagement in international programmes

This Attribute assesses whether access to (or indeed the formation of) international programmes could aid the eventual deployment of a reactor system. The single Attribute assesses the information on the credibility of the route and on its possible timescale for deployment.

4a.1 Re-engagement in international programmes - references

Insert

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4b. Time and Cost to Deployment

Summary

Significant R&D is required regarding the development and testing of computer codes, materials and numerous reactor systems (e.g. chemistry control and reactor instrumentation). The development programme is judged to take at least 25 years until a prototype LFR could be constructed. Historically, prototype fast reactors have operated for around 10 years until subsequent reactor iterations have been constructed. Therefore deployment before 2060 is deemed unlikely.

Assessed as 'Major Challenge'

Attributes

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Description

References

4b. Time and Cost to Deployment

This Strategic Attribute takes in information from the assessment of Strategic Attributes 1a, 1b, 1c and from Attribute 4a above, to assess the overall timescale on which the system could be deployed. This will be placed in the context of the relative economics of the system and its match to the market, which are examined under High Level Discriminator 2 – Competitiveness. The Technology Readiness level will be an assessment, with the grounds for that assessment given, while the Deployment Time should be a time in years, with the reasons and uncertainties stated.

In determining the timescale, funding for R&D activities will be assumed to be available as required, and regulatory effort will also be assumed to be available. Funding for reactor build will also be assumed to be available as required. The estimated time to deployment will be the time from the GFA to the time of power production by the first UK reactor

4b. Time and Cost to Deployment - references

NNL 12415 – Manchester Report on TRL of Gen IV Systems

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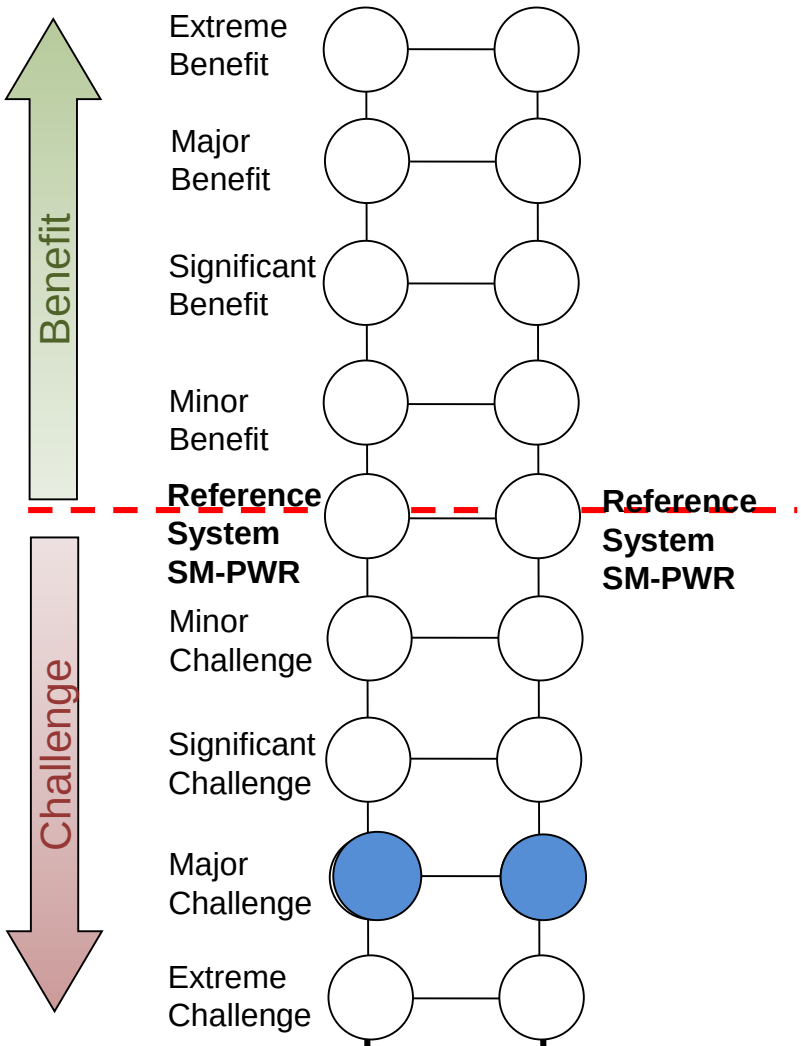
4b. Time and Cost to Deployment



4b.2 Technology Readiness level

4b.1 Commercial availability. Deployment time, plus feed from 1 and 2a

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Description

4b.1 Commercial availability – Deployment Time

Significant R&D is required regarding the development and testing of computer codes, materials and numerous reactor systems (e.g. chemistry control and reactor instrumentation). The development programme is judged to take at least 25 years until a prototype LFR could be operated. Historically, prototype fast reactors have operated for around 10 years until subsequent reactor iterations have been constructed. Therefore, assuming a 5 year GDA and 5 year FOAK build time, deployment before 2060 is deemed unlikely.

Assessed as 'Major Challenge'

Metrics

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Description

References

4b.1 Commercial availability – Deployment Time

4b.1 (Deployment time) is the earliest time until the first unit could become operational. It builds on the assessment under in Strategic Attributes 1a, 1b, 1c and 2, and the effect of any international programmes available from 4a.1.

4b.1 Commercial availability – Deployment Time - references

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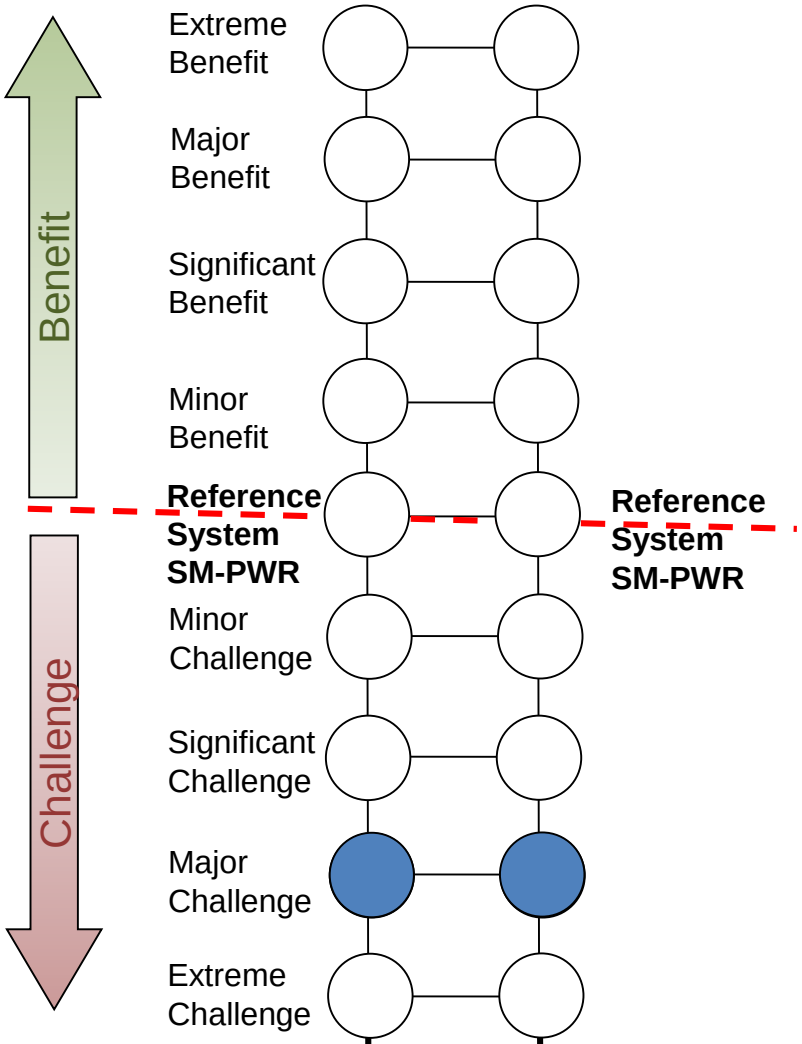
4b.1 Commercial availability



30. Timescales for deployment

25. Development costs

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25. Development costs

Considerable R&D must be performed in a number of areas (see Timescales for Deployment metric – no. 30). Therefore Development costs is judged to be a Major Challenge.

Assessed as 'Major Challenge'

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Description

References

25. Development costs

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.

25. Development costs - references

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30. Timescales to deployment

Considerable R&D needs to be performed to demonstrate that systems (fuel, pumps, instrumentation, etc…) are capable of withstanding the harsh environment of an LFR. An extensive materials test programme that includes corrosion and mechanical performance tests must be carried out. Tests that also include exposing fuel materials to normal and transient conditions must be performed. Material testing is likely to take at least 10-15 years, once factoring in Post Irradiation Examinations, and may be considerably longer if candidate materials require modifications.

In addition to material testing, systems such as chemistry control will require demonstration and data must be generated to validate reactor physics and thermal-hydraulics computer codes. Some of these programmes can be performed in parallel but eventually accurate computer simulation will be required to determine operational boundary conditions that materials and control systems can be certified against. Therefore the development time is likely to require at least 25 years. Furthermore, a prototype system (with extensive instrumentation) would likely be required to demonstrate that all of the various components work as intended in a reactor system set up. Historically, prototype systems have operated for around 10 years before subsequent reactor iterations have been built. Therefore, assuming a 5 year GDA and 5 year FOAK build time, deployment before 2060 is deemed unlikely.

Assessed as 'Major Challenge'

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Description

References

30. Timescales to deployment

The timescale at which any new system could be deployed would be of high relevance to strategic planning in the UK.

In determining the timescale, funding for R&D activities will be assumed to be available as required, and regulatory effort will also be assumed to be available. Funding for reactor build will also be assumed to be available as required. The estimated time to deployment will be the time from the GFA to the time of power production by the first UK reactor

30. Timescales to deployment - references

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4b.2 Technology Readiness Level

SM-LFR is assessed as TRL 2-5.

The fundamental principles behind utilising lead-based alloys as a coolant in a fast reactor have been demonstrated in Russian submarines. However, submarines are a poor proxy for the operating conditions of a commercial reactor, where reloading times and power histories differ substantially. SM-LFRs with coolant temperatures limited to approximately 500°C and using candidate materials that have undergone testing in lead-based coolant environments are considered to be at TRL 5. At higher temperature (>550°C) limited to no testing has been performed and therefore SM-LFRs operating at such temperatures are considered to be TRL 2.

Assessed as 'Major Challenge'

Metric - 31 Technology Readiness Level

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Description

References

4b.2 Technology Readiness Level

4b.1. and 4b.2 combine to give a likely timescale for deployment in the UK. For reactor systems which are already commercially available, this is determined by the lead time for pre-licensing in the UK, the lead time for site approval and the construction time. For systems which are not yet commercially available, an additional lead time would be required for the system to be developed to commercial readiness, with the lead time being longest for systems which are at an early stage of R&D.

This assessment will give an idea of the likely deployment time in the UK. This needs to be compared with the timescales indicated in the Strategic Attributes 1a, 1b and 1c, to come to a consolidated overall view.

4b.2 Technology Readiness Level - references

NNL 12415 – Manchester Report on TRL of Gen IV Systems

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31. Technology Readiness Level

SM-LFR is assessed as TRL 2-5.

The fundamental principles behind utilising lead-based alloys as a coolant in a fast reactor have been demonstrated in Russian submarines. However, submarines are a poor proxy for the operating conditions of a commercial reactor, where reloading times and power histories differ substantially. SM-LFRs with coolant temperatures limited to approximately 500°C and using candidate materials that have undergone testing in lead-based coolant environments are considered to be at TRL 5. At higher temperature (>550°C) limited to no testing has been performed and therefore SM-LFRs operating at such temperatures are considered to be TRL 2.

Assessed as 'Major Challenge'

31. Technology Reference Level

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

31. Technology Readiness Level - - references

NNL 12415 – Manchester Report on TRL of Gen IV Systems

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4c. Meet and enable UK supply chain

Summary

SM-LFR presents increased opportunity for UK involvement in the supply chain, but the ability of the UK to realise this potential will be challenging.

The deployment of more mature SMR technology would seem to offer limited potential for UK supply chain involvement, with the UK largely restricted to manufacturing components to a given design/specification.

By contrast, less mature designs may offer increased potential for UK supply chain, with the possibility of UK design expertise being input to develop component designs from the beginning and higher value.

Assessed as 'Significant Benefit'

Attribute - 4c.1 Supply chain opportunities

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Description

References

4c. Meet and enable UK supply chain

Summary

This Strategic Attribute examines the possibility of opportunities for the UK supply chain, providing an additional incentive for UK involvement in any particular reactor system.

4c. Meet and enable UK supply chain - references

Insert here

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4c.2 Supply chain opportunities

On account of its low TRL, SM-LFR presents increased opportunity for UK involvement in the supply chain, but the ability of the UK to realise this potential will be challenging.

Assessed as 'Significant Benefit'

4c.2 Supply chain opportunities

This Attribute should attempt to assess the level of UK supply chain involvement that could accompany the development and deployment of a given system

4c.2 Supply chain opportunities - references

Insert

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5a Meets Energy Requirements - load follow capability

The impact of power cycling on the SM-LFR systems compared with the SM-PWR Reference case is not clear but oxide fuel systems are likely to suffer pellet-clad interactions (PCI) with cycling in a similar way to PWRs . PCI will limit the rate of power change permitted. Both reactor physics and practice has shown that fast reactor systems are more resilient on reactivity effects on power reductions than thermal systems, ie the Xe poisoning effect that places restrictions on low power operation and start-up after trips.

Assessed as 'Minor Benefit'

Attribute - 5a.1 Flexibility – load follow capability

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Description

References

5a Meets Energy Requirements - load follow capability

This Strategic Attribute assesses the ability of systems to respond to particular features of a future energy market. For example, if the percentage of nuclear electricity on the grid is high, and coupled with a significant randomly variable output from renewables, then nuclear systems may be required to load follow. Some systems are much more amenable to this than others.

4c.2 Supply chain opportunities - references

Insert

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5a.1 Flexibility – load follow capability

The design of SM-LFR is insufficiently developed to assess it load-follow capability. However thermal cycling effects may be increased due to the large difference between inlet and outlet temperatures compared with the SM-PWR Reference System. SM-LFR is assessed as posing a Minor Challenge to the SM-PWR Reference System. Market mechanisms will be needed accommodate load follow operation, otherwise nuclear utilities will suffer significant loss of revenue. The market mechanisms would recognise that providing a load-follow capability helps support the grid system.

Assessed as 'Minor Challenge'

Metric – 28. Load follow capability

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Description

References

5a.1 Flexibility – load follow capability

5a.1 measures the ability of the reactor system to operate in non-baseload or load-follow mode. This is the ability of the reactor to increase or decrease output either in response to short term grid demands or in pre-planned load scheduling. If the total installed capacity of nuclear stations in the UK is only a small or modest fraction of the grid capacity, there is unlikely to be a major requirement for load-follow capability. However, if the nuclear capacity grows sufficiently, with only limited electricity storage capacity, there may come a point at which load-follow will be required, as is the case currently in France. Many current reactors are able to load-follow, but with limitations. Future reactor systems may be able to operate in load-follow mode without such restrictions, hence their ability to load follow will be compared, both from one system to another, and with the current LWR reference systems.

5a.1 Flexibility – load follow capability - references

Insert

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28. Load follow capability

The design of SM-LFR is insufficiently developed to assess it load-follow capability. However thermal cycling effects may be increased due to the large difference between inlet and outlet temperatures compared with the SM-PWR Reference System. SM-LFR is assessed as posing a Minor Challenge to the SM-PWR Reference System. Market mechanisms will be needed accommodate load follow operation, otherwise nuclear utilities will suffer significant loss of revenue. The market mechanisms would recognise that providing a load-follow capability helps support the grid system.

Assessed as 'Minor Challenge'

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Description

References

28. Load follow capability

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.

28. Load follow capability - references

Insert

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Description

5b. Meets energy requirements – Process Heat

SM-LFR is expected to operate at significantly higher working temperatures (~550°C) than the SM-PWR Reference System (~300°C), which is capable of supplying only low grade heat. Therefore SM-LFR is assessed as offering Significant Benefit.

Assessed as 'Significant Benefit'

Attribute - 5b.1 Industrial process heat – potential to drive thermal processes

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Description

References

5b. Meets energy requirements – Process Heat

This Strategic Attribute assesses the ability of systems to respond to particular features of a future energy market. For example If sectors such as transport are to be decarbonised, for example by use of hydrogen as an energy vector, then the ability of a reactor system to provide high grade heat (rather than electricity) to power chemical processes could be a significant advantage.

5b. Meets energy requirements – Process Heat - references

Insert

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Description

5b.1 Industrial process heat – potential to drive thermal processes

Not relevant to current UK market, but potential for future market to develop. SM-LFR can potentially supply higher temperature processes than the SM-PWR Reference System.

There are a significant number of energy intensive processes that require process heat temperatures up to ~550°C.

Assessed as 'Significant Benefit'

Metrics

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Description

References

5b. 1 Industrial process heat – potential to drive thermal processes

5b.1 indicates whether the system has the potential to drive thermal processes, such as combined heat and power (CHP), hydrogen production, synthetic fuel production and as a heat source for other industrial processes to displace carbon emitting fossil fuel heating. For thermal applications, a high operating temperature is beneficial, which leads to a simple description based on three levels of temperature:

- LOW TEMPERATURE – Low operating temperatures similar to those of current Light Water Reactors (LWRs) ~300-320°C.
- MEDIUM TEMPERATURE – Medium operating temperatures in range 320-600°C beyond the range accessible with LWRs.
- HIGH TEMPERATURE – High operating temperatures >600°C.

5b. 1 Industrial process heat – potential to drive thermal processes - references

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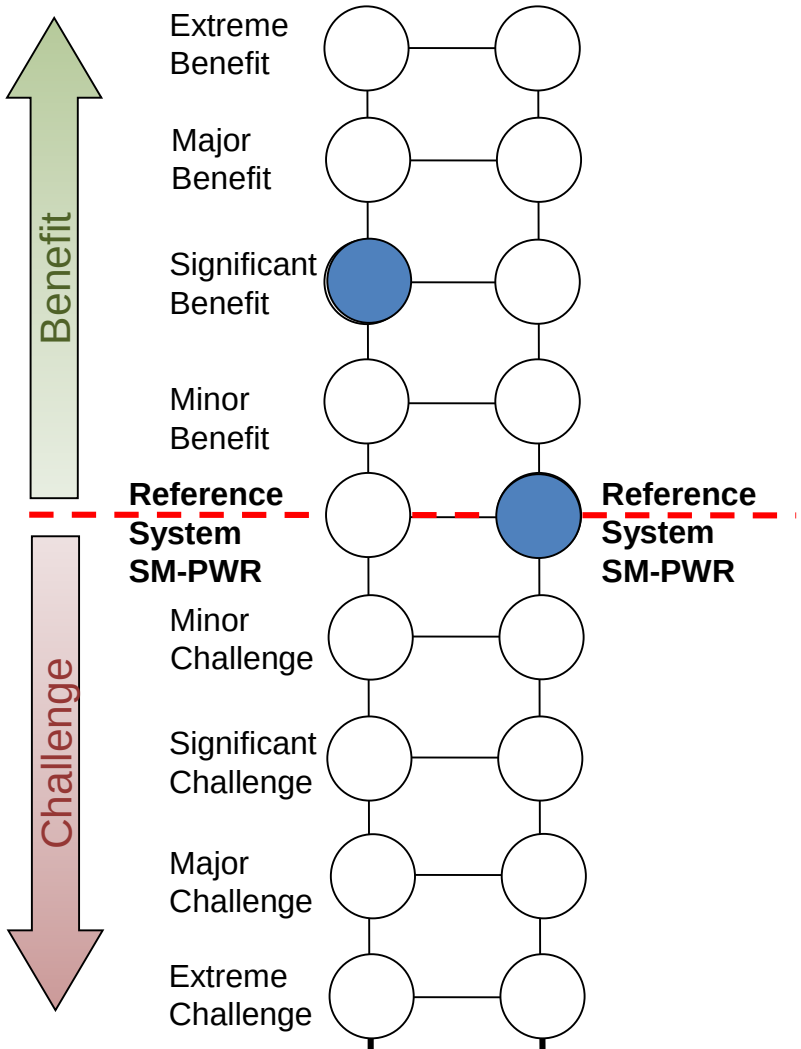
Description

5b.1 Industrial process heat – potential to drive thermal processes



42. Primary purpose

40. Potential to drive thermal processes

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Description

40. Potential to drive thermal processes

Not relevant to current UK market, but potential for future market to develop. SM-LFR can potentially supply higher temperature processes than the SM-PWR Reference System.

There are a significant number of energy intensive processes that require process heat temperatures up to ~500°C.

Assessed as 'Significant Benefit'

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Description

References

40. Potential to drive thermal processes

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 systems (eg GFR, MSR and VHTR) have very primary circuit operating temperatures compatible with high temperature process heat applications.

40. Potential to drive thermal processes - references

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42. Primary purpose

The primary purpose of SM-LFRs is to provide competitive low-carbon electricity, which is the primary purpose of SM-PWRs.

Assessed as 'Reference'

42. Primary purpose

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.

42. Primary purpose - references

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Work in Progress

NATIONAL NUCLEAR LABORATORY

The Generic Feasibility Assessment:
An Essential Ingredient in Nuclear Policy making

Assessment Matrix with Descriptions

Subject System: **Generic SM-MSFR**

Reference System: **Generic SM-PWR**

Template: **14**

Date of Assessment: **24th February 2016** Modified to generalise references to Regulators. 20th December 2017

Skip to Assessment

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IDM
integrated decision management

Reference and Subject Systems

Reference System:

Small Modular PWR (SM-PWR)

Subject System:

A Generic Small Modular Fast Spectrum MSR (SM-MSFR) with an electric capacity of less than 300 MWe. It should be capable of being deployed in multiple units. It is novel technology which has not been demonstrated at any level and which will require long term development. SM-MSFR is assumed to require a secondary salt circuit. SM-MSFR can operate with a uranium-plutonium (U-Pu) or a thorium-uranium (Th-U) fuel cycle. SM-MSFR is assumed to operate with full on-line recycle, with removal of fission products and separation of fissile materials. The Stable Salt Reactor (SSR) is a variant of SM-MSFR, which has a different fuel form and does not incorporate on-line fuel salt processing. SSR is claimed to have an on-line date between SM-SFR and SM-MSFR.

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Version Development

2015.08.08 Initial GFA of Generic SMR based on 2014 assessment inserted into updated format Template 12

2015.12.08 Kevin Hesketh & Aiden Peakman

2016.01.11 Modified following 5 Jan 2016 meeting

2016.01.25 Modified after considering Jon Brooking comments

2016.02.08 Minor connection glitches removed – slides 62-82

2016.02.24 Checked/mods accepted for Draft Report

2017.12.20 Modified to generalise references to Regulators

References

This Generic Feasibility Assessment draws upon extensive work by NNL on nuclear energy technology assessment, IAEA, OECD/NEA, USDOE and other international literature. Individual references have not been included in the current draft GFA. It is anticipated that as more information becomes available relating to specific Attributes or Metrics, this might either further validate or modify the GFA. This additional information can then be referenced in the appropriate places in the GFA Template.

IDM
integrated decision management

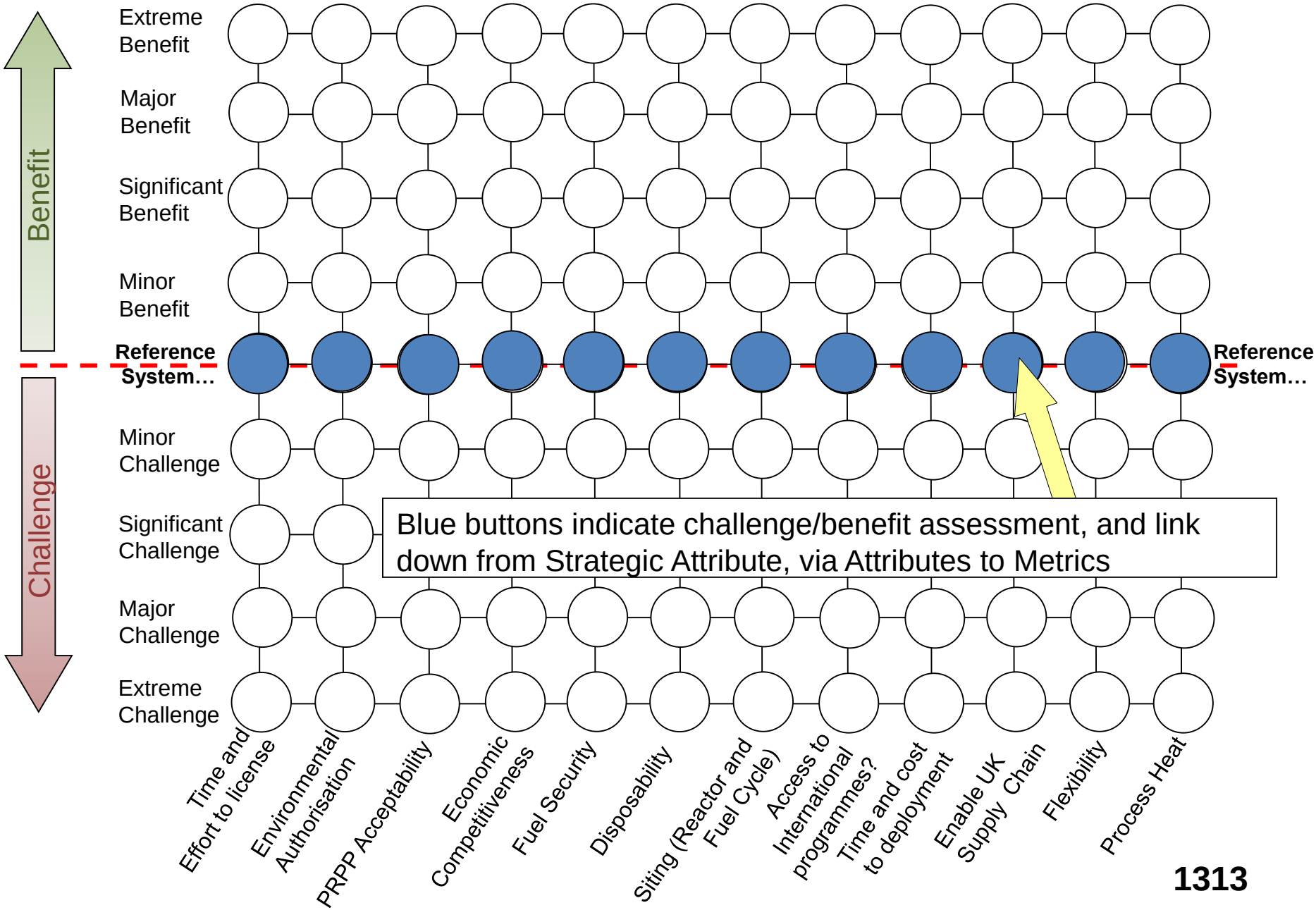
What is Generic Feasibility Assessment?

- GFA was developed for DECC to provide a high level strategic evaluation of nuclear reactor and fuel cycle systems
- It operates by making comparisons between the 'Subject System' and a Reference System, initially 'once-through LWR' as envisaged for new nuclear build in the UK
- The analysis uses 12 Strategic Attributes, using public domain information and informed professional judgement to assess the relative degree of benefit or challenge offered by the Candidate System.

What is Generic Feasibility Assessment?

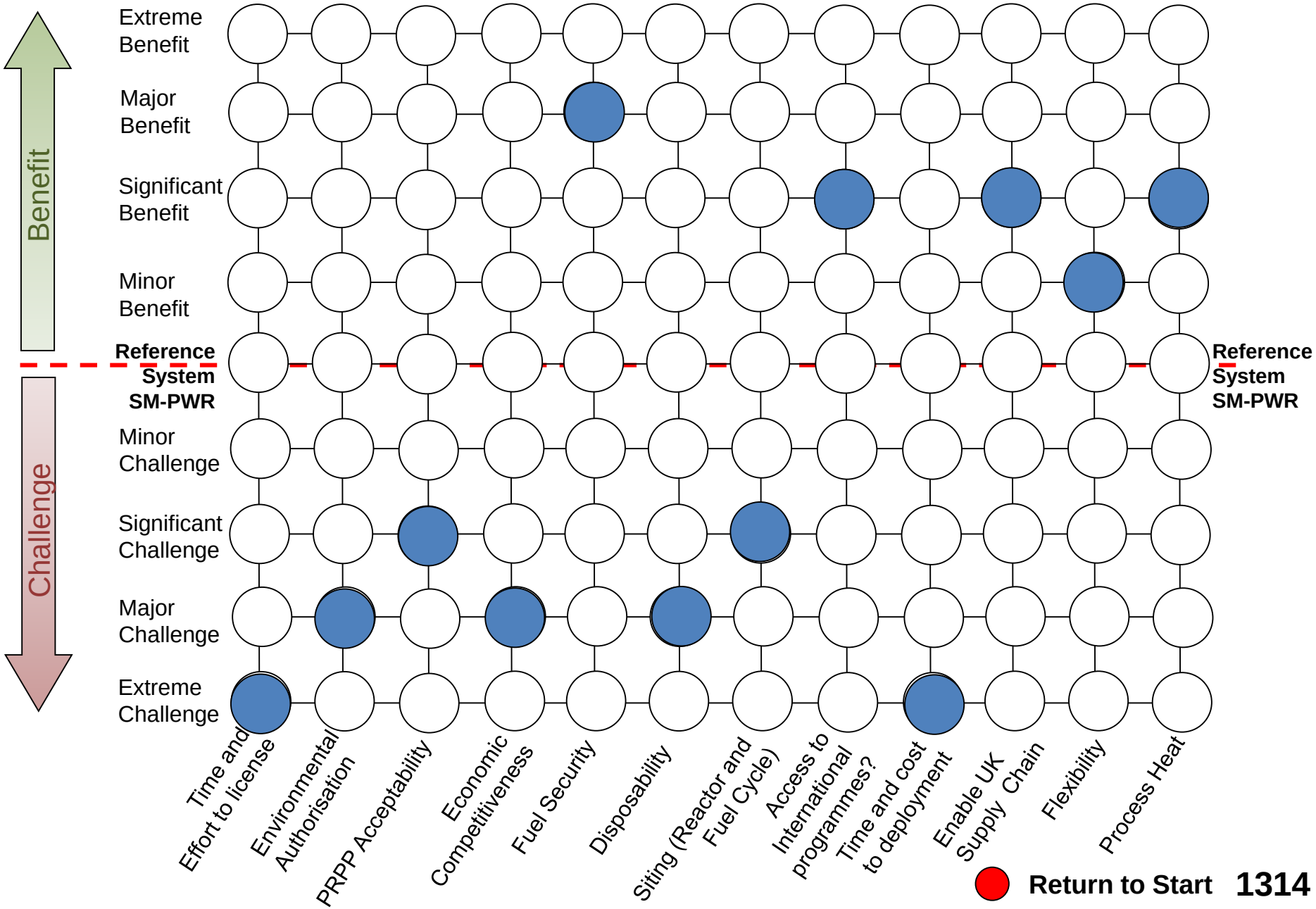
- GFA presents a high level, accessible visual representation of benefits and challenges, while allowing more detailed interrogation of the underpinning rationale and data
- As all information is public domain, any additional evidence can, and will, lead to modification of the assessment: GFA assessments are always 'Work in Progress'
- A full description of how GFA was derived and developed is available at: www.dalton.manchester.ac.uk/gfa
- This Visualisation provides a guide to how GFA is built up, the definitions of Strategic Attributes, Attributes and Metrics, and demonstrates how the information and logic tree can be navigated.

GFA Assessment Subject System: SM-MSFR Reference System: Generic SM-PWR – *Work in Progress*



Blue buttons indicate challenge/benefit assessment, and link down from Strategic Attribute, via Attributes to Metrics

GFA Assessment Subject System: SM-MSFR Reference System: Generic SM-PWR – *Work in Progress*



1a. Time and Effort to License

Summary

The overall assessment is that SM-MSFR will require considerably more design and development effort than the SM-PWR Reference System and the timescales for commercial readiness will be correspondingly longer.

Assessed as 'Extreme Challenge'

Attributes

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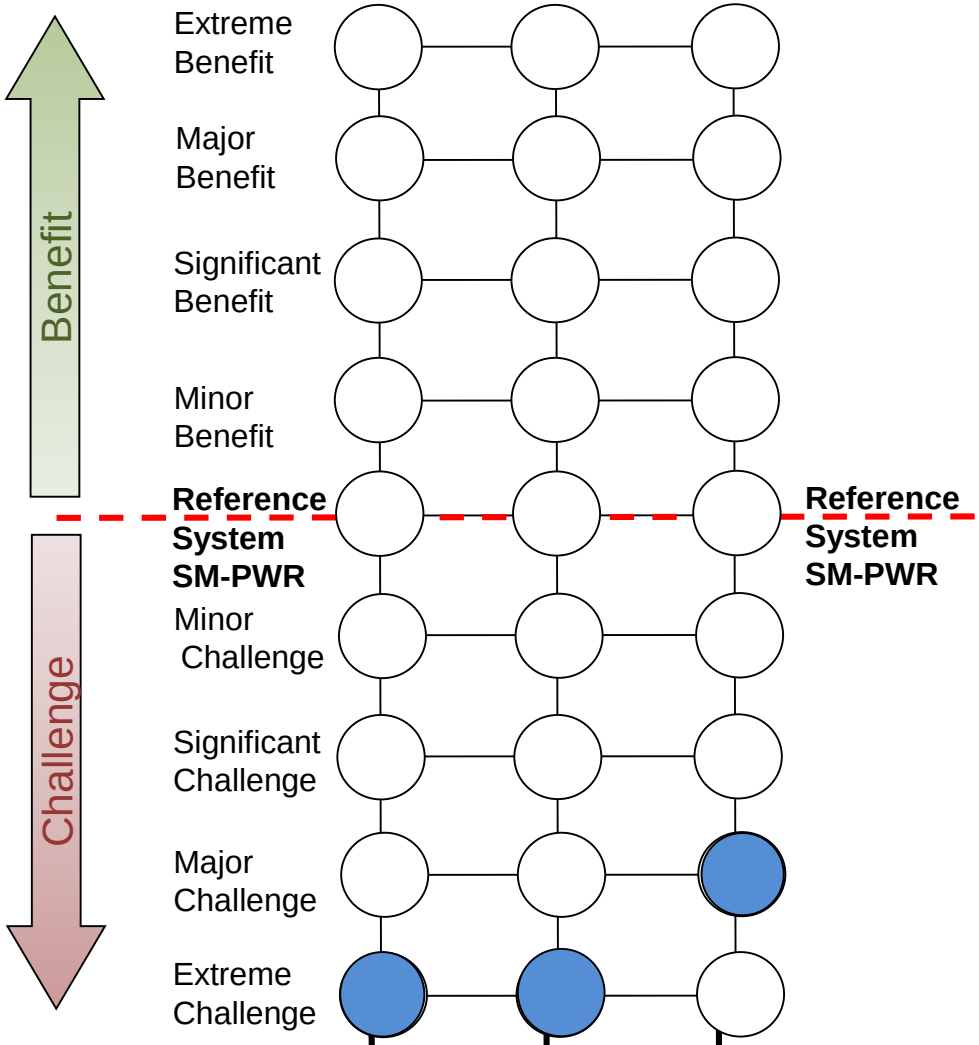
Description

1a. Time and Effort to License



1a.3 Effort to meet radiological regulations

1a.2 Timescale required to demonstrate that Safety Regulation Requirements can be satisfied

1a.1 Effort to satisfy Safety Regulation Requirements

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Description

1a. Time and Effort to License

Nuclear facilities in the UK are required to comply with the requirements set down by the appropriate regulatory bodies. Safety and licensing requirements are the responsibility of the Office of Nuclear Regulation (ONR), which also sets the radiological protection requirements for occupational exposure and members of the public.

Any reactor system to be deployed in the UK must be demonstrated to be safe, and to do so the reactor system must adhere to the fundamental safety principles as laid down by the licensing regulator. ONR has defined a series of Safety Assessment Principles known by the acronym 'SAPs'. These SAPs are seen as the top level goals which any system for deployment in the UK must be able to meet. The SAPs framework provides ONR with a set of guidelines by which ONR inspectors can make consistent judgements on nuclear safety assessment.

The top level safety criterion can be posed as: ***How much time and effort will be involved to allow the reactor system to meet the various UK safety regulatory requirements?***

From this top level criterion, the following attributes are obtained:

- ***Nuclear safety and regulation. What challenges must be met to enable the reactor system to meet well developed*** **Safety Regulation Requirements** ***(SAPs) (Button 1a.1)and on what timescale can such compliance be demonstrated? (Button 1a.2)***
- ***Radiological regulation. What challenges must be met to enable the reactor system to comply with the radiological dose limits defined by regulators for workers and members of the public? (Button 1a.3)***

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1a.1 Effort to satisfy Safety Regulation Requirements

Summary

SM-MSFR will require a long term design and development programme before it is ready for licensing. SM-MSFR has not been demonstrated at any level and is at a lower TRL than SM-MSRth.

Assessed as 'Extreme Challenge'

Metrics

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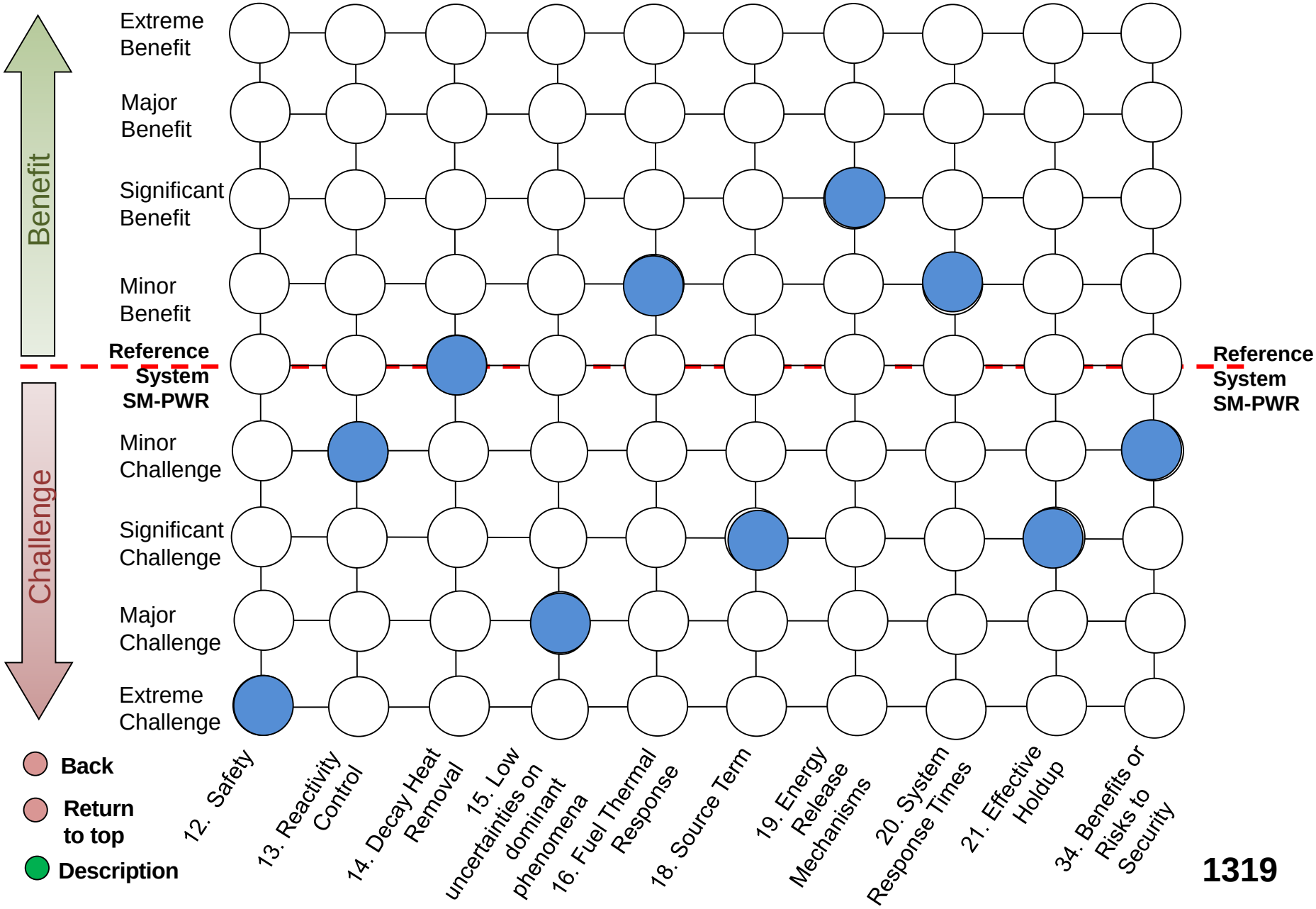
Description

References

GFA Assessment Subject System: SM-MSFR Reference System: Generic SM-PWR – *Work in Progress*

1a.1 Effort to satisfy Safety Regulation Requirements



1a.1 Effort to satisfy Safety Regulation Requirements

1a.1 assesses the challenge faced by a reactor system in meeting the goals defined by the Safety Regulation Requirements. Levels of challenge would be expected to increase as the system examined moves further away from current experience, for example:

- Systems which are already deployed commercially or whose designs are already licensed in other countries.
- Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.
- Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.
- Systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

Assessments will assume that regulatory effort is available when and as required

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12. Safety

The approach to constructing a safety case for SM-MSFR will necessarily be very different to those for a conventional solid fuel reactor. This is dictated by the fact that in an MSR the normal operating condition is with the fuel melted and therefore some of the barriers to release of fission products, actinides and activation products in a solid fuel reactor no longer apply. Although MSR designs are typically characterised by strong negative temperature feedback coefficients, un-pressurised systems, tolerance of high temperatures, large thermal inertias and passive decay heat removal, these features per se may not necessarily make the safety case easy to demonstrate. There will need to be extensive experimental test data available that will substantiate all aspects of the safety case. At present this database does not exist.

Assessed as 'Extreme Challenge'

12. Safety

Any new reactor system deployed in the UK would need to meet very stringent safety standards. Some of the systems considered will rely on passive safety and this might distinguish them from other systems that rely on conventional active safety systems.

12. Safety - references

Insert here

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13. Reactivity Control

The strong negative temperature feedback coefficients that are typical of MSRs are generally considered a favourable feature. However, the Reference SM-PWR also is characterised by strong negative temperature coefficients for most of its operating cycle, so in this sense the two systems are more similar than they might at first appear to be. Strongly negative feedback coefficients do not eliminate the need for two independent reactor shutdown systems and indeed the positive reactivity insertion on cool-down to shutdown conditions is made worse by strong negative feedback. Cooldown faults are also adversely affected.

Demonstrating adequate reactivity control is assessed to be a Minor Challenge on account of the novelty of SM-MSFR.

Assessed as 'Minor Challenge'

13. Reactivity Control

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. Shutdown means that the reactor must be demonstrated to be sub-critical (k-eff < 0.95), taking account of calculation uncertainties and one stuck control/shutdown rod with the reactor cooled to ambient temperature.

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.

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13. Reactivity Control - references

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14. Decay Heat Removal

The generic SM-MSFR is assumed to have passive decay heat removal, as does the Reference System. It is expected that a considerable amount of design and development effort, including test data will be needed to support the safety case for decay heat removal.

.

Assessed as 'Reference'

14. Decay Heat Removal

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. SM-MSFR would typically rely on passive decay heat removal, which is the same as the Reference System.

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.

14. Decay Heat Removal - references

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15. Low uncertainties on dominant phenomena

The safety behaviour of SM-MSFR is not demonstrated and therefore the dominant phenomena necessarily have large uncertainties.

Assessed as 'Major Challenge'

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Description

References

15. Low uncertainties on dominant phenomena

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.

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15. Low uncertainties on dominant phenomena - references

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16. Fuel Thermal Response

SM-MSFR would be expected to have a large thermal inertia on account of the mass and specific heat capacity of the molten salt, though possibly countered by a high power density. Compared with the Reference System, fuel thermal response times would be slower, which is beneficial.

Assessed as 'Minor Benefit'

16. Fuel Thermal Response

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.

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16. Fuel Thermal Response - references

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18. Source Term

The source term for an MSR is substantially different to that from a solid fuel reactor, since the fission products, actinides and fuel activation products are in the molten salt. The mobilities of the various radionuclide species in the molten salt under normal operating and fault conditions are uncertain and will need to be substantiated.

The source term for SM-MSFR will be lower than for conventional reactors if fission products are actively removed during operation, which may be a significant benefit. The equilibrium fission product inventory depends on the rate of fuel salt processing and the decontamination factors that are achievable. At present, fuel salt processing is at the conceptual design stage and it is too soon to know what is achievable. Different fission products may achieve different equilibrium levels, if the decontamination factors vary. This will certainly apply to gaseous fission products. There is a tendency to focus on the fission product equilibrium inventories in the core and this potentially overlooks the fact that the fission products will still be physically present at the reactor site and therefore there will retain their hazard potential.

The timescale and effort required to substantiate the Source Term leads to the assessment of Significant Challenge, despite there potentially being a significant performance benefit.

Assessed as 'Significant Challenge'

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Description

References

18. Source Term

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.

18. Source Term - references

Insert

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19. Energy Release Mechanisms

The fuel salt is relatively inert and not vulnerable to oxidative reactions.
This is an area where SM-MSFR ranks highly compared with conventional reactors because of the absence of fuel cladding that can undergo energetic oxidation.

Assessed as 'Significant Benefit'

19. Energy Release Mechanisms

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.

19. Energy Release Mechanisms - references

Insert

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20. System response times

The system response for SM-MSFR depends on the specific rating, which in some designs may be higher than LWR. A large mass of fuel salt in a pool-type arrangement would increase system response times. This suggests fuel thermal response times somewhat larger than LWRs, but with high specific ratings extended thermal response times cannot be expected.

Assessed as 'Minor Benefit'

20. System response times

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.

20. System response times - references

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21. Effective Holdup

This refers to the holdup of volatile fission products in accident scenarios. The containment for SM-MSFR will differ considerably compared with conventional reactors and the uncertainties associated with holdup calculations will require extensive integral systems testing.

Assessed as 'Significant Challenge'

21. Effective Holdup

Effective hold-up refers to mechanisms in the design of a plant for containing radioactive material following an accident condition. The hold-up of volatile fission product will impact the containment design will affect whether there is a requirement for off-site evacuation procedures to be in place.

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21. Effective Holdup - references

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34. Benefits or challenges for security

In SM-MSFR the molten fuel salt, either in the reactor or in the associated fuel cycle plant, is in principle more vulnerable to fissile material diversion than a solid fuel form. Therefore inherent self-protection might be considered to be reduced relative to the Reference System. Security requirements will not be affected by considerations of inherent self-protection.

Assessed as 'Minor Challenge'

34. Benefits or challenges for security

Inherent Proliferation Resistance and Proliferation Protection PRPP is an area which needs to be assessed for new reactor systems according with best practice set out by IAEA INPRO and GIF. The threats considered are diversion of fissile material by a state and acquisition of radioactive materials by an illegal sub-national group. Both threats are considered by OCNS as part of defining the security and safeguards requirements and these requirements are not affected in inherent PRPP. Inherent PRPP is simply to be regarded as a fall-back protective feature that would apply in the hypothetical case of a nuclear system falling outside national controls.

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34. Benefits or challenges for security - references

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1a.2 Timescale required to demonstrate that Safety Regulation Requirements can be satisfied

In the UK the Generic Design Approval (GDA) process is new and only EPR has been through it in its entirety. The process for EPR took almost 6 years, but the experience gained should allow future LWRs to gain approval within 4 years or so. ONR already had expertise in PWR safety assessment and this must have been helpful for the GDA. For MSR there is currently no expertise within ONR. ONR would require an application for a GDA from an MSR designer before building up an assessment team. It is unlikely that the GDA process would be as straightforward as EPR because the safety case approach will be substantially different to conventional reactors and may require a reinterpretation of the Safety Assessment Principles.

A reasonable expectation might be that the SM-MSFR designer would already have developed the design and safety justification to a very mature stage before applying for GDA, with a significant amount of development testing having already taken place to support the design and safety justification. Given the immature present state of design, this is not considered likely in less than 45 years including build and operation of the prototype. Assuming a minimum 5 years for ONR to assess the design and 5 years' build time, this leads to a minimum timescale of 55 years for commercial deployment of SM-MSFR. The Gen IV MSFR project also quotes 2070 as the expected deployment date.
.

Assessed as 'Extreme Challenge'

1a.2 Timescale required to demonstrate that Safety Regulation Requirements can be satisfied

1a.2 assesses how long it might reasonably be expected to take to demonstrate that the system can satisfy stringent Safety Regulation Requirements**.** Levels of challenge would be expected to increase as the system examined moves further away from current experience, for example:

- Systems which are already deployed commercially or whose designs are already licensed in other countries.
- Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.
- Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.
- Systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

Assessments will assume that regulatory effort is available when and as required

Back

1a.2 Timescale required to demonstrate that SAPs can be satisfied - references

Insert

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1a.3 Effort to meet radiological regulations

In the absence of engineered designs, it is not possible at this stage to assess the ability of SM-MSFR to meet radiological regulations. There are likely to be major challenges with maintenance of primary circuit components (moderator, pumps, valves and heat exchangers) which will be highly contaminated with fission products and will need to be engineered for remote inspection and maintenance. Radiological doses in the gas and solid fission product processing plants will also need to be addressed, as will doses in the plants used to condition and dispose of the fuel salt.

.

Assessed as 'Major Challenge'

Metric - 11. Worker Exposures

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Description

References

1a.3 Effort to meet radiological regulations

1a.3 assesses the difficulty likely to be experienced in meeting the worker radiological protection requirements defined by regulators, noting that this includes the reactor and its fuel cycle. Levels of challenge would be expected to increase as the system examined moves further away from current experience, for example:

- Systems which are already deployed commercially or whose designs are already licensed in other countries.
- Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.
- Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.
- Systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

Assessments will assume that regulatory effort is available when and as required

1a.3 Effort to meet radiological regulations - references

Insert

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11. Worker Exposures

It is difficult to assess worker exposures for SM-MSFR because none of the proposed designs have yet been developed to the stage where detailed understanding of the maintenance requirements and dose uptake is available. Given that SM-MSFR deviates considerably from solid fuel reactors and the large radionuclide inventories in the fuel salt in the primary circuit, this is assessed as posing a Major Challenge.

Assessed as 'Major Challenge'

11. Worker Exposures

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.

11. Worker Exposures - references

Insert

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1b. Time and Effort for Environmental Permitting

Summary

SM-MSFR is assessed to require considerable further design and development in order to be able to satisfy environmental permitting requirements.

Assessed as 'Major Challenge'

Attribute – 1b.1 Effort to meet environmental regulations

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Description

References

1b. Time and Effort for Environmental Permitting

Nuclear facilities in the UK are required to comply with the requirements set down by the appropriate regulatory bodies. Environmental regulations are the responsibility of the Environment Agencies (EA, NRW, SEPA, Natural Resources Wales) and are implemented through the granting of site aerial and liquid Discharge Authorisations. The Environment Agencies are also responsible for the authorisation of solid waste disposal.

1b. Time and Effort for Environmental Permitting - References

Insert

1b.1 Effort to meet environmental regulations

It is too soon to judge whether SM-MSFR and its associated fuel cycle will be able to meet environmental regulatory requirements. MSR represents a major departure from solid fuel experience and environmental discharge routes for gases are insufficiently understood.

With respect to doses to the workforce, it is likely that small modular SM-MSFR will display substantial differences. The details will be design specific and currently none of the proposed small modular LWR designs are likely to be mature enough for this requirement to be addressed.

Assessed as 'Major Challenge'

Metric – 06 Environmental Impact

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Description

References

1b.1 Effort to meet environmental regulations

1b.1 assesses the challenge faced by a reactor system in meeting the environmental impact requirements defined by the regulators, noting that this includes the reactor and its fuel cycle. This parameter is assumed to refer to routine operational environmental discharges. Levels of challenge would be expected to increase as the system examined moves further away from current experience, for example:

- Systems which are already deployed commercially or whose designs are already licensed in other countries.
- Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.
- Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.
- Systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

Assessments will assume that regulatory effort is available when and as required

1b.1 Effort to meet environmental regulations - references

Insert

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06. Environmental Impact

It is too soon to know if SM-MSFR and its associated fuel cycle plants are capable of meeting environmental regulations. In terms of discharges to the environment and doses to members of the public, the proposed are not yet developed to the point where discharges can be reliably estimated.

Assessed as 'Major Challenge'

06. Environmental Impact

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.

06. Environmental Impact - references

Insert

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1c. Proliferation Resistance and Physical Protection (PRPP) Acceptability

Summary

The once-through LWR fuel cycle is internationally recognised as the reference system for inherent PRPP assessments. Given that the fuel form of SM-MSFR makes access to fissile material and other radioactive materials potentially more accessible than spent fuel from solid fuel reactors, there is the potential for the inherent PRPP performance to be less favourable.

PRPP is taken to have a dual meaning, with Proliferation Resistance referring to state involvement in diversion of fissile materials and Physical Protection concerned with the threat of acquisition of nuclear materials by a sub-national group. The assessments are potentially different for the two aspects.

Assessed as 'Significant Challenge'

Attributes

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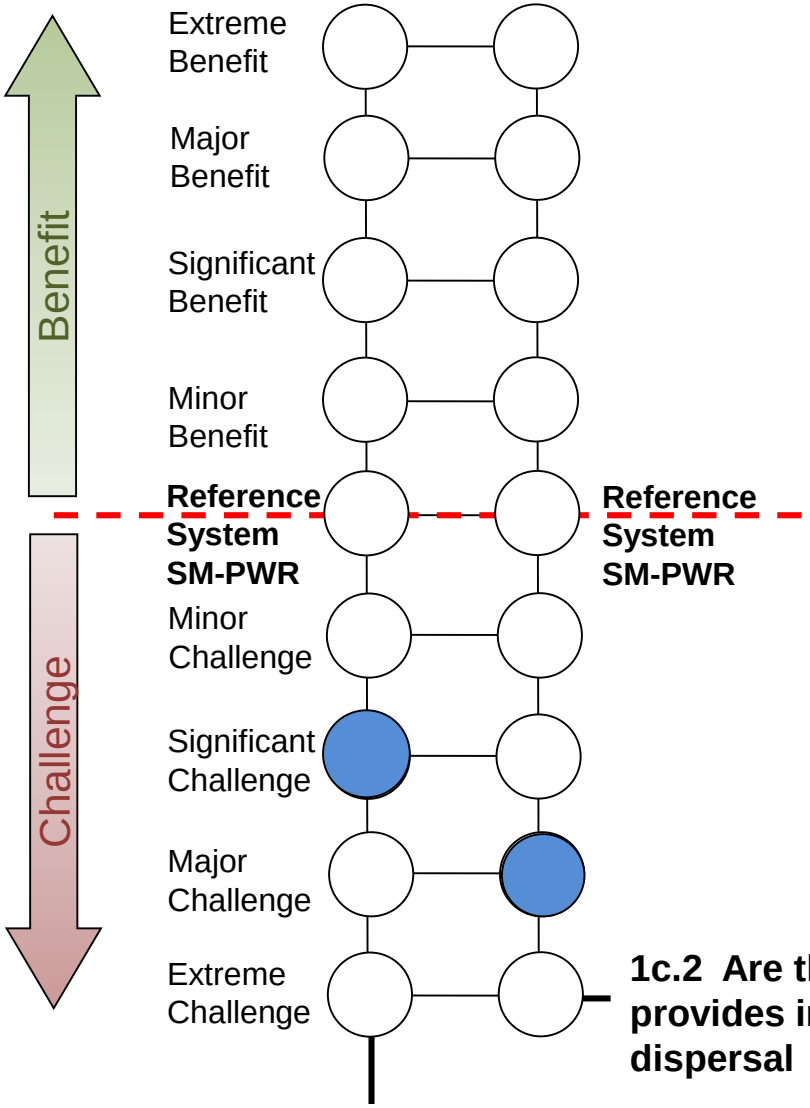
Description

1c. Proliferation Resistance and Physical Protection (PRPP) Acceptability



1c.2 Are the nuclear materials in a form that provides inherent self-protection against theft or dispersal

1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage

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1c. Proliferation Resistance and Physical Protection (PRPP) Acceptability

Any new system deployed in the UK will be required to satisfy the Nuclear Industries Security Regulations 2003. This is a system which responds to the nuclear processes being carried out and the amount and form of nuclear materials being used, and ensures that a system is in place which will “prevent the theft or sabotage of nuclear material or the sabotage of nuclear facilities”. The Office of Civil Nuclear Security (OCNS) is the responsible regulator.

UK situation is that, while systems may not accord with the ideals of PRPP, yet there are systems, monitored and enforced by OCNS, which ensure risks of theft or sabotage are maintained at acceptably low levels. Thus while it is highly relevant to monitor the PRPP characteristics of nuclear reactor systems, the value of this Attribute in the UK context is predominantly to be judged by policy makers. The assessment will, however, give an indication of the challenges to be met in order to generate an approved Security Plan for the candidate system.

The top level PRPP criterion can be posed as: *“Are the nuclear materials produced in the fuel cycle difficult to access?”*

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1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage

Depending on the specific fuel cycle SM-MSFR may produce separated fissile material by irradiation of fertile material, which is unfavourable relative to the once-through LWR fuel cycle.

Assessed as 'Significant Challenge'

Metrics

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Description

References

1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage

This attribute accounts for the physical forms of fissile materials in the fuel cycle. The levels of challenge will vary between:

Fuel cycles in which high grade fissile materials are present at any stage, for example high enriched uranium (HEU) or plutonium, which will be considered to present considerable PRPP challenges. Examples would include a fuel cycle based on HEU fuel or the separation of pure plutonium for recycle (as in conventional PUREX reprocessing).

A LWR fuel cycle with low enriched uranium (LEU) and a once-through fuel cycle will present a lower level of PRPP challenge.

Back

1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage - references

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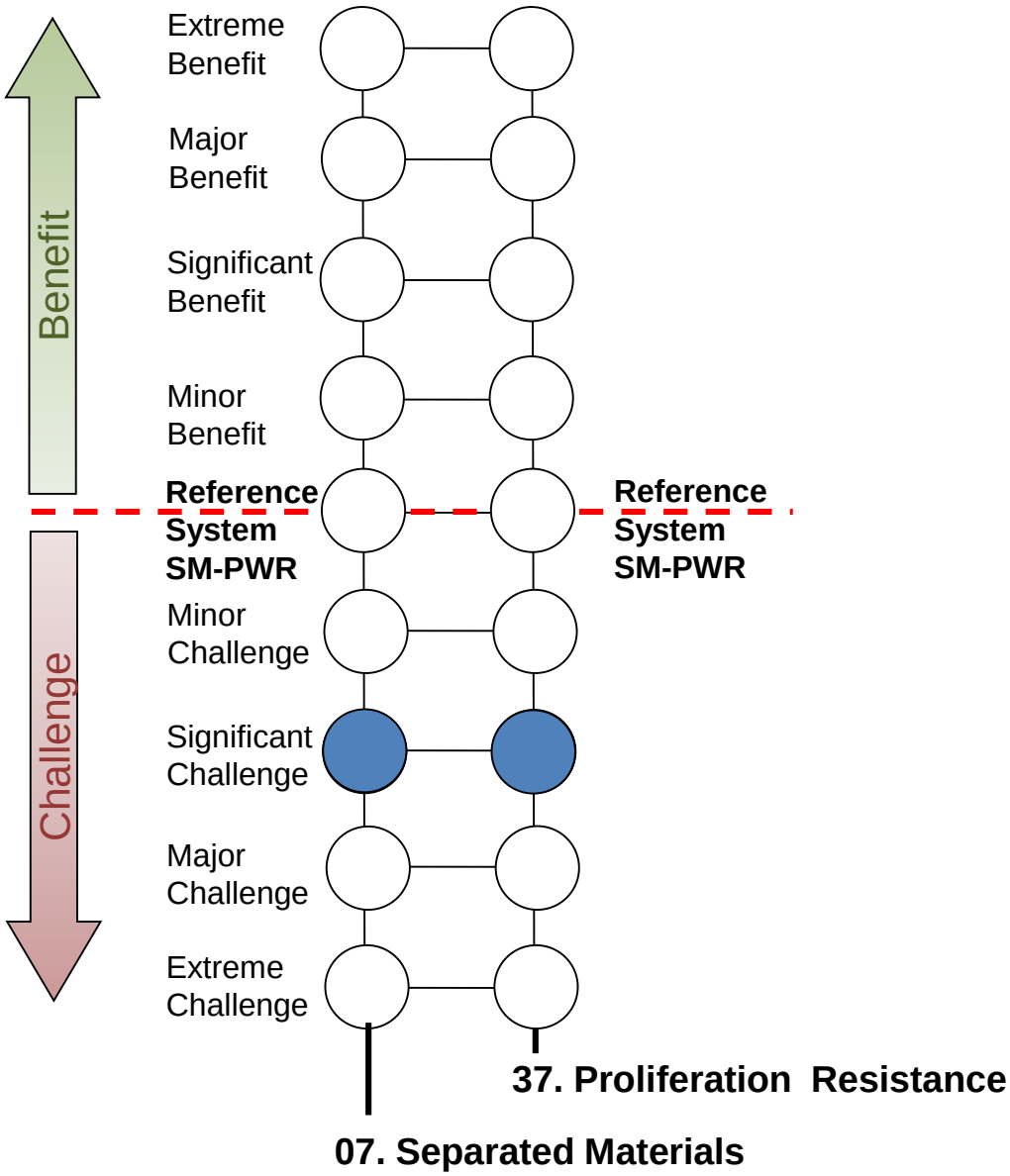
1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage



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07. Separated Materials

Depending on the specific fuel cycle SM-MSFR may produce separated fissile material by irradiation of fertile material, which is unfavourable relative to the once-through LWR fuel cycle. SM-MSFR is assumed to separate fissile material in the breeder blanket.

Assessed as 'Significant Challenge'

07. Separated Materials

One of the PRPP goals of advanced systems is that they 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.

07. Separated Materials - references

Insert

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37. Proliferation Resistance

The once-through LWR fuel cycle is internationally recognised as the reference system for inherent PRPP assessments. Given that the fuel form of SM-MSFR makes access to fissile material and other radioactive materials potentially more accessible than spent fuel from solid fuel reactors, there is the potential for the inherent PRPP performance to be less favourable. The assumption of full-scope reprocessing creates the potential for diversion/theft of nuclear materials and is unfavourable for PRPP.

Assessed as 'Significant Challenge'

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Description

References

37. Proliferation Resistance

There is increasing interest in international reactor systems development to be able to demonstrate increased proliferation resistance by design, and different reactor systems may be considerably differentiated by inherent proliferation resistance. 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. SM-MSFR fuel comprises molten salt where the fissile material is relatively easily separated in an on-line reprocessing plant.

37. Proliferation Resistance – references

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1c.2 Are the nuclear materials in the fuel cycle in a form which provides inherent self-protection against theft or dispersal

The nuclear materials from a SM-MSFR may potentially be in a form which offers substantially less self-protection than the LWR once-through fuel cycle. Depending on the fuel cycle adopted, SM-MSFR may produce separated U-233. Although the U-233 would be expected to be contaminated with U-232, the daughter products of which produce a strong gamma emitter. However, the radiation field so produced, although too intense to allow unshielded handling in a licensed fuel cycle plant, would be insufficient to result in rapid incapacitation in a scenario where a sub-national group attempted to acquire fissile material without shielding measures.

Assessed as 'Major Challenge'

Metrics

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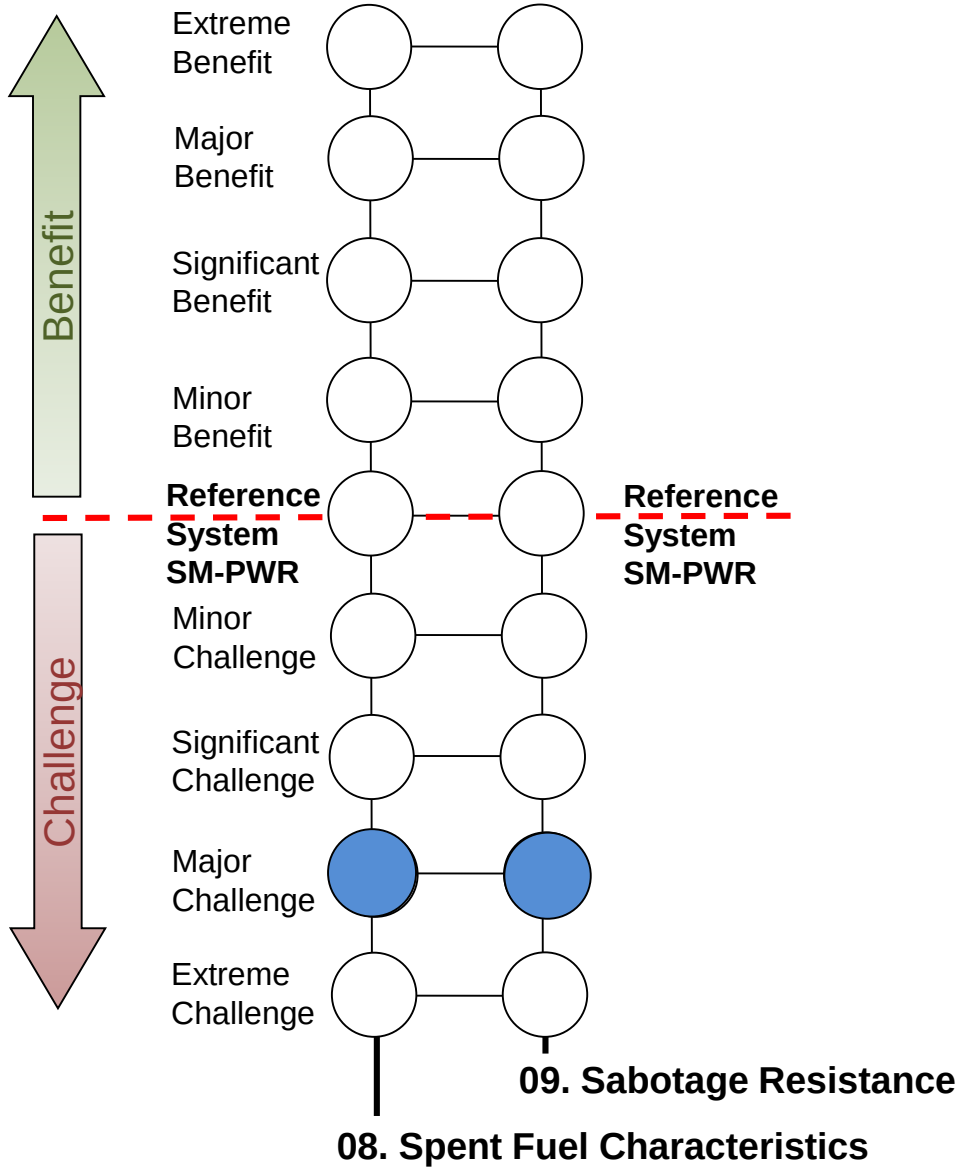
Description

References

1c.2 Are the nuclear materials in the fuel cycle in a form which provides inherent self-protection against theft or dispersal



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Description

1c.2 Are the nuclear materials in the fuel cycle in a form which provides inherent self-protection against theft or dispersal

1c.2 (Inherent PRPP). This attribute tests whether nuclear material is inherently protected by physical or chemical form, or by a strong self-protective radiation field. It is also intended to test whether the material is in a form that could be readily dispersed. Illustrations of levels of challenge are:

- a once-through fuel cycle with uranium oxide fuel in which there are multiple inherent barriers to accessing fissile material.
- fuel cycles which involve the production at some stage of unirradiated HEU fuel or plutonium oxide powder which present no inherent barriers.

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1c.2 Are the nuclear materials in the fuel cycle in a form which provides inherent self-protection against theft or dispersal - references

Insert

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08. Spent fuel characteristics

In SM-MSFR spent salt may require interim storage, transport, immobilisation and disposal. MSR designs to date have not reached the stage of maturity where detailed design consideration of spent fuel salt management has been made. Pyro-processing technology is at a low stage of technology readiness. Detailed assessment of potential immobilisation forms for spent fuel salt will be required.

Assessed as 'Major Challenge'

08. Spent fuel characteristics

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. SM-MSFR fuel comprises molten salt where the fissile material is in principle relatively easily separated in an on-line reprocessing plant.

08. Spent fuel characteristics - references

Insert

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09. Sabotage resistance

A detailed design assessment of the vulnerability of SM-MSFR to sabotage/missile attack will need to be made. The designs currently proposed are not at the stage where such an assessment can be made. By nature, fuel salt is very different to solid fuel reactors and this is assessed as posing a Major Challenge.

Assessed as 'Major Challenge'

09. Sabotage resistance

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 but in some of the systems, for example small modular PWRs, the nuclear island is largely sited underground and therefore exceptionally well protected.

09. Sabotage resistance - references

Insert

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2a. Economic Competitiveness

Summary

Although SMRs have the theoretical potential to improve economic competitiveness, there are some significant challenges that will need to be addressed. SM-MSFR are likely be penalised by historic scaling laws that favour large plants and will need to rely on new compensating mechanisms, such as cost savings from factory replication, lower risk financing and more favourable grid connection charges. In the absence of evidence to the contrary, SM-MSFR is assumed subject to the same scaling laws as the SM-PWR reference system. SM-MSFR is assessed at different levels for economic competitiveness, with R&D costs penalising it, which leads to an overall assessment as Major Challenge.

Assessed as 'Major Challenge'

Attributes

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Description

2a. Economic Competitiveness

The electrical generation cost is one of the principal criteria against which a nuclear system will be assessed – without a demonstrably economically competitive system, utilities are unlikely to invest.

The top level economics Attribute can be posed as: *Will the reactor system be economically competitive in the electricity generation market or in possible future heat generation markets?*

From this Strategic Attribute, the following Criteria are obtained:

Overnight construction cost. The cost of building and financing the nuclear system, usually expressed as £/MWe.

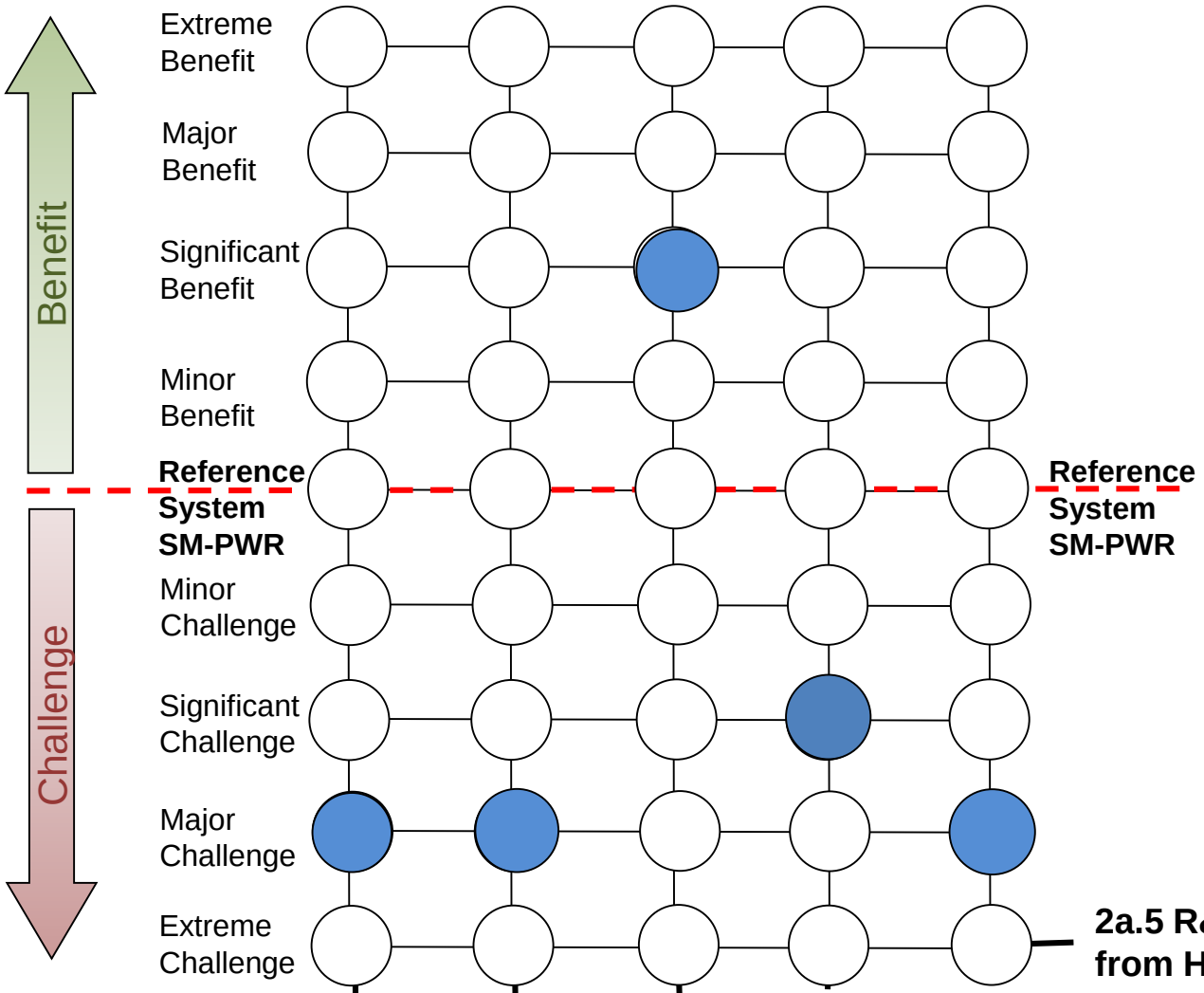
Operating and maintenance cost: This is the cost of operating and maintenance (O&M), taken to include staffing costs, operating costs (excluding fuel), the cost of routine maintenance and other related costs, usually expressed as a levelised cost in £/MWh.

Fuel cycle cost: This criterion is intended to capture the cost of operating the fuel cycle, both procuring new fuel and all the back-end costs associated with spent fuel management or reprocessing/recycle, usually expressed as a levelised cost in £/MWh.

Decommissioning cost: This is the actual cost of decommissioning *without* applying financial discounting, expressed as £/MWe.

R&D cost: This is the cost of the research and development programme needed to bring a system to commercial readiness. This will generally be an infeed into this attribute from High Level Discriminator 1 – Regulatory Challenges and Timescales.

2a. Economic Competitiveness



2a.5 R&D cost – feed from HLD1

2a.4 Decommissioning cost

2a.3 Fuel cycle cost – front and back end combined

2a.2 Operating and Maintenance cost

2a.1 Overnight construction cost

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Description

2a1. Overnight construction cost

For SMR generally there is an economy of scale penalty (for which there is a consensus), but with potential for savings from replication, factory build and increased modularisation. There is also the Potential for first module to finance later modules but note need for common infrastructure to be in place for the first module.

SM-MSFR is considered equivalent to the SM-PWR Reference System in this respect, with no evidence available that there will be different scaling laws on account of the design differences. However, the requirement for a secondary salt circuit in SM-MSFR takes the assessment to Significant Challenge. The need for on-line reprocessing facilities further adds to the overnight construction cost. Although SM-MSFR has an unpressurised primary circuit vessel, the vessel will nevertheless need to meet a very high standard of containment, which may require a second vessel.

Assessed as 'Major Challenge'

Metrics

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Description

References

2a.1 Overnight construction cost

2a.1 (Overnight construction cost). The cost of building and financing the nuclear system, usually expressed as £/MWe. This attribute is the cost of construction and of financing construction, usually taken as the overnight construction cost with all financing costs discounted to the date at which the plant becomes operational. Included in this context, is the construction cost of any fuel cycle plants needed for fuel reprocessing, recycle or waste management. Illustrations of levels of challenge are:

- Plants with a high degree of modularisation and short construction times.
- Plants with a limited degree of modularisation and moderate construction times. This might apply to current large PWRs operating a once-through fuel cycle, for example.
- Complex plants with long and difficult construction demands. This might apply to systems involving extensive reprocessing and recycle.

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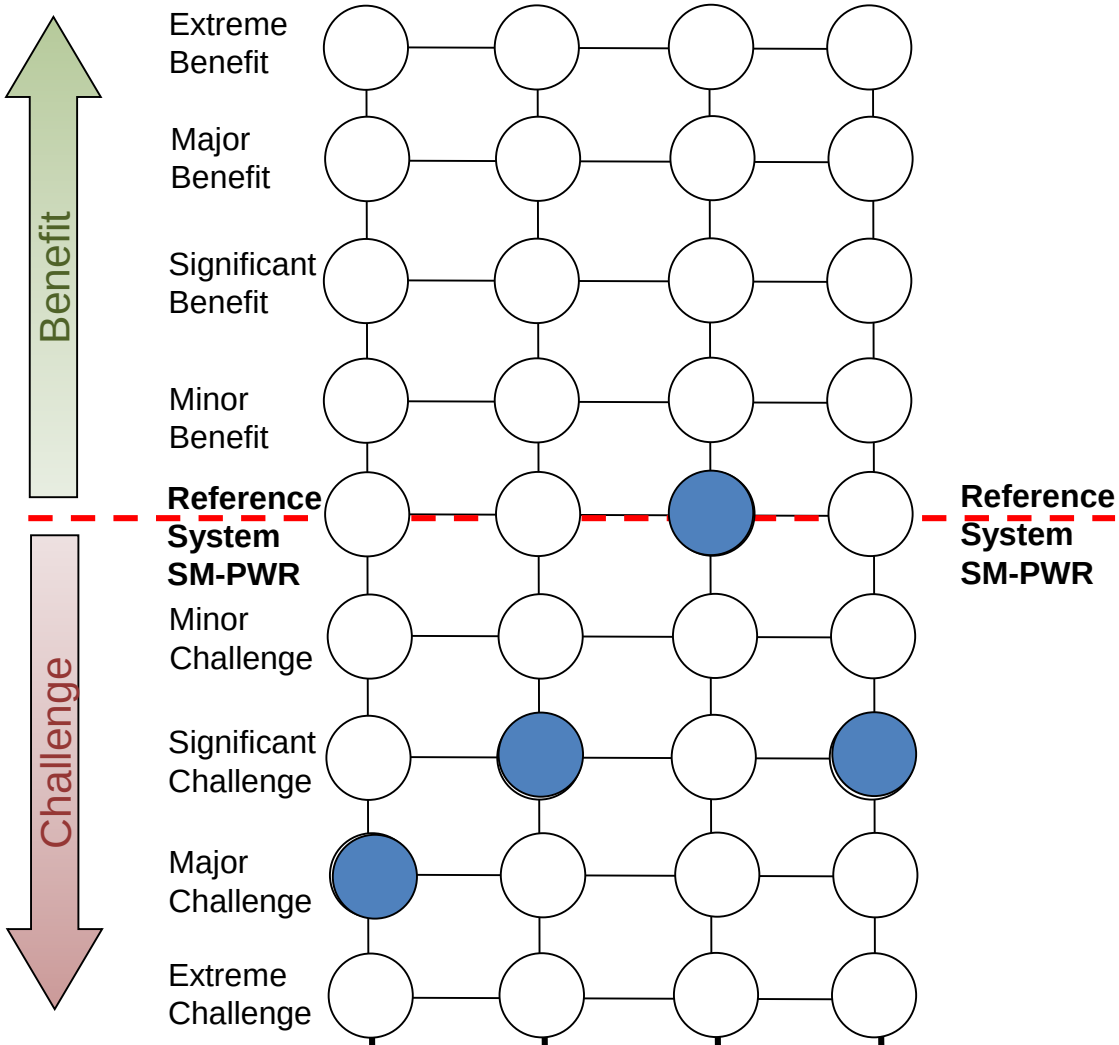
2a.1 Overnight construction cost



34. Ease of Construction

29. Scaleability

24. Construction Duration

22. Overnight construction cost

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Description

22. Overnight construction cost

For SMR generally there is an economy of scale penalty (for which there is a consensus), but with potential for savings from replication, factory build and increased modularisation. There is also the Potential for first module to finance later modules but note need for common infrastructure to be in place for the first module.

SM-MSFR is considered equivalent to the SM-PWR Reference System in this respect, with no evidence available that there will be different scaling laws on account of the design differences. The requirement for a secondary salt circuit takes the assessment to Significant Challenge. The need for on-line reprocessing facilities further adds to the overnight construction cost.

Assessed as 'Major Challenge'

22 Overnight construction cost

22 (Overnight construction cost). The cost of building and financing the nuclear system, usually expressed as £/MWe. This attribute is the cost of construction and of financing construction, usually taken as the overnight construction cost with all financing costs discounted to the date at which the plant becomes operational. Included in this context, is the construction cost of any fuel cycle plants needed for fuel reprocessing, recycle or waste management. Illustrations of levels of challenge are:

- Plants with a high degree of modularisation and short construction times.
- Plants with a limited degree of modularisation and moderate construction times. This might apply to current large PWRs operating a once-through fuel cycle, for example.
- Complex plants with long and difficult construction demands. This might apply to systems involving extensive reprocessing and recycle.

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22. Overnight construction costs - references

None of the SM-MSFR designs currently being developed have reached the stage where there is a detailed breakdown of construction costs.

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24. Construction duration

Short construction times reduces finance cost and risk with theoretically lower £/kWe. SM-MSFR designs currently being developed are not yet at the stage where short construction times are demonstrated. The goal of achieving short construction times can be considered no more than an aspiration at present. SM-MSFR is assessed as Significant Challenge compared with the generic SM-PWR because the plant layout is judged to be more complex on account of the requirement for a secondary circuit that would make short construction times more difficult to achieve.

Assessed as 'Significant Challenge'

24. Construction duration

The duration of plant construction has already been discussed under Item 22 (overnight construction cost) and the same assessment applies.

References

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24. Construction duration - references

Insert here

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29. Scaleability

Better fit to small grid systems. Not applicable to current UK grid. SM-MSFR is regarded equivalent to the SM-PWR Reference System in this respect.

Assessed as 'Reference'

29. Scaleability

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.

29. Scaleability - references

Insert

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34. Ease of Construction

Potential for SM-MSFR to reduce finance costs through lower risk in exactly the same way as the SM-PWR Reference System. Although SM-MSFR has an unpressurised primary circuit vessel, the vessel will nevertheless need to meet a very high standard of containment, which may require a second vessel and the assessment is that ease of construction is equivalent to the SM-PWR Reference. SM-MSFR is assessed as Significant Challenge compared with the generic SM-PWR because the plant layout is judged to be more complex on account of the requirement for a secondary circuit that would make short construction times more difficult to achieve

Assessed as 'Significant Challenge'

34. Ease of Construction

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.

34. Ease of Construction - references

Insert here

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2a.2 Operating and maintenance cost

Economy of scale penalty potentially offset by reduced maintenance requirements . Minimum manning level agreed with regulator a potential issue.
Grid connection cited as an area where SMRs can be beneficial, but not demonstrated. Operating and maintenance costs are potentially very challenging for SM-MSFR with active fuel salt potentially causing heavy contamination of the primary circuit. SM-MSFR is therefore assessed as a Major Challenge compared with SM-PWR Reference System.

Assessed as 'Major Challenge'

Metrics

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Description

References

2a.2 Operating and maintenance cost

This Attribute covers the cost of operating and maintenance, taken to include staffing costs, operating costs (excluding fuel), the cost of routine maintenance and other related costs. Illustrations of levels of O&M costs are:

- Plants such as LWRs with long operating lives and no requirement for mid-life refurbishment of major plant items
- Plants with a requirement for through-life replacement of major components
- Complex plants with difficult operational requirements

2a.2 Operating and maintenance cost - references

None of the SM-MSFR designs currently being developed have reached the stage where there is a detailed breakdown of O&M costs.

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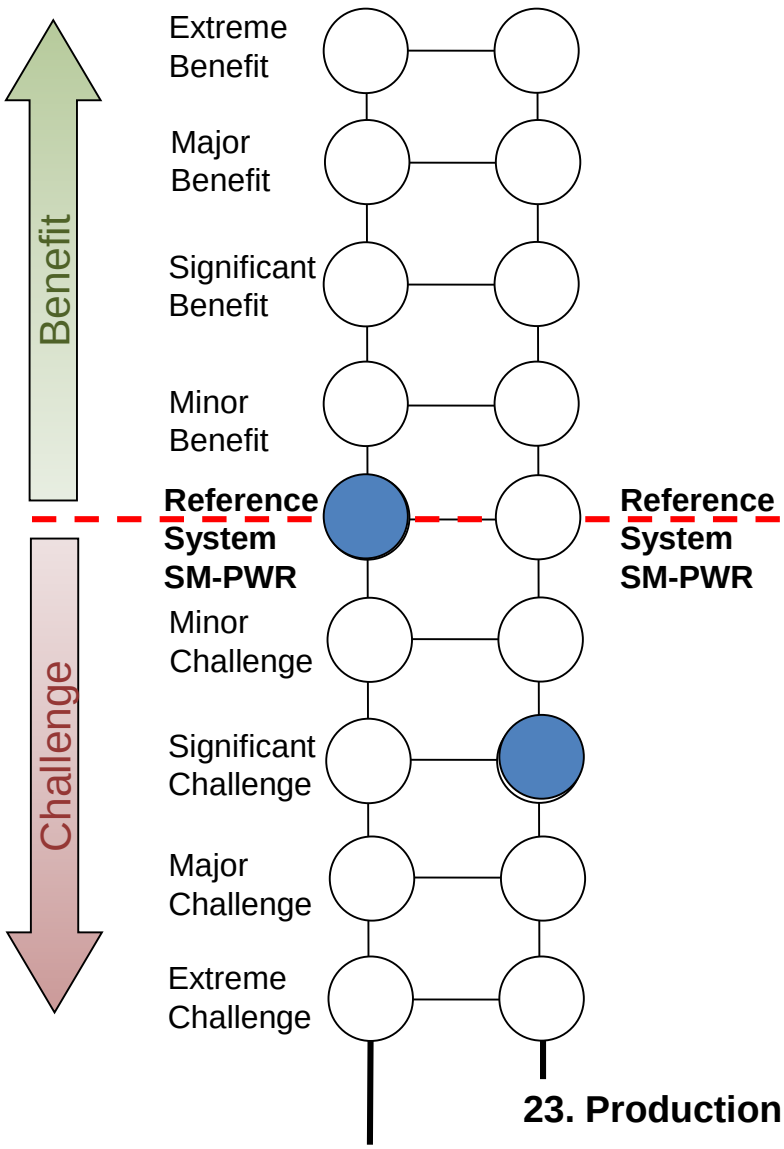
2a.2 Operating and maintenance cost



23. Production costs (O&M)

10. Reliability

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10. Reliability

Potential reduction in grid connection charge due to smaller loss of capacity from a single unit. But risk of loss of capacity of entire power station from common factors (eg loss of grid connection) unaffected. SM-MSFR equivalent to Reference SM-PWR Reference System in this respect.

Assessed as 'Reference'

10. Reliability

This is the forced outage rate, which should be very low. It is an operational safety and reliability issue, but it is also important for economics. Best operational practice at modern PWRs 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.

10. Reliability - references

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23. Production costs (O&M)

Economy of scale penalty potentially offset by reduced maintenance requirements .
Minimum manning level agreed with regulator a potential issue.
Grid connection cited as an area where SMRs can be beneficial, but not demonstrated.
It will be necessary inspect and maintain highly active primary circuit components and therefore SM-MSFR assessed as Significant Challenge compared with SM-PWR Reference System.

Assessed as 'Significant Challenge'

23. Production costs (O&M)

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. SM-MSFR is assumed penalised relative to the SM-PWR Reference System on account of the need for inspection and maintenance of highly active primary circuit components.

23. Production costs (O&M) - references

None of the SM-MSFR designs currently being developed have reached the stage where there is a detailed breakdown of O&M costs.

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2a.3 Fuel cycle costs (front and back-end combined)

SM-MSFR designs will operate with continuous fission product removal and fissile top-up leading to reduced spent fuel throughput. This is an advantage over the SM-PWR Reference System taken to use a multi-batch refuelling scheme.

Assessed as 'Significant Benefit'

2a.3 Fuel cycle costs (front and back-end combined)

2a.3 (Fuel cycle cost). This attribute is intended to capture the cost of operating the fuel cycle, both procuring new fuel and all the back-end costs associated with spent fuel management or reprocessing/recycle. Illustrations of varying levels of challenge with choice of fuel cycle are:

- the once-through LWR fuel cycle
- the closed LWR fuel, cycle (i.e. thermal recycle)
- a fast reactor system with recycle, especially if there was recycle of minor actinides.

2a.3 Fuel cycle costs (front and back-end combined) - references

Insert

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2a.4 Decommissioning costs

41. Decommissioning costs

No information available on decommissioning. But with active fuel salt to be managed at reactor closure, assumed a significant challenge compared with SM-PWR Reference System.

Assessed as 'Significant Challenge'

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Description

References

2a.4 Decommissioning costs

41. Decommissioning costs

2a.4 (Decommissioning cost). This attribute is intended to represent the actual cost of decommissioning without applying financial discounting. The decommissioning cost represents a significant risk element in financial analysis, even though the discounted cost is usually very low. Levels of challenge are illustrated by:

- A nuclear system with small, modular components compatible with disposal as self-contained units.
- Current LWRs where, after defueling, there are only medium active components that need to be decommissioned in the core.
- Systems with graphite moderation, such as the UK's legacy gas cooled reactors, due to the need to deal with large masses of material.

2a.4 Decommissioning costs - references

41. Decommissioning costs

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2a.5 R&D cost

R&D costs for SM-MSFR will be significant, since many aspects are currently at a very low Technology Readiness Level (TRL). The time and effort needed for R&D is much higher than the SM-PWR Reference System.

Assessed as 'Major Challenge'

Metrics

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Description

References

2a.5 R&D cost

This Attribute covers the cost of the research and development programme needed to bring a system to commercial readiness. Illustrations of levels of R&D cost are:

- Those associated with an existing system or a minor development of an existing system
- Those associated with the evolution of a current system
- Those associated with novel systems involving significant innovations and long and extensive R&D

2a.5 R&D cost - references

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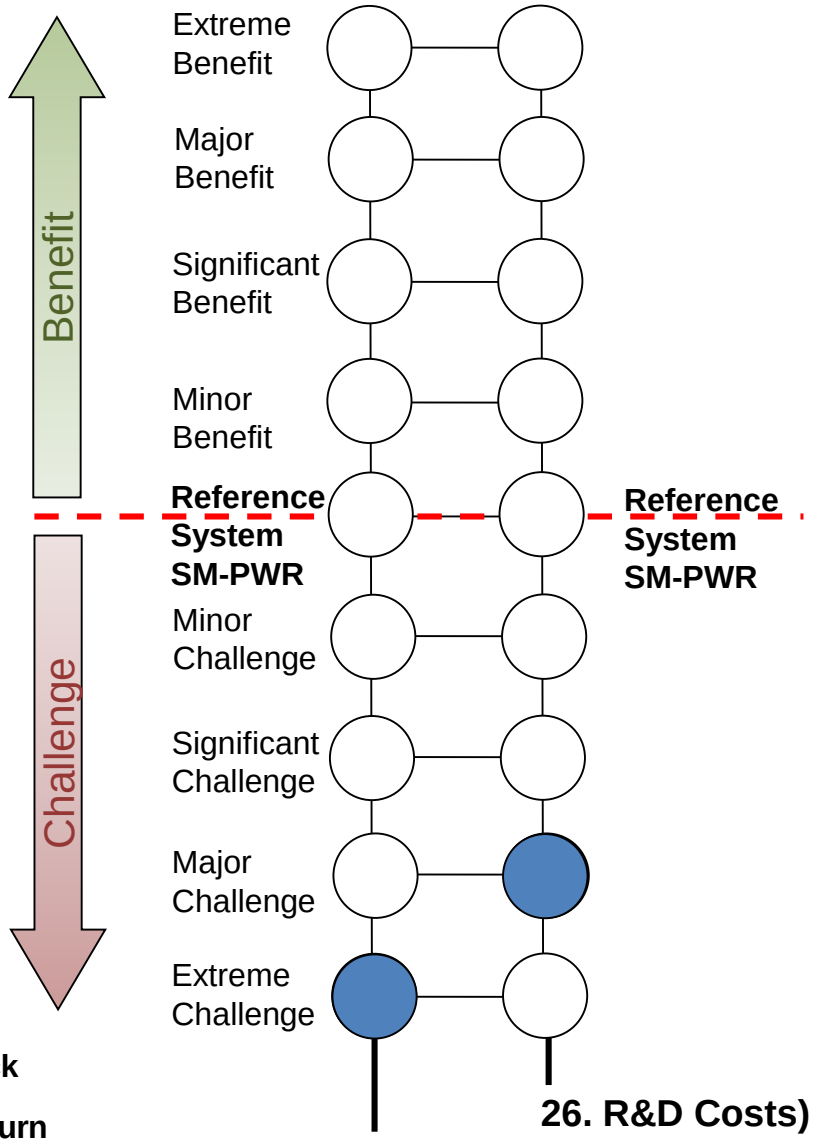
2a.5 R&D cost



26. R&D Costs)

17. Integral experiment scaleability

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17. Integral experiment scaleability

Integral experiment data for SM-MSFR does not exist. This represents an Extreme Challenge relative to the SM-PWR Reference System.

Assessed as 'Extreme Challenge'

17. Integral experiment scaleability

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.

17. Integral experiment scaleability - references

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26. R&D costs

R&D costs for SM-MSFR will be significant, since many aspects are currently at a very low Technology Readiness Level (TRL). The time and effort needed for R&D is much higher than the SM-PWR Reference System.

.

Assessed as 'Major Challenge'

26. R&D costs

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. However, if the UK was to buy into technology that was not being developed elsewhere, the UK could incur the R&D costs and risks.

26. R&D costs - references

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3a. Fuel Security

Summary

With a U-Pu or Th-232/U-233 fuel cycle SM-MSFR could in principle operate with a breeding cycle. SM-MSFR is assumed to operate with full scope reprocessing, with gas extraction, fission products extracted on-line, fissile material extracted from the breeder blanket and inserted in the core and fertile material top-up in the blanket. The system could operate independent of the world uranium market, which is beneficial for fuel security. Also, the fuel form does not require fuel assembly fabrication and so is less tied to specific fuel vendors. This is assessed as a Major Benefit.

Assessed as 'Major Benefit'

Attributes

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Description

References

3a. Fuel Security

Summary

This Strategic Attribute assesses whether fissile materials are available to start up a reactor system, and whether the supplies are sufficient and secure enough to fuel the reactor(s) over their projected lifetime

3a. Fuel Security - references

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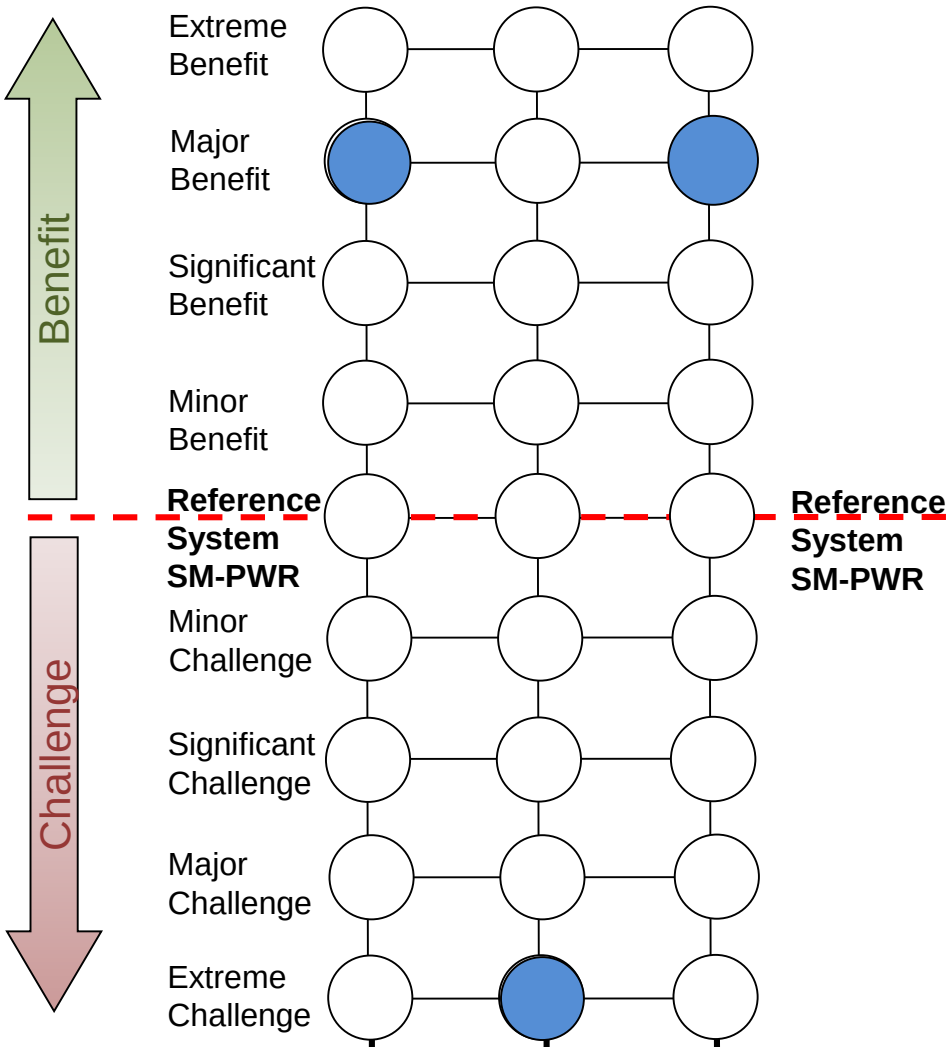
3a. Fuel Security



3a.3 Uranium dependence

3a.2 Spent fuel characteristics – compatible with existing reprocessing technology?

3a.1 Ability to deploy – fissile material availability

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Description

3a.1 Ability to deploy – fissile material availability

SM-MSFR is in principle capable of operating a breeder cycle. In this case, its dependence on uranium available on the international market would be eliminated or considerably reduced in the very long term. In the shorter term, SM-MSFR would remain dependent on uranium or plutonium.

Assessed as 'Major Benefit'

3a.1 Ability to deploy – fissile material availability

3a.1 (Fissile material availability) applies specifically to closed fuel cycle systems which may have limitations on the rate at which new reactors could be deployed because of the need to acquire and/or build up the necessary fissile material. The levels of challenge vary between open and closed fuel cycle systems:

OPEN - this designates an open fuel cycle in which reactors are fuelled by LEU, which as natural uranium or LEU is available on the world market. In this instance the deployment rate would not be restricted, provided that world market supplies are sufficient and sufficient reactor build capacity was available.

CLOSED – this designates a closed fuel cycle which will eventually operate virtually independently of uranium availability, but which may be subject to constraints on the initial rate of deployment depending on the availability of fissile material. Limitations to closed cycle deployment can be calculated for any assumed future nuclear generation scenario.

3a.1 Ability to deploy – fissile material availability - references

Insert

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3a.2 Spent fuel characteristics – compatible with existing reprocessing technology?

No. The spent fuel characteristics of SM-MSFR are incompatible with existing reprocessing technology and will demand an entirely new fuel cycle infrastructure based on pyro processing. The waste forms will also be different and will need to be assessed for compatibility with disposal in the GDF.

Assessed as 'Extreme Challenge'

3a.2 Spent fuel characteristics – compatible with existing reprocessing technology?

3a.2 (Spent fuel characteristics).
Spent fuel characteristics: Is the spent fuel of a form that is compatible with established reprocessing methods, or are there features that would preclude its reprocessing using current reprocessing methods? This Attribute tests whether or not the spent fuel form is compatible with established reprocessing technologies and gives a measure of the accessibility of the contained fissile material and hence the ability to affect any closed cycle deployment limitations in 3a.1.

Conventional spent oxide or metallic fuel, irrespective of whether the main fissile material is uranium or plutonium, are compatible with existing reprocessing technologies.

Unconventional fuels, such as fuels based on thorium matrix or coated particle TRISO fuels (used in high temperature gas reactors) are incompatible with established reprocessing methods. Fuel which is not straightforward to reprocess represents an intrinsic barrier to accessing fissile material.

3a.2 Spent fuel characteristics – compatible with existing reprocessing technology?

References

Insert

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3a.3 Uranium dependence

SM-MSFR is in principle capable of operating a breeder cycle. In this case, its dependence on uranium available on the international market would be eliminated or considerably reduced in the very long term, putting it in the LOW uranium dependence category. In the shorter term, SM-MSFR would remain dependent on uranium or plutonium. Therefore the Major Benefit applies only in the very long term and is not immediately accessible during the transition to equilibrium.

Assessed as 'Major Benefit'

Metrics

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Description

References

3a.3 Uranium dependence

The uranium usage Attribute poses the questions: "*Will there be sufficient uranium available on the world market to meet the requirements of the reactor system over its operational lifetime?"* and therefore *"Is the system more or less dependent on uranium ore availability/supply on the world market?*"

3a.3 therefore categorises the dependence of the nuclear system on uranium obtained from the world market. Illustrations of levels of uranium usage are:

LWRs have a specific uranium requirement of approximately 200 tU/GWye. CANDU reactors have a lower specific uranium requirement of approximately 160 tU/GWye.

Systems with high conversion ratios or with partial recycle of fissile materials are less dependent on uranium ore, defined as specific uranium requirements in the range 20 to 160 tU/GWye.

The lower range is set arbitrarily to 20 tU/GWye to allow for systems with high conversion ratios that are not quite self-sustained. Systems which have full recycle of fissile materials and operate a breeding cycle totally independent of external uranium supplies.

3a.3 Uranium dependence - References

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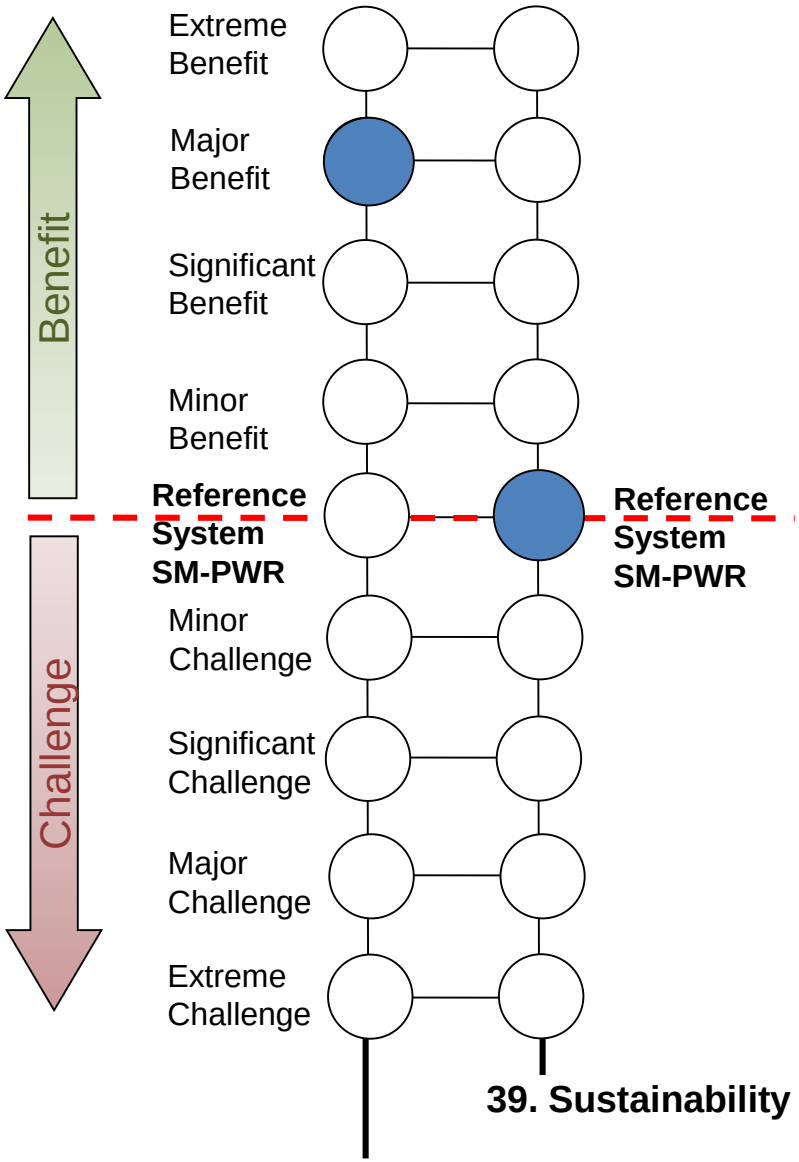
3a.3 Uranium dependence



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Description

01. Fuel utilisation

SM-MSFR is in principle capable of operating a breeder cycle or a high conversion cycle when operating with thorium as a fertile material and full recycle of U-233. In this case, its dependence on uranium available on the international market would be eliminated or considerably reduced in the very long term, putting it in the LOW uranium dependence category. In the shorter term, SM-MSFR would remain dependent on uranium or plutonium to provide the neutrons needed to convert Th-232 to U-233 until the equilibrium fuel cycle is established. Therefore the Major Benefit applies only in the very long term and is not immediately accessible during the transition to equilibrium.

Assessed as 'Major Benefit'

01. Fuel utilisation

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.

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.

01. Fuel utilisation - references

Insert

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39. Sustainability

This is potentially a broad area encompassing the uranium ore requirement, environmental impact, waste arisings and others. SM-MSFR operating with full recycle is assessed as 'Major Benefit' with respect to uranium ore demand, once the equilibrium fuel cycle is established. However, it is too soon to assess other areas such as environmental impact and waste arisings, both of which are likely to require significant design and development work. For this reason, SM-MSFR is assessed 'As Reference' against sustainability, with the long term benefits on uranium demand balanced by challenges on the other issues.

Assessed as 'Reference'

39. Sustainability

Sustainability is potentially a broad area encompassing the uranium ore requirement, environmental impact, waste arisings and others.

39. Sustainability - references

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3b. Waste storage and disposability

Summary

The spent fuel characteristics of SM-MSFR are incompatible with existing reprocessing technology and will demand an entirely new fuel cycle infrastructure based on pyro processing. The waste forms will also be different and will need to be assessed for compatibility with disposal in the GDF. Although there are aspects which would give a Significant Benefit, the overall assessment is dominated by the Extreme Challenge posed by the waste form. Overall assessment Major Challenge

Assessed as 'Major Challenge'

Attributes

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Description

References

3b. Waste storage and disposability

Summary

All nuclear reactors generate nuclear waste that needs to be managed as part of the fuel cycle. The management and disposability of nuclear waste is one of the key long term considerations for the nuclear power industry. The current solution sought for long term disposability is to encapsulate waste into solid forms which are then protectively packaged and placed into a geological disposal facility (GDF). It is therefore required that any spent fuel, high level or intermediate level waste arising must be suitable for encapsulation and safe long term disposal in a GDF.

The waste management Strategic Attribute can be posed as: *Can the waste arisings from reactor systems be managed and eventually disposed of in a safe manner that is compatible with the acceptance criteria for existing or anticipated waste treatment plants and disposal facilities?*

From this top level Strategic Attribute, the following attributes are obtained:

Compatibility of waste forms: The masses and volumes of waste forms for disposal.

Suitability for disposal in GDF: Waste incorporation rate, long term decay heat and radiotoxicity.

3b. Waste storage and disposability - References

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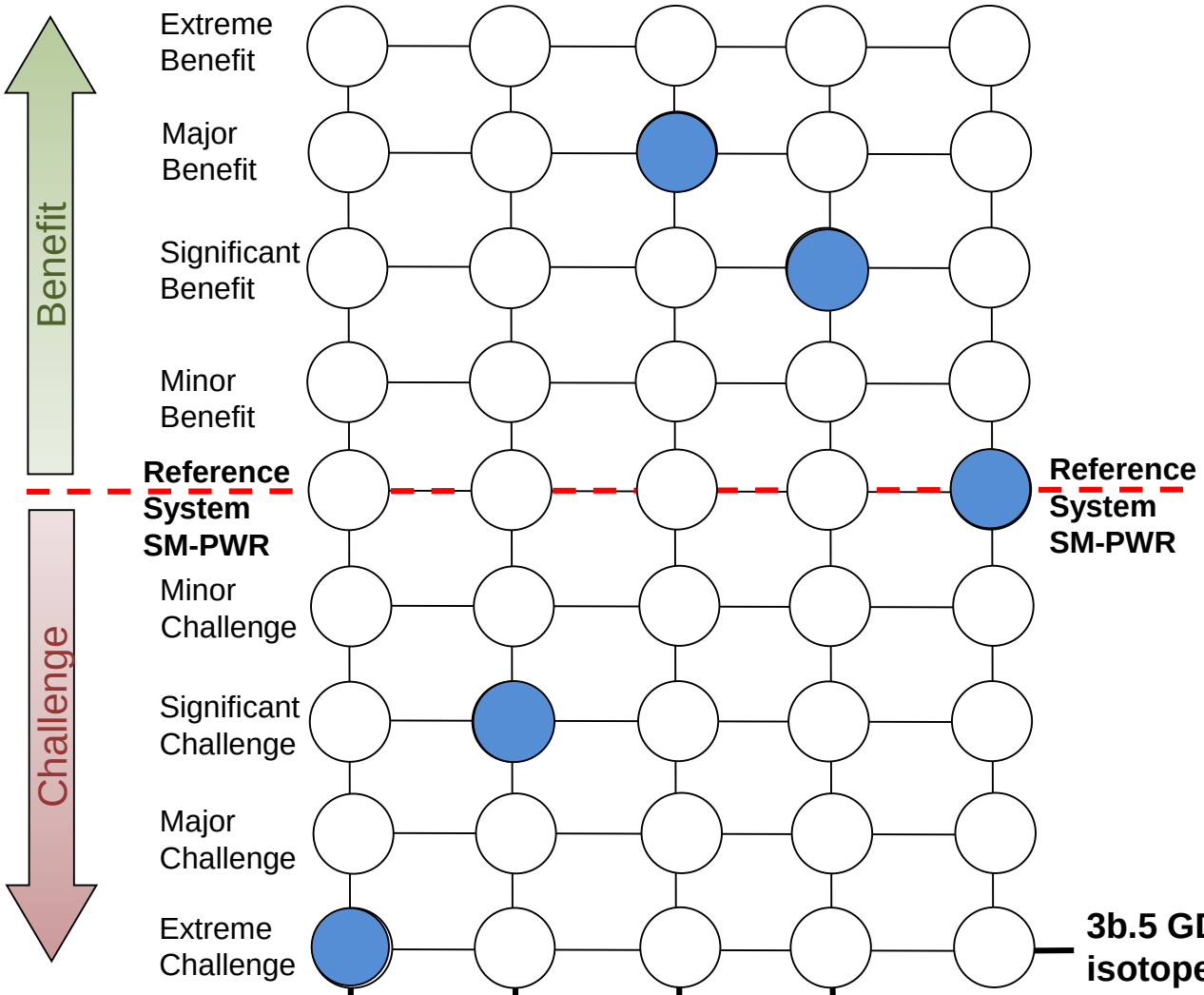
GFA Assessment Subject System: SM-MSFR Reference System: Generic SM-PWR – *Work in Progress*

3b. Waste storage and disposability



3b.5 GDF disposal impact – isotopes driving safety case

3b.4 GDF disposal impact – long term radiotoxicity

3b.3 GDF disposal impact – long term decay heat

3b.2 GDF disposal impact – waste incorporation rate

3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology?

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3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology?

There may be benefits in terms of reduced waste volume and radiotoxicity. However, the spent fuel characteristics of SM-MSFR are incompatible with existing reprocessing technology and will demand an entirely new fuel cycle infrastructure based on pyro processing. The waste forms will also be different and will need to be assessed for compatibility with disposal in the GDF.

Assessed as 'Extreme Challenge'

3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology?

3b.1 (Number and type of waste forms). This attribute accounts for the number of different waste forms produced. It is intended to take account of waste forms that are incompatible with existing or expected future waste packaging and disposal facilities. Any incompatible waste forms produced will require the construction and operation of new facilities to deal with them.

3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology? References

Insert

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3b.2 GDF disposal impact – waste incorporation rate

SM-MSFR is insufficiently developed to understand the impact of fuel disposal and waste incorporation. This leads to it being assigned as 'Significant Challenge' in recognition of the effort that will be required to underpin its performance against this attribute.

Assessed as 'Significant Challenge'

Metric - 33. Waste arisings – volumes of HLW, ILW, LLW

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Description

References

3b.2 GDF disposal impact – waste incorporation rate

3b.2 (Waste Incorporation rate). Waste packages for disposal in the GDF mass may consist of spent fuel assemblies or immobilised high level waste forms (such as glass blocks) depending upon the fuel cycle. For the disposal of spent fuel assemblies, disposal canisters would normally be designed to accommodate uranium fuel assemblies with a relatively low long term decay heat output. Other types of fuel assemblies, for example MOX assemblies, would have a higher long term decay heat output and the disposal canister might be able to accommodate fewer of them, giving a low incorporation rate. Immobilised high level waste from reprocessing of low burnup fuels contains relatively low amounts of transuranics contributing to heat and neutron output and therefore can give a high incorporation rate. High burnup fuels are characterised by high transuranic content, with high heat and neutron outputs that may results in reduced incorporation rates. Illustrations of levels of waste incorporation rate are:

HIGH – Applies to reactor systems producing waste forms with relatively low heat and neutron outputs compatible with current waste forms.

LOW – Applies to reactor systems producing waste forms with relatively high heat and neutron outputs that are incompatible with current waste forms.

3b.2 GDF disposal impact – waste incorporation rate - references

Insert

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References

33. Waste arisings – volumes of HLW, ILW, LLW

SM-MSFR is insufficiently developed to understand the HLW, ILW and LLW waste volumes. This leads to it being assigned as 'Significant Challenge' in recognition of the effort that will be required to underpin its performance against this attribute.

Assessed as 'Significant Challenge'

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Description

References

33. Waste arisings – volumes of HLW, ILW, LLW

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.

33. Waste arisings – volumes of HLW, ILW, LLW - references

Insert

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3b.3 GDF disposal impact – long term decay heat

A SM-MSFR operated with Th-232/U-233 recycle would produce much reduced quantities of heat producing transuranics once equilibrium was established. This applies in the period from 100 years to 1E4 years during which transuranics dominate the heat output in the SM-PWR Reference System.

Assessed as 'Significant Benefit'

Metrics

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Description

References

3b.3 GDF disposal impact – long term decay heat

This is a measure of the long term decay heat of spent fuel or high level waste in interim storage pending disposal and in the GDF. Decay heat is important, because it determines how long spent fuel or immobilised high level waste will need to be held in interim storage prior to final disposal. Also, decay heat loading is the principal determinant of repository footprint. Spent uranium fuel or immobilised high level waste derived from uranium fuels sets the baseline for low long term decay heat. Spent fuel containing higher inventories of transuranics (such as MOX fuels) or immobilised high level waste originating from such fuels will have elevated decay heat output. Immobilised high level waste from fast spectrum systems with recycle of transuranics and from thorium systems would be expected to have a low inventory of transuranics and therefore low decay heat.
Illustrations of levels of long term decay heat are:

LOW – Applies to reactor systems producing waste forms with relatively low long term decay heat output consistent with long, but manageable interim storage times.

HIGH – Applies to reactor systems producing waste forms with relatively high long term decay heat output that would lead to unfeasibly long interim storage times.

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3b.3 GDF disposal impact – long term decay heat - references

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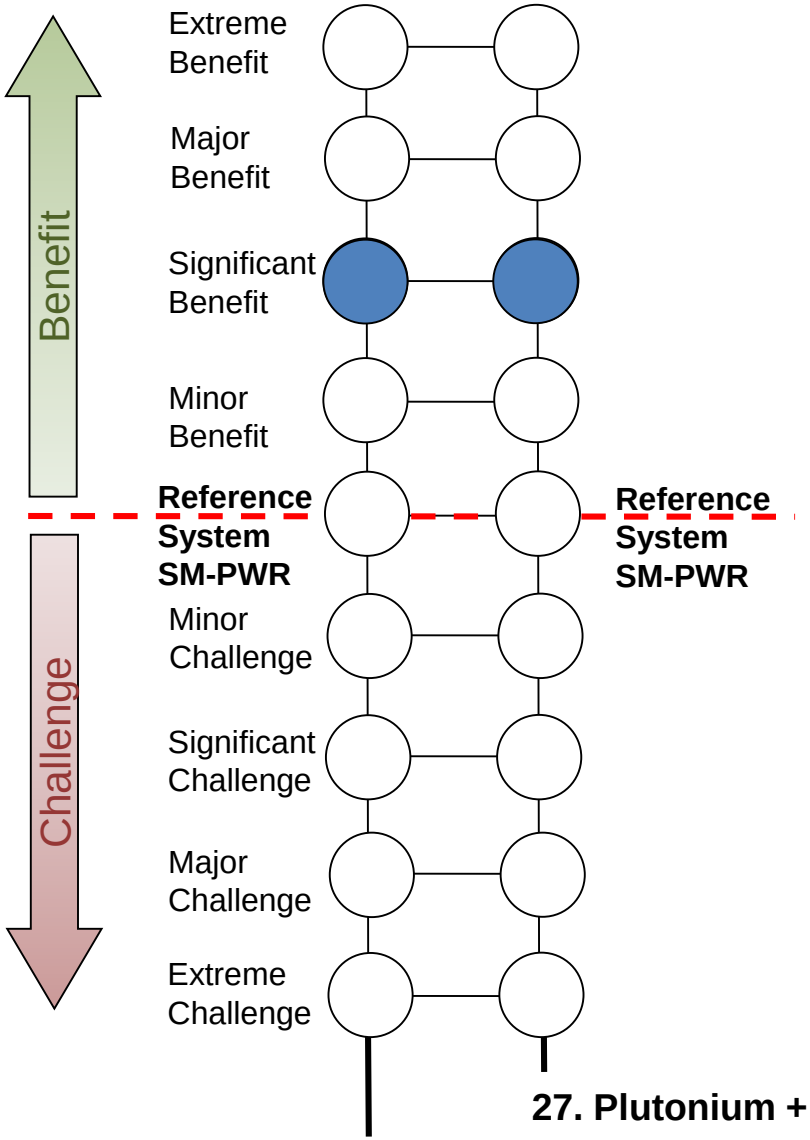
3b.3 GDF disposal impact – long term decay heat



27. Plutonium + minor actinide management

04. Long term heat output

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04. Long term heat output

A SM-MSFR operated with Th-232/U-233 recycle would produce much reduced quantities of heat producing transuranics once equilibrium was established. This applies in the period from 100 years to 1E4 years during which transuranics dominate the heat output in the SM-PWR Reference System.

Assessed as 'Significant Benefit'

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Description

References

04. Long term heat output

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.

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

04. Long term heat output - references

Insert

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27. Plutonium and minor actinide management

SM-MSFR is expected to be more flexible at plutonium and minor actinide management than the SM-PWR Reference System, because there is no requirement for fuel fabrication and the system's inherent tolerance of different fuel compositions.

Assessed as 'Significant Benefit'

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Description

References

27. Plutonium and minor actinide management

Most systems are capable in principle of recycling plutonium and some would also be capable of destroying minor actinides (principally neptunium and americium). This ability to manage plutonium and minor actinides is assessed in this attribute.

27. Plutonium and minor actinide management - references

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3b.4 GDF Disposal Impact – Long Term Radiotoxicity

A SM-MSFR Th-232/U-233 breeder will have lower radiotoxicity than the SM-PWR Reference System in the period between 100 years and 1E5 years, but after 1E5 years, radiotoxicity will be higher. A SM-MSFR reactor with U/Pu fuel will have a long term radiotoxicity comparable to the SM-PWR Reference System.

Assessed as 'Significant Benefit'

Metrics

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Description

References

3b.4 GDF Disposal Impact – Long Term Radiotoxicity

For cooling times up to approximately 500 years, it is the fission products that determine the radiotoxicity of spent fuel or immobilised high level waste and only marginal differences are expected between different systems. Beyond 500 years, where there are transuranics present in the spent fuel or immobilised high level waste, it is these that dominate radiotoxicity for up to 10^5 years. Low radiotoxicity on a timeframe of the order of 500 years is sometimes regarded as a desirable attribute of a fuel cycle because it might be feasible to argue that engineering barriers might retain their effectiveness up to that point. Spent uranium or MOX fuel assemblies and immobilised high level waste from uranium or MOX fuels will have high inventories of transuranics and therefore high long term radiotoxicity. Recycling transuranics in fast reactors can reduce the inventory in repository, possibly leading to low long term radiotoxicity. Fuel cycles based on the Th-232/U-233 fuel cycle have low transuranic inventories which give an intermediate level of radiotoxicity for spent thorium assemblies (in the once-through thorium cycle) and a lower level for immobilised waste from a closed Th-232/U-233 fuel cycle. Th-232/U-233 generally have higher radiotoxicities after 1E5 years.

3b.4 GDF Disposal Impact – Long Term Radiotoxicity - references

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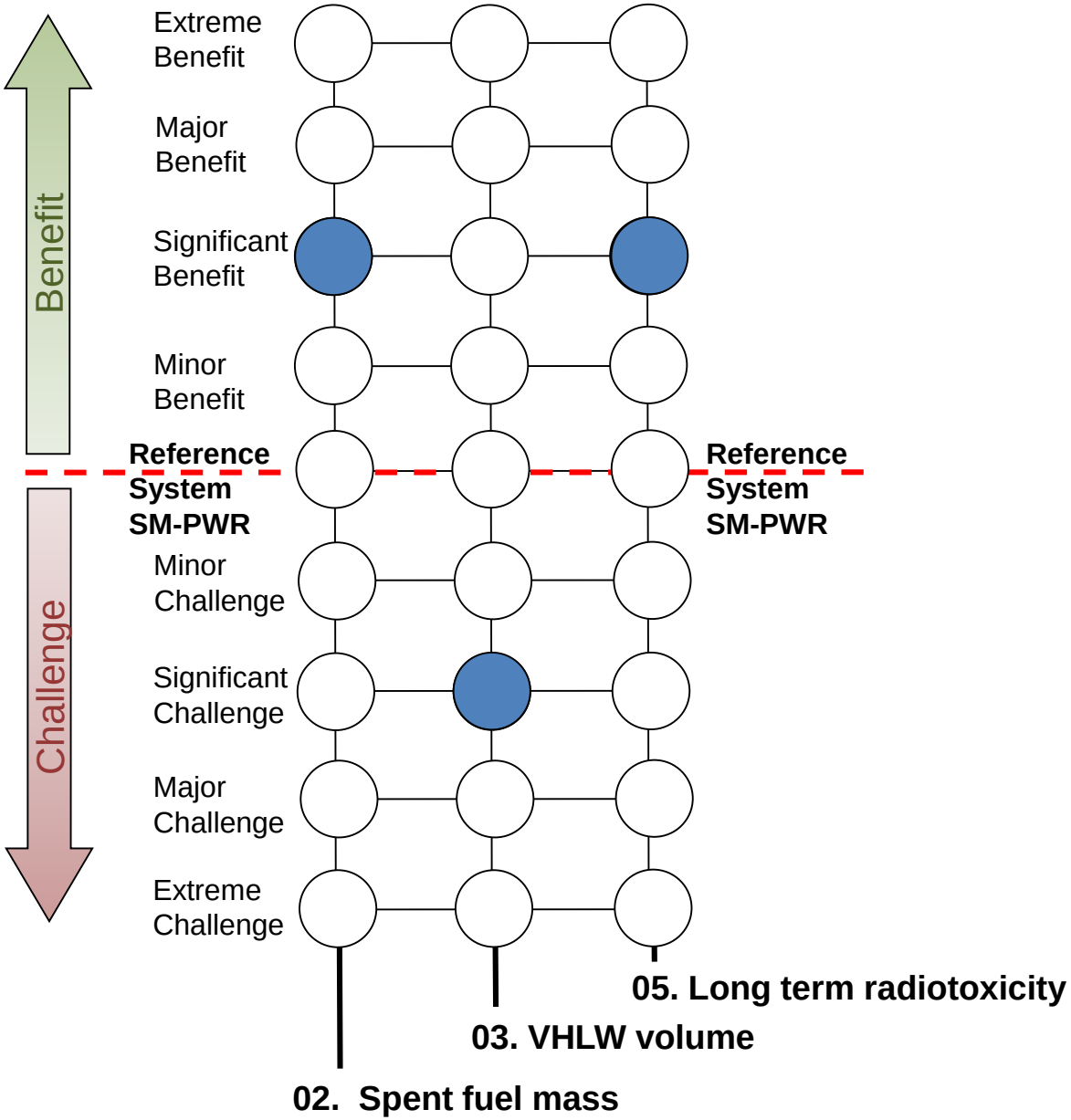
3b.4 GDF disposal impact – long term radiotoxicity



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02. Spent fuel mass

SM-MSFR will have lower spent fuel arisings than the SM-PWR Reference System on account that the fuel salt remains in the reactor for the entire design life. Fission products are removed and fertile material added to make up for heavy metal mass destroyed by fission.

Assessed as 'Significant Benefit'

02. Spent fuel mass

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).

For the recycle options the spent fuel arising is important only in that it determines the throughput and capacity of reprocessing plants,

02. Spent fuel mass - references

Insert

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03. VHLW volume

VLHW arisings from SM-MSFR are not known. The mass of fission products is closely equivalent to that of the SM-PWR Reference System (there is some variation depending on the relative thermal efficiencies), but the fact that the fuel cycle is entirely new introduces a Significant Challenge in developing a new high level waste form that is compatible with molten salt fuel.

Assessed as 'Significant Challenge'

03. VHLW volume

This is the volume of high activity (heat generating) waste, expressed in m3 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.

03. VHLW volume - references

Insert

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05. Long term radiotoxicity

A SM-MSFR Th-232/U-233 breeder of high converter will have lower radiotoxicity than the SM-PWR Reference System in the period between 100 years and 1E5 years, but after 1E5 years, radiotoxicity will be higher. A SM-MSFR reactor with U/Pu fuel will have a long term radiotoxicity comparable to the SM-PWR Reference System.

Assessed as 'Significant Benefit'

05. Long term radiotoxicity

The radiotoxicity is a measure of the hazard potential of radioactive material. Radiotoxicity can be measured as the potential dose from the waste in Sieverts (Sv) per Gwye, or by Toxic Potential, which measures the dilution required to allow dissolved waste to meet dose standards if used for drinking.

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 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.

05. Long term radiotoxicity - references

Insert

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3b.5 GDF disposal impact – isotopes driving safety case

SM-MSFR is assessed to be essentially equivalent to large PWRs.
The reason for this is that the isotopes driving the repository safety case are fission and activation products which are similar for both SM-MSFR and SM-PWR.

Assessed as 'Reference'

3b.5 GDF disposal impact – isotopes driving safety case

As GDF safety cases are generally driven by long-lived mobile fission and activation products rather than by radiotoxicity per se, this attribute assesses any material differences in mobile isotope yields on a per GWye basis.

3b.5 GDF disposal impact – isotopes driving safety case - references

Insert

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3c. Siting

Summary

SM-MSFR is assessed to pose a Significant Challenge relative to the SM-PWR Reference System with respect to siting. SM-MSFR assumes there is full scope reprocessing and therefore major issues with a co-located reprocessing plant.

Assessed as 'Significant Challenge'

Attributes

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Description

References

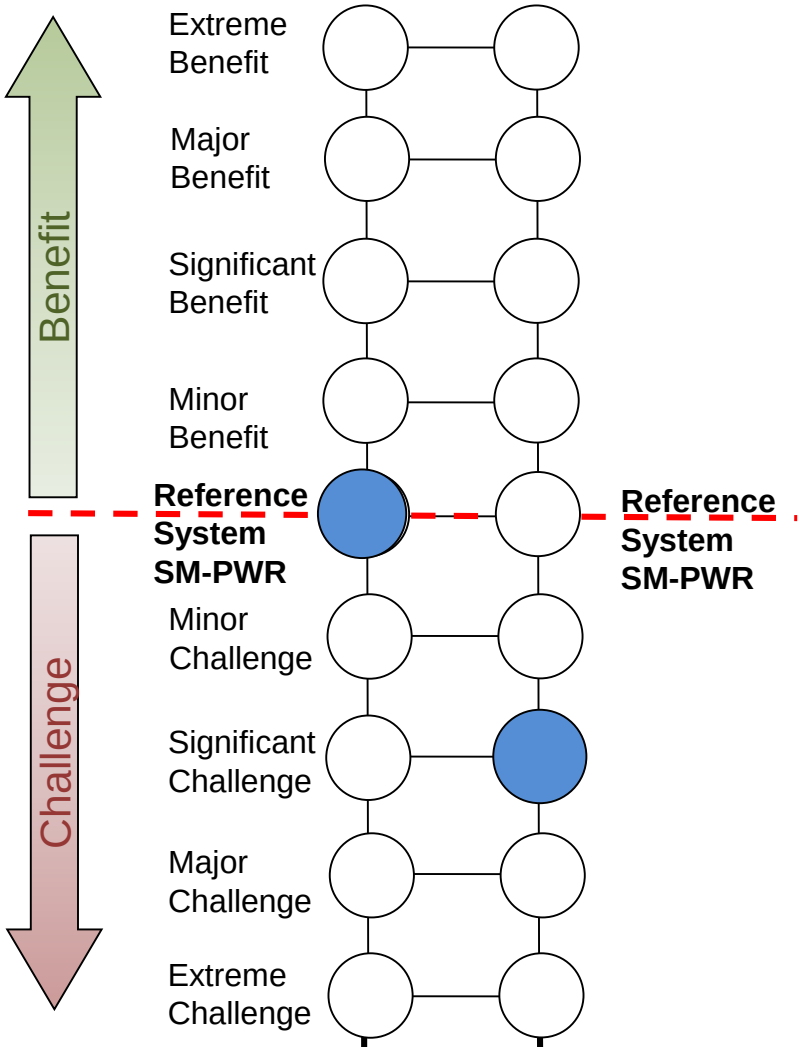
3c. Siting

Reactor systems can be commercially available, competitive, and reliable but all require sites with adequate access to cooling water, power transmission. This Strategic Attribute therefore examines the relative technical suitability of siting reactors and fuel cycle plants across the range of total generation capacity which may be required.

3c Siting - references

Insert

3c. Siting



3c.2 Siting – associated fuel cycle plants

3c.1 Siting - number and size of reactors c/f likely site availability

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Description

3c.1 Siting – number and size of reactors c/f likely site availability

SM-MSFR is assumed equivalent to SM-PWR wrt siting. SM-MSFR assumes there is full scope reprocessing and therefore major issues with a co-located reprocessing plant. Reprocessing operations will have an impact on radiological release in normal operation and in accident conditions and will also introduce a new aspect to the safety case.

Assessed 'Significant Challenge'

Metrics

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Description

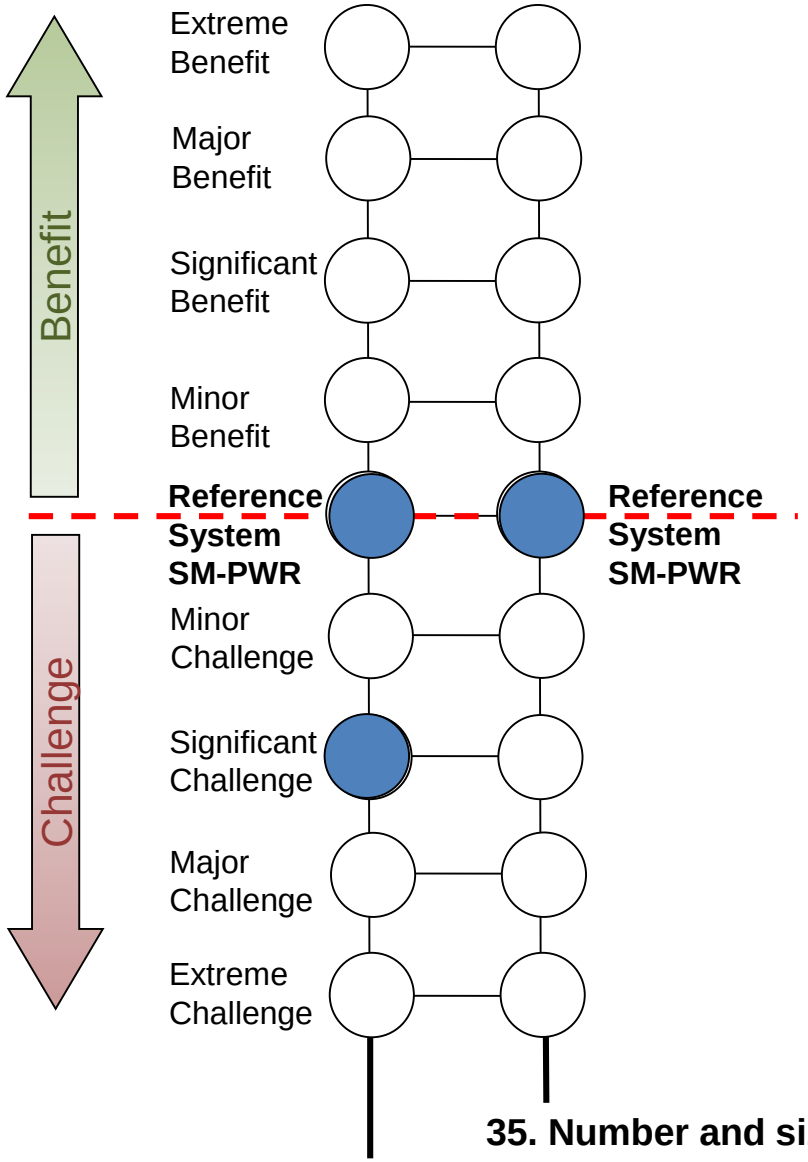
3c.1 Siting – number and size of reactors

3c.1 is intended to measure of how flexible reactor siting would be. It may be possible for small reactors to be sited at locations that would be unsuitable for large reactors on account of reduced land area required and reduced cooling water requirement. It may be possible for a reactor system which, in the event of Design Basis accidents, does not require evacuation outside the site boundary, to be sited more closely to dense concentrations of population.

3c.1 Siting – number and size of reactors - references

Insert

3c.1 Siting - number and size of reactors c/f likely site availability



35. Number and size of reactors needed

32. Flexibility of location

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32. Flexibility of location

Significant improvement for small power station outputs. Less so for large outputs (>0.5 GWye). Potential benefits for small modular LWRs with respect to cooling water availability, ultimate heat sink (for decay heat), grid connections and avoidance of off-site evacuation zone and transmission infrastructure compatibility.

Small modular LWRs may offer increased scope for development on alternative locations, such as former coal fired power stations or other former industrial sites.

Assessed as 'Significant Benefit' (dispersed siting) to 'Reference' (GWe-sized groupings)

32. Flexibility of location

Reactors will have varying siting demands depending on their output and any dependence of co-siting with, for example, fuel cycle plants. Small reactors will make smaller demands on cooling water and grid connections, but will require more sites to reach the same installed output.

32. Flexibility of location - references

Insert

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35. Number and size of reactors needed

SM-MSFR is assumed equivalent to the SM-PWR Reference System

Assessed as 'Reference'

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Description

References

35. Number and size of reactors needed

The size of individual reactors will directly affect the number of reactors needed per GWe installed. The effects on numbers of sites and on economics are examined elsewhere,

35. Number and size of reactors needed - references

Insert

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3c.2 Siting – associated fuel cycle plants

SM-MSFR assumes extensive on-line reprocessing which is likely to place restrictions on siting.

Assessed as 'Significant Challenge'

Metric - 36. Fuel cycle plants

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Description

References

3c.2 Siting – associated fuel cycle plants

3c.2 covers the need of closed reactor systems for reprocessing, waste processing and fuel refabrication plants. Many outline schemes assume co-location of reactor and fuel cycle plants – but, in nuclear scenarios with large contributions from closed systems, this carries the consequence of either (a) very large generation capacity at one site or (b) multiple sites and fuel cycle plants.

3c.2 Siting – associated fuel cycle plants - references

Insert

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36. Fuel cycle plants

Sm-MSRth would require entirely new fuel cycle plants.

Assessed as 'Extreme Challenge'

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Description

References

36. Fuel cycle plants

The fuel cycle plants needed for the various reactor system options are potentially very different.

36. Fuel cycle plants - references

Insert

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4a. Access to international programmes

SM-MSFR offers strong potential for international collaboration, on account of its low TRL. UK engagement in design, modelling and testing would be a fertile area for maintaining and developing expertise. It would help provide a positive focus for UK nuclear R&D.

Assessed as 'Significant Benefit'

Metric - 4a.1 Re-engagement in international programmes

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Description

References

4a. Access to international programmes

This Strategic Attribute assesses whether access to (or indeed the formation of) international programmes could aid the eventual deployment of a reactor system. The single Attribute assesses the information on the credibility of the route and on its possible timescale for deployment.

4a. Access to international programmes - references

Insert

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4a.1 Re-engagement in international programmes

Strong potential for international collaboration. SM-MSFR would help provide a positive focus for UK nuclear R&D.

Assessed as 'Significant Benefit'

4a.1 Re-engagement in international programmes

This Attribute assesses whether access to (or indeed the formation of) international programmes could aid the eventual deployment of a reactor system. The single Attribute assesses the information on the credibility of the route and on its possible timescale for deployment.

4a.1 Re-engagement in international programmes - references

Insert

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4b. Time and Cost to Deployment

Summary

SM-MSFR is judged to be at TRL 2-3 and is estimated to have an earliest deployment date of 2070.

This represents an Extreme Challenge when compared to the SM-PWR Reference System.

Assessed as 'Extreme Challenge'

Attributes

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Description

References

4b. Time and Cost to Deployment

This Strategic Attribute takes in information from the assessment of Strategic Attributes 1a, 1b, 1c and from Attribute 4a above, to assess the overall timescale on which the system could be deployed. This will be placed in the context of the relative economics of the system and its match to the market, which are examined under High Level Discriminator 2 – Competitiveness. The Technology Readiness level will be an assessment, with the grounds for that assessment given, while the Deployment Time should be a time in years, with the reasons and uncertainties stated.

In determining the timescale, funding for R&D activities will be assumed to be available as required, and regulatory effort will also be assumed to be available. Funding for reactor build will also be assumed to be available as required. The estimated time to deployment will be the time from the GFA to the time of power production by the first UK reactor

4b. Time and Cost to Deployment - references

NNL 12415 – Manchester Report on TRL of Gen IV Systems

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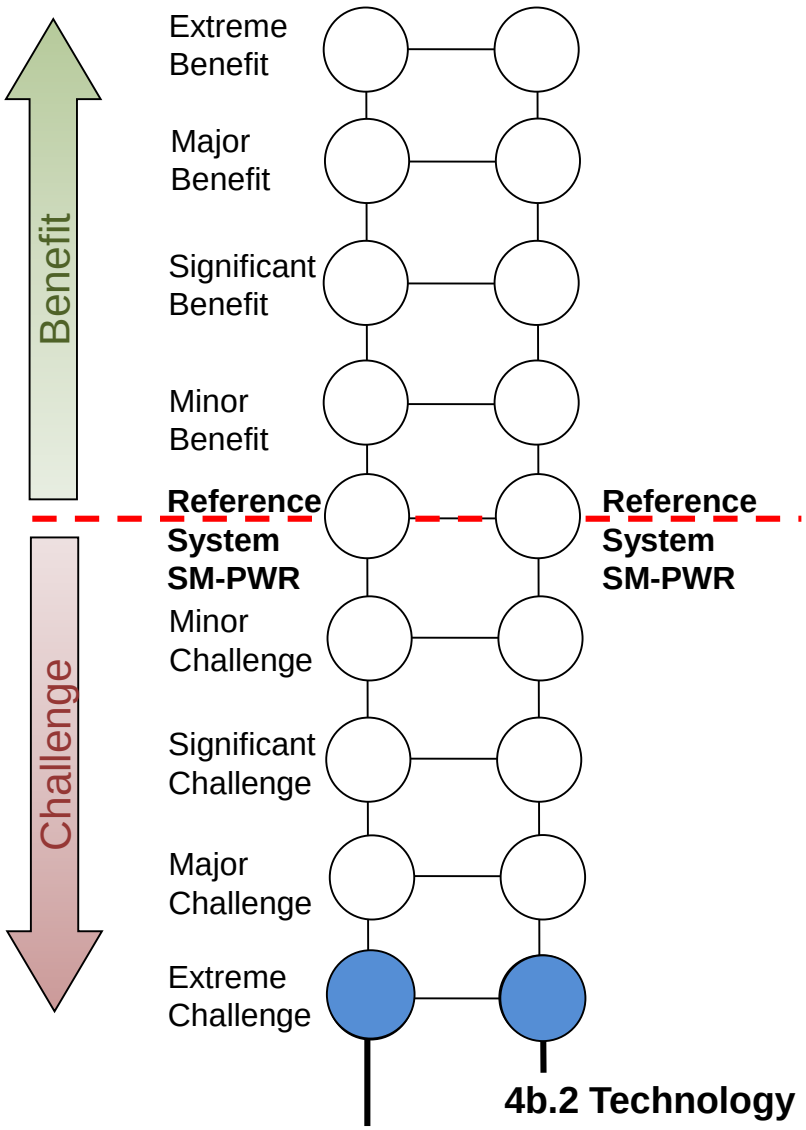
4b. Time and Cost to Deployment



4b.2 Technology Readiness level

4b.1 Commercial availability. Deployment time, plus feed from 1 and 2a

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Description

4b.1 Commercial availability – Deployment Time

Deployment in the UK will involve completing the development and testing of a design to the extent that it can apply for GDA, going through the GDA process, and then building the reactor on a selected UK site. Current designs of SM-MSFR are judged to be at least 45 years from being ready for GDA for a commercial plant. A prototype would be required and need to operate for 10 years to build-up operating experience. It is estimated that 35 years' development time is required before a prototype could begin operation.

The GDA process itself has been seen to last around 5 years, so a build time of 5 years after approval would give reactors operational around 2070. The Gen IV MSFR is envisaged for deployment in 2070 and is in agreement with this estimate.

Assessed as 'Extreme Challenge'

Metrics

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Description

References

4b.1 Commercial availability – Deployment Time

4b.1 (Deployment time) is the earliest time until the first unit could become operational. It builds on the assessment under in Strategic Attributes 1a, 1b, 1c and 2, and the effect of any international programmes available from 4a.1.

4b.1 Commercial availability – Deployment Time - references

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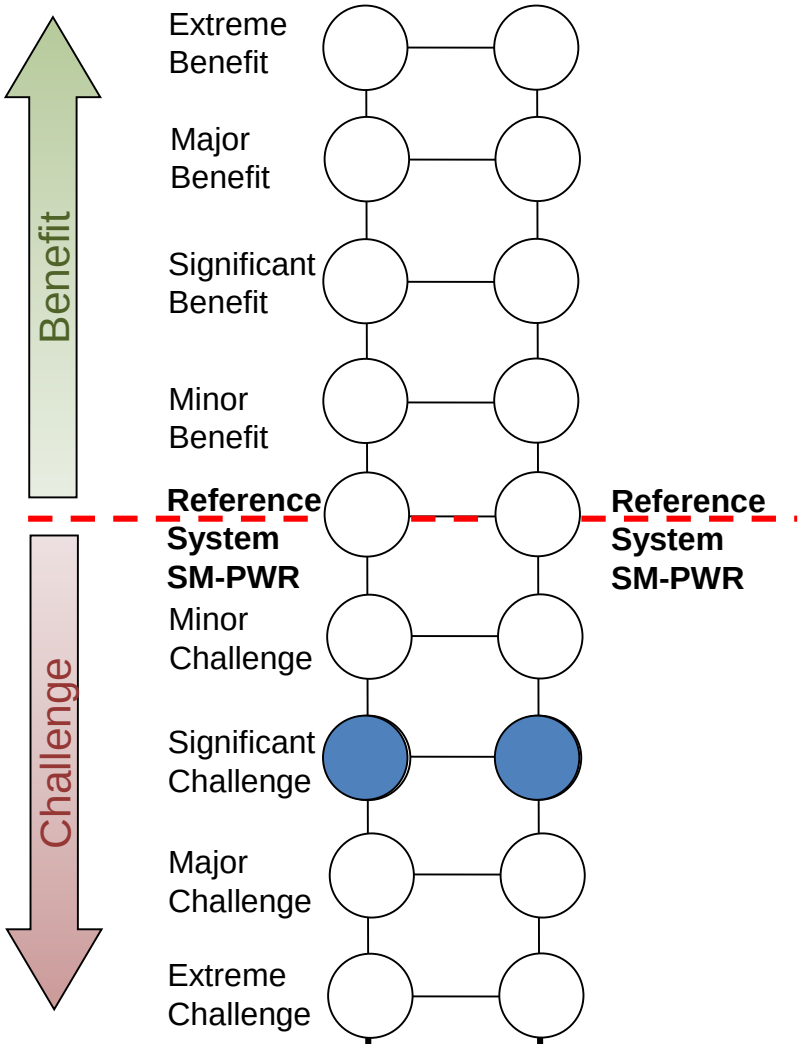
4b.1 Commercial availability



30. Timescales for deployment

25. Development costs

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25. Development costs

SM-MSFR will have significant development costs, more onerous than the SM-PWR Reference System. Beyond reach for reactor vendors without help from governments and/or consortia.

Assessed as 'Significant Challenge'

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Description

References

25. Development costs

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.

25. Development costs - references

Insert

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30. Timescales to deployment

SM-MSFR will require an estimated minimum 45 years to complete licensing, including build time and 10 years' operational time for a prototype. See 1a.2 Timescale required to demonstrate that SAPs can be satisfied.

Allowing 5 years for GDA a FOAK build time of 5 years would give a current timescale for a reactor 'on the bars' of 2070.

Assessed as 'Significant Challenge'

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Description

References

30. Timescales to deployment

The timescale at which any new system could be deployed would be of high relevance to strategic planning in the UK.

In determining the timescale, funding for R&D activities will be assumed to be available as required, and regulatory effort will also be assumed to be available. Funding for reactor build will also be assumed to be available as required. The estimated time to deployment will be the time from the GFA to the time of power production by the first UK reactor

30. Timescales to deployment - references

Insert

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4b.2 Technology Readiness Level

SM-MSFR is assessed at TRL 2-3 (Concept level). This determines the minimum timescale to deployment. The timescales for progressing from TRL 2 to TRL 9 increase progressively.

Assessed as 'Extreme Challenge'

Metric - 31 Technology Readiness Level

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Description

References

4b.2 Technology Readiness Level

4b.1. and 4b.2 combine to give a likely timescale for deployment in the UK. For reactor systems which are already commercially available, this is determined by the lead time for pre-licensing in the UK, the lead time for site approval and the construction time. For systems which are not yet commercially available, an additional lead time would be required for the system to be developed to commercial readiness, with the lead time being longest for systems which are at an early stage of R&D.

This assessment will give an idea of the likely deployment time in the UK. This needs to be compared with the timescales indicated in the Strategic Attributes 1a, 1b and 1c, to come to a consolidated overall view.

4b.2 Technology Readiness Level - references

NNL 12415 – Manchester Report on TRL of Gen IV Systems

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31. Technology Readiness Level

SM-MSFR is assessed at TRL 2-3 (Concept level). This determines the minimum timescale to deployment. The timescales for progressing from TRL 2 to TRL 9 increase progressively.

Assessed as 'Extreme Challenge'

31. Technology Reference Level

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

31. Technology Readiness Level - - references

NNL 12415 – Manchester Report on TRL of Gen IV Systems

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4c. Meet and enable UK supply chain

Summary

SM-MSFR presents increased opportunity for UK involvement in the supply chain, but the ability of the UK to realise this potential will be challenging.

The deployment of more mature SMR technology would seem to offer limited potential for UK supply chain involvement, with the UK largely restricted to manufacturing components to a given design/specification.

By contrast, less mature designs may offer increased potential for UK supply chain, with the possibility of UK design expertise being input to develop component designs from the beginning and higher value.

Assessed as 'Significant Benefit'

Attribute - 4c.1 Supply chain opportunities

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Description

References

4c. Meet and enable UK supply chain

Summary

This Strategic Attribute examines the possibility of opportunities for the UK supply chain, providing an additional incentive for UK involvement in any particular reactor system.

4c. Meet and enable UK supply chain - references

Insert here

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4c.2 Supply chain opportunities

On account of its low TRL, SM-MSFR presents increased opportunity for UK involvement in the supply chain, but the ability of the UK to realise this potential will be challenging.

Assessed as 'Significant Benefit'

4c.2 Supply chain opportunities

This Attribute should attempt to assess the level of UK supply chain involvement that could accompany the development and deployment of a given system

4c.2 Supply chain opportunities - references

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5a Meets Energy Requirements - load follow capability

SM-MSFR is not limited in load-follow operation by fuel thermal limits or by xenon build-up. However, thermal cycling effects are likely to be more onerous than the SM-PWR Reference System on account of the higher temperature changes experienced in the Primary Circuit. Overall assessment as Minor benefit.

Assessed as 'Minor Benefit'

Attribute - 5a.1 Flexibility – load follow capability

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Description

References

5a Meets Energy Requirements - load follow capability

This Strategic Attribute assesses the ability of systems to respond to particular features of a future energy market. For example, if the percentage of nuclear electricity on the grid is high, and coupled with a significant randomly variable output from renewables, then nuclear systems may be required to load follow. Some systems are much more amenable to this than others.

4c.2 Supply chain opportunities - references

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5a.1 Flexibility – load follow capability

The design of SM-MSFR is insufficiently developed to assess it load-follow capability, however because SM-MSFR is not limited in load-follow operation by fuel thermal limits or by xenon build-up it is assessed as Minor Benefit relative to the SM-PWR Reference System. Market mechanisms will be needed accommodate load follow operation, otherwise nuclear utilities will suffer significant loss of revenue. The market mechanisms would recognise that providing a load-follow capability helps support the grid system.

Assessed as 'Minor Benefit'

Metric – 28. Load follow capability

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Description

References

5a.1 Flexibility – load follow capability

5a.1 measures the ability of the reactor system to operate in non-baseload or load-follow mode. This is the ability of the reactor to increase or decrease output either in response to short term grid demands or in pre-planned load scheduling. If the total installed capacity of nuclear stations in the UK is only a small or modest fraction of the grid capacity, there is unlikely to be a major requirement for load-follow capability. However, if the nuclear capacity grows sufficiently, with only limited electricity storage capacity, there may come a point at which load-follow will be required, as is the case currently in France. Many current reactors are able to load-follow, but with limitations. Future reactor systems may be able to operate in load-follow mode without such restrictions, hence their ability to load follow will be compared, both from one system to another, and with the current LWR reference systems.

5a.1 Flexibility – load follow capability - references

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28. Load follow capability

The design of SM-MSFR is insufficiently developed to assess it load-follow capability, however because SM-MSFR is not limited in load-follow operation by fuel thermal limits or by xenon build-up it is assessed as Minor Benefit relative to the SM-PWR Reference System. Market mechanisms will be needed accommodate load follow operation, otherwise nuclear utilities will suffer significant loss of revenue. The market mechanisms would recognise that providing a load-follow capability helps support the grid system.

Assessed as 'Minor Benefit'

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Description

References

28. Load follow capability

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.

28. Load follow capability - references

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Description

5b. Meets energy requirements – Process Heat

SM-MSFR is expected to operate at much higher working temperatures than the SM-PWR Reference System, which is capable of supplying only low grade heat. Therefore SM-MSFR is assessed as offering a Significant Benefit.

Assessed as 'Significant Benefit'

Attribute - 5b.1 Industrial process heat – potential to drive thermal processes

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Description

References

5b. Meets energy requirements – Process Heat

This Strategic Attribute assesses the ability of systems to respond to particular features of a future energy market. For example If sectors such as transport are to be decarbonised, for example by use of hydrogen as an energy vector, then the ability of a reactor system to provide high grade heat (rather than electricity) to power chemical processes could be a significant advantage.

5b. Meets energy requirements – Process Heat - references

Insert

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Description

5b.1 Industrial process heat – potential to drive thermal processes

Not relevant to current UK market, but potential for future market to develop. SM-MSFR can potentially supply higher temperature processes than the SM-PWR Reference System

Assessed as 'Significant Benefit'

Metrics

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Description

References

5b. 1 Industrial process heat – potential to drive thermal processes

5b.1 indicates whether the system has the potential to drive thermal processes, such as combined heat and power (CHP), hydrogen production, synthetic fuel production and as a heat source for other industrial processes to displace carbon emitting fossil fuel heating. For thermal applications, a high operating temperature is beneficial, which leads to a simple description based on three levels of temperature:

- LOW TEMPERATURE – Low operating temperatures similar to those of current Light Water Reactors (LWRs) ~300-320°C.
- MEDIUM TEMPERATURE – Medium operating temperatures in range 320-600°C beyond the range accessible with LWRs.
- HIGH TEMPERATURE – High operating temperatures >600°C.

5b. 1 Industrial process heat – potential to drive thermal processes - references

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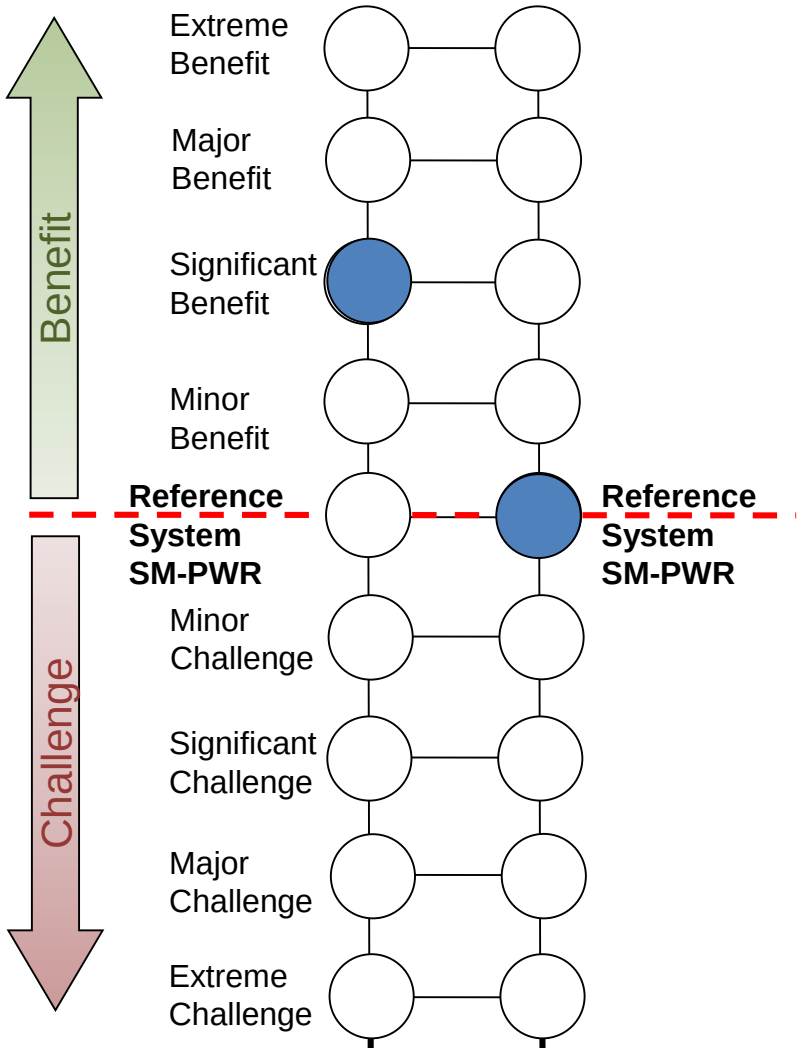
Description

5b.1 Industrial process heat – potential to drive thermal processes



42. Primary purpose

40. Potential to drive thermal processes

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Description

40. Potential to drive thermal processes

Not relevant to current UK market, but potential for future market to develop. SM-MSFR can potentially supply higher temperature processes than the SM-PWR Reference System

Assessed as 'Significant Benefit'

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Description

References

40. Potential to drive thermal processes

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 systems (eg GFR, MSR and VHTR) have very primary circuit operating temperatures compatible with high temperature process heat applications.

40. Potential to drive thermal processes - references

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42. Primary purpose

Not relevant to current UK market, but potential for future market to develop. Widespread adoption of electric cars may change grid demand.

Assessed as 'Reference'

42. Primary purpose

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.

42. Primary purpose - references

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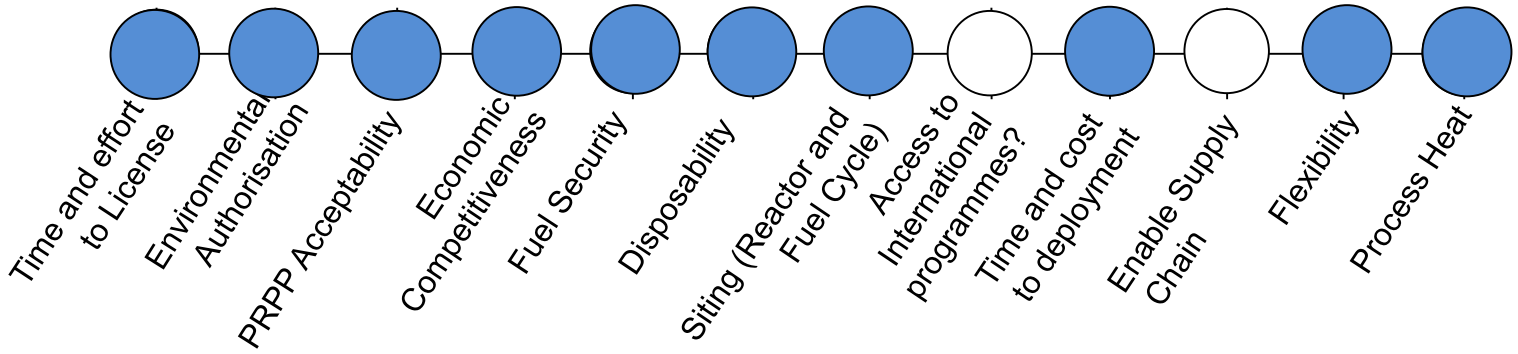
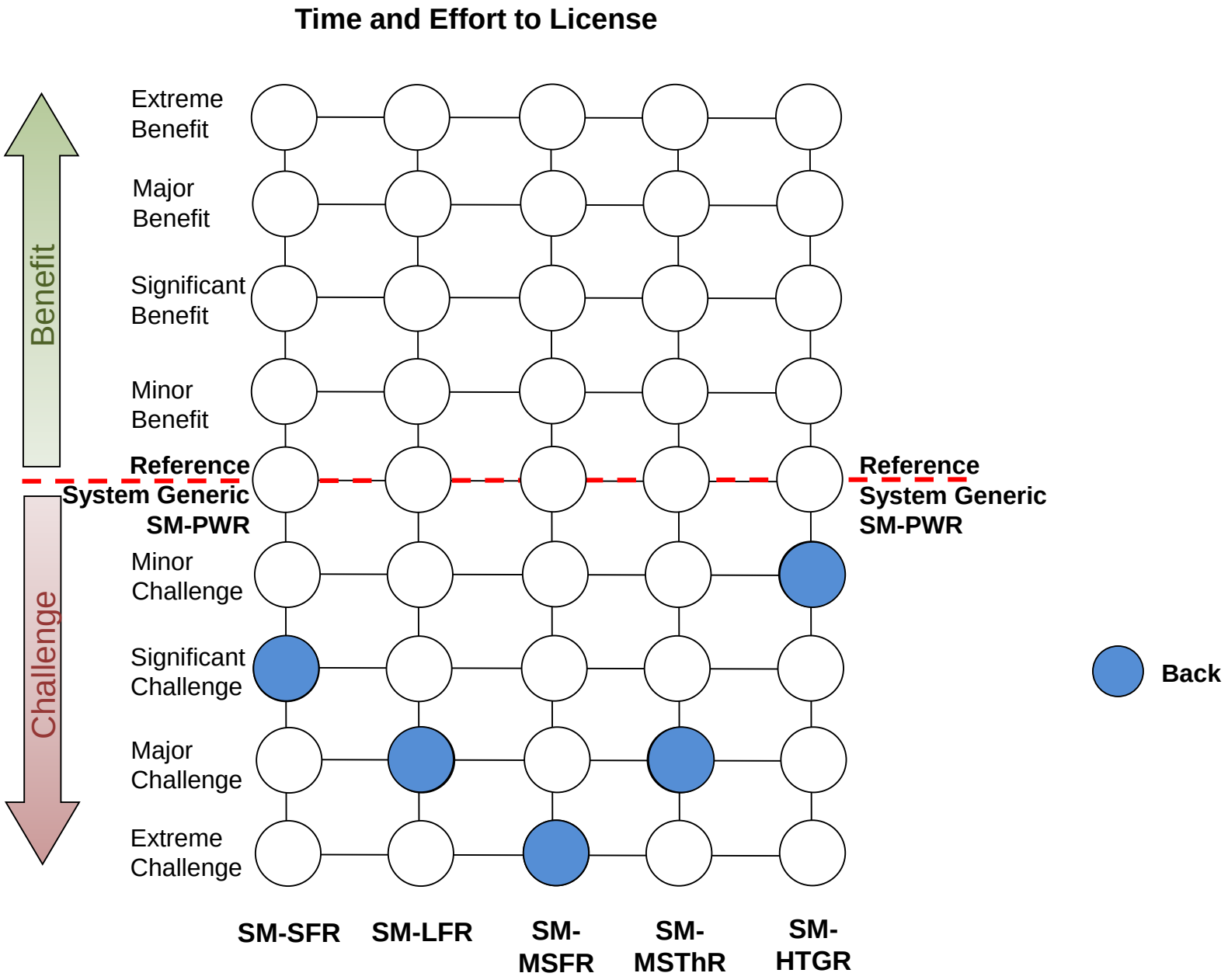
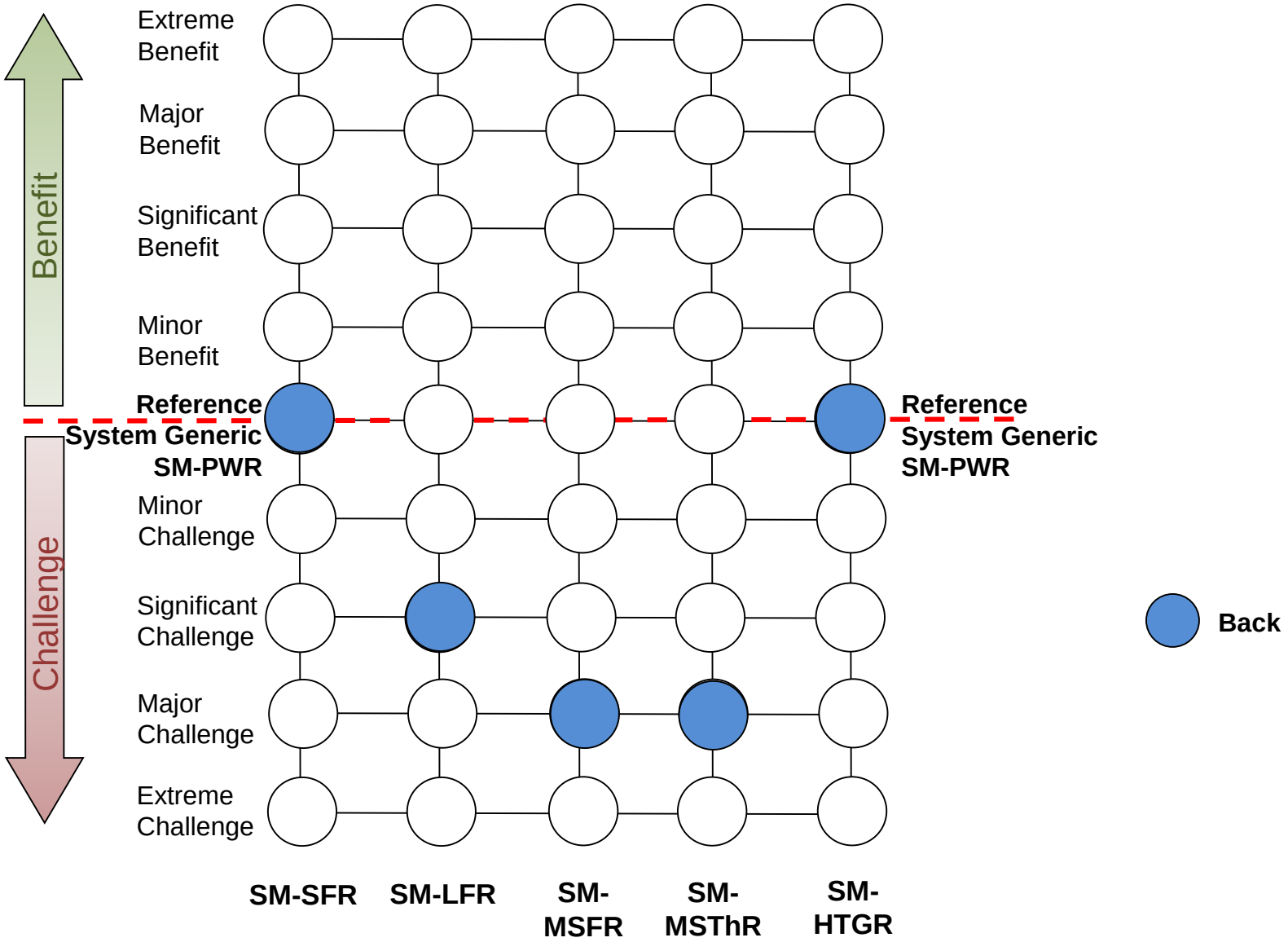
Comparative Benefits/Challenges for Attributes Assessed



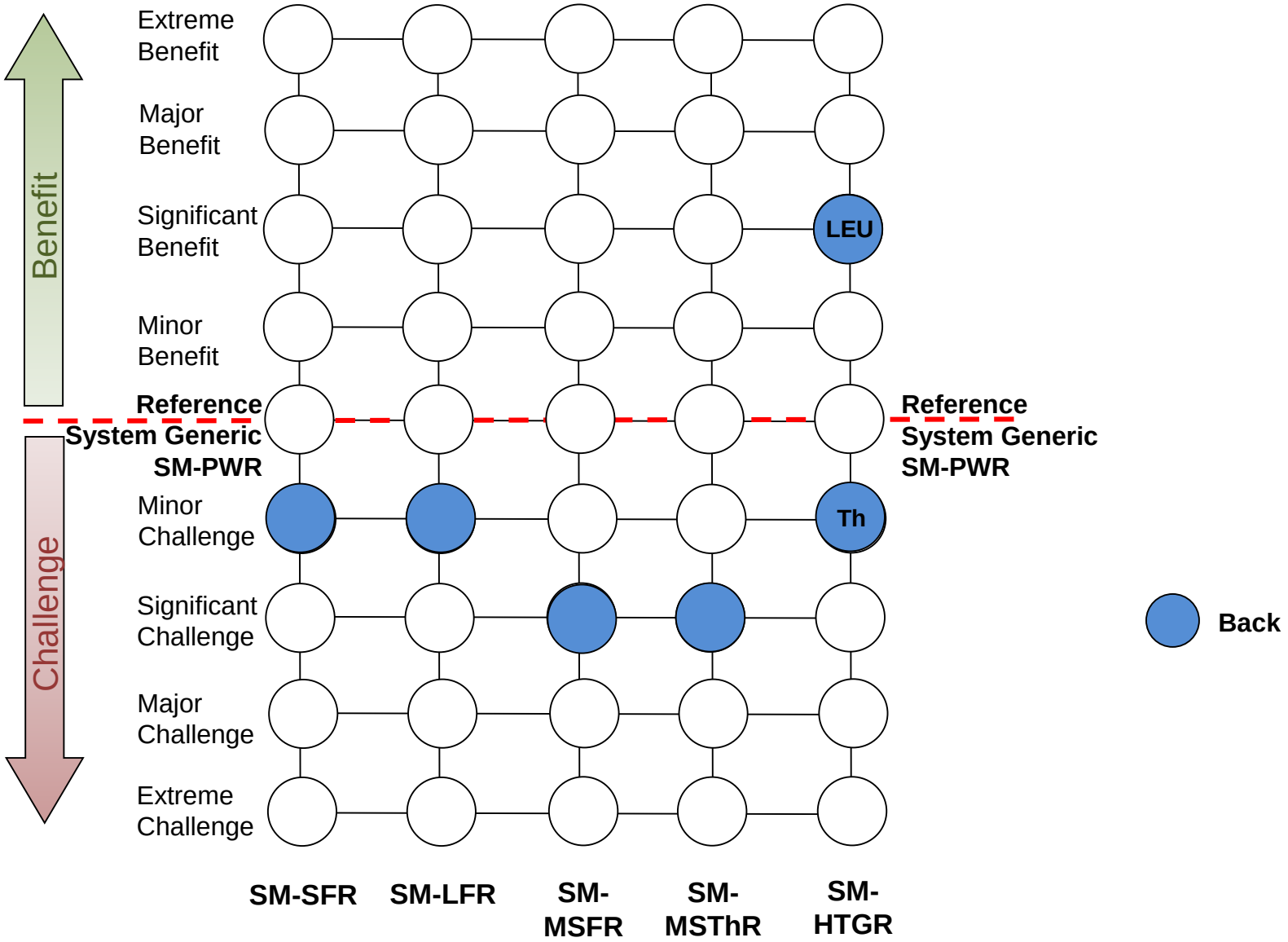
Back to Main Menu


Time and Effort to License
Benefit
Challenge
Extreme Benefit
Major Benefit
Significant Benefit
Minor Benefit
Reference System Generic SM-PWR
Minor Challenge
Significant Challenge
Major Challenge
Extreme Challenge
Reference System Generic SM-PWR
Back
SM-SFR
SM-LFR
SM-MSFR
SM-MSThR
SM-HTGR

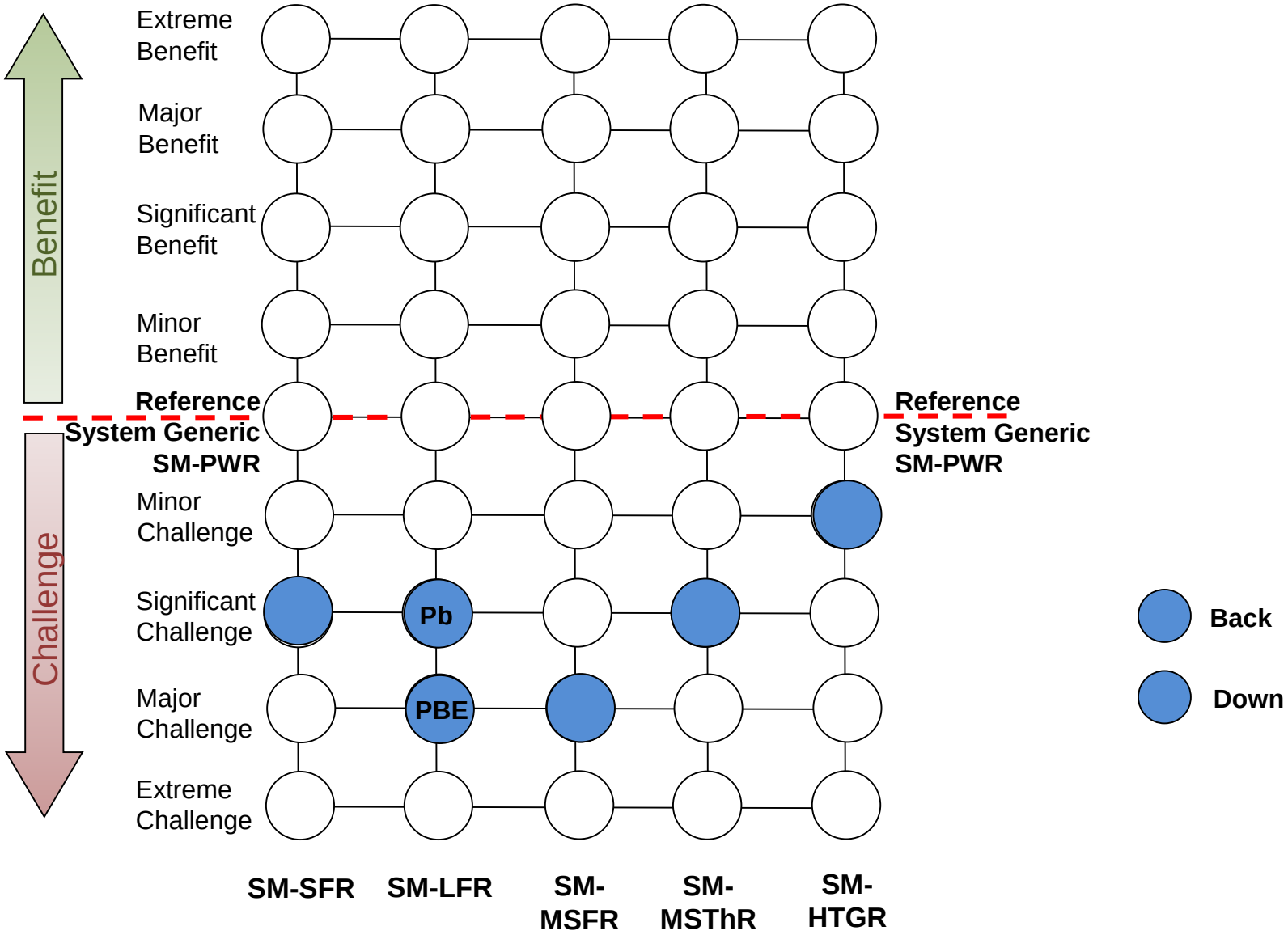
Environmental Authorisation



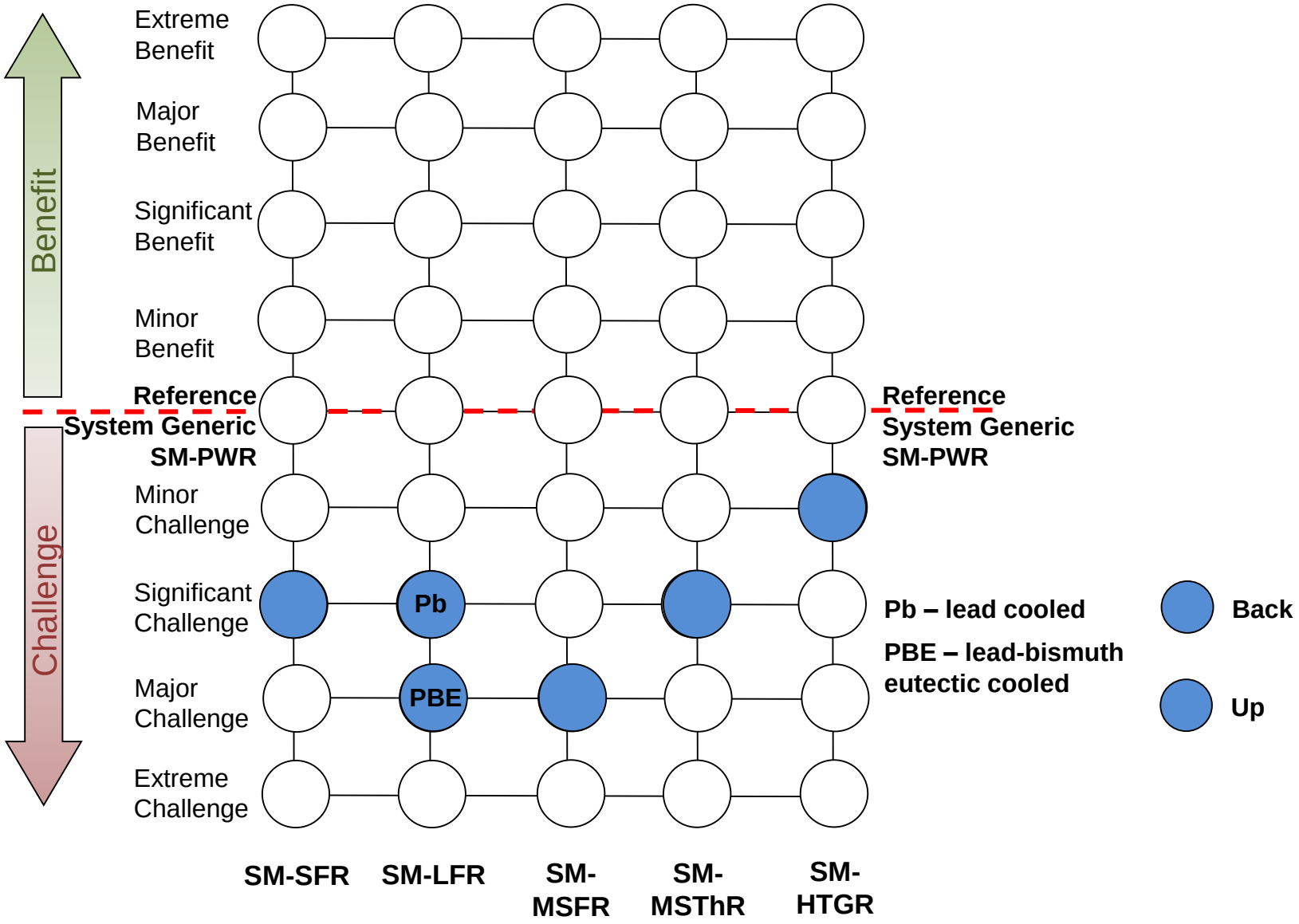
PRPP Acceptability

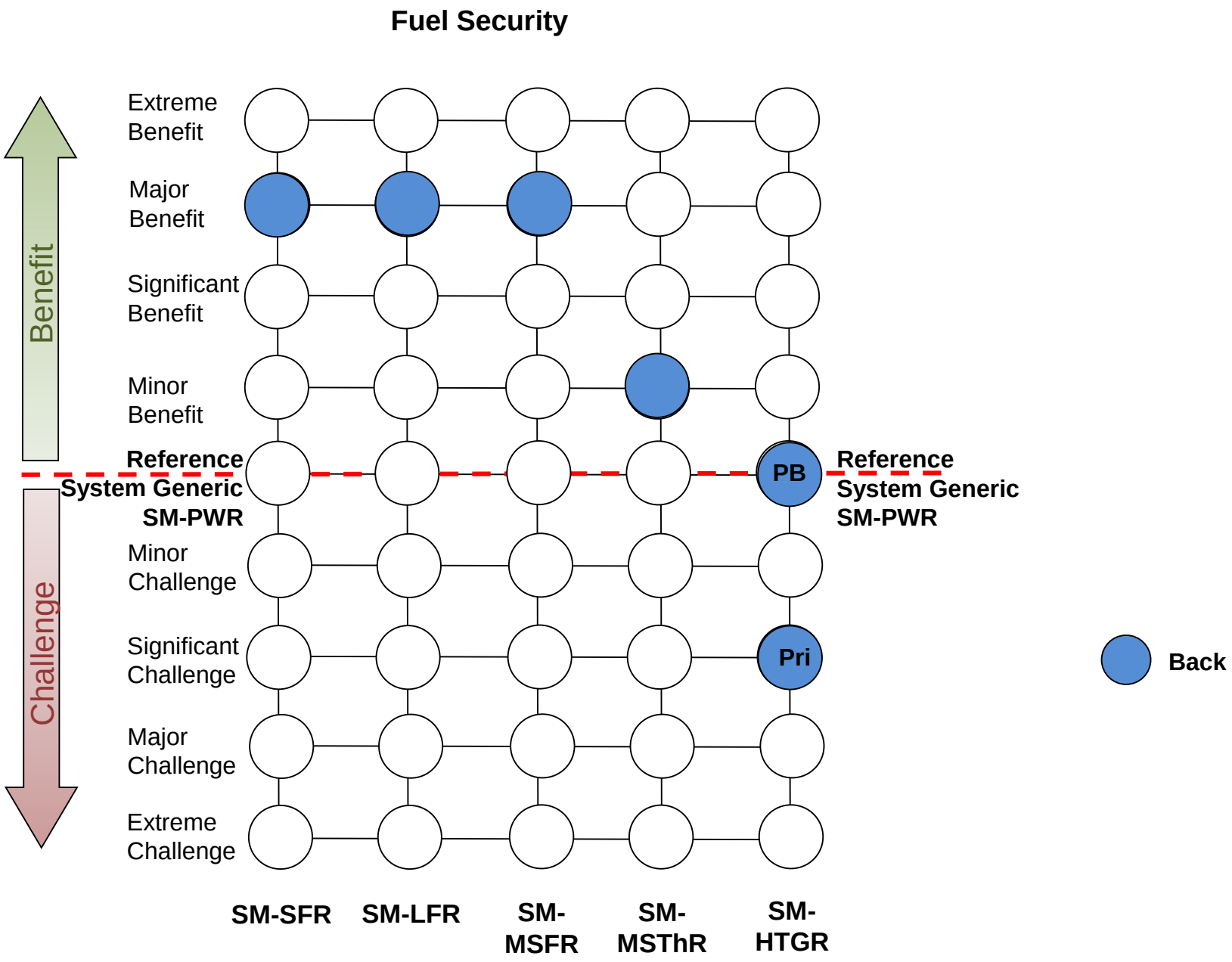


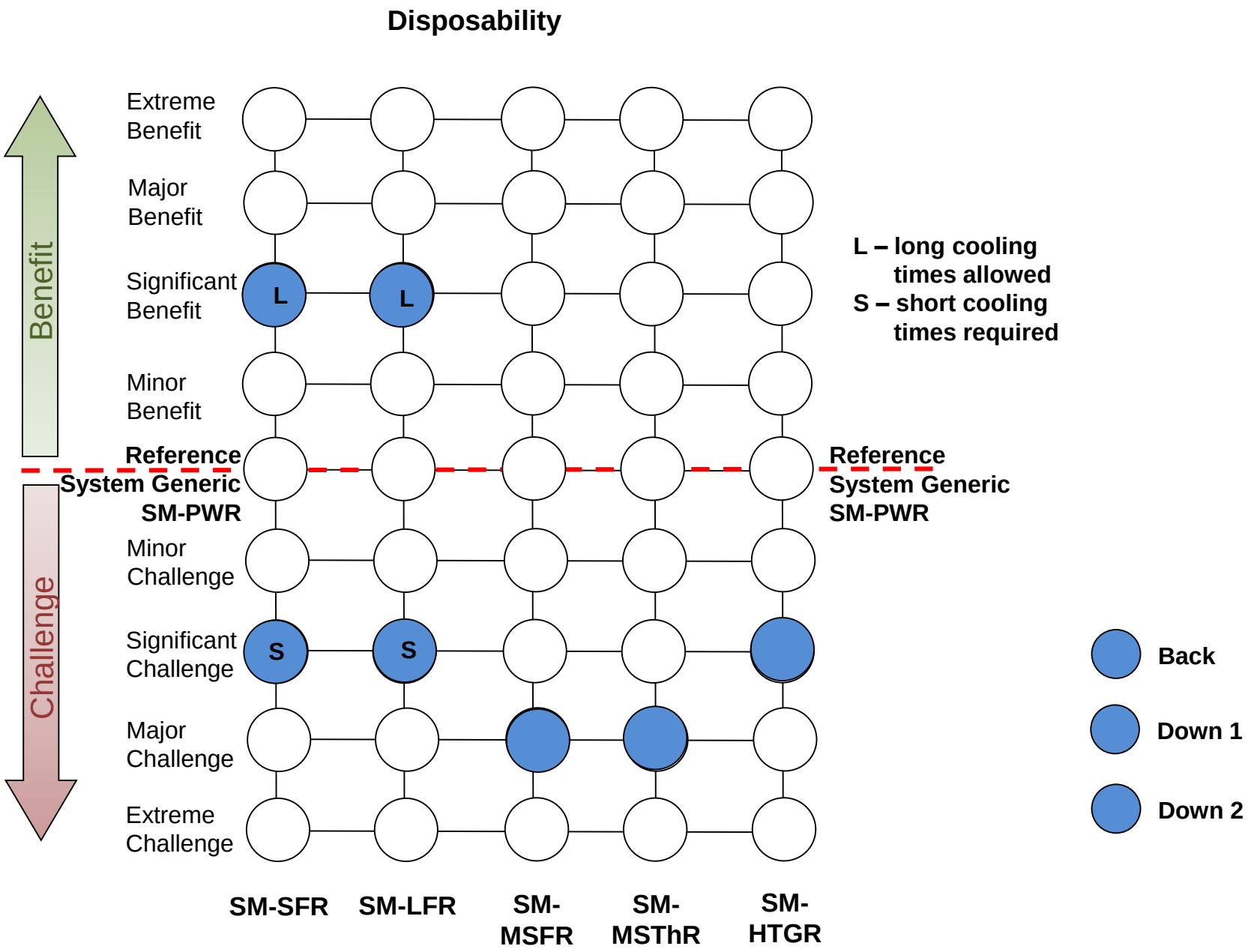
Economic Competitiveness



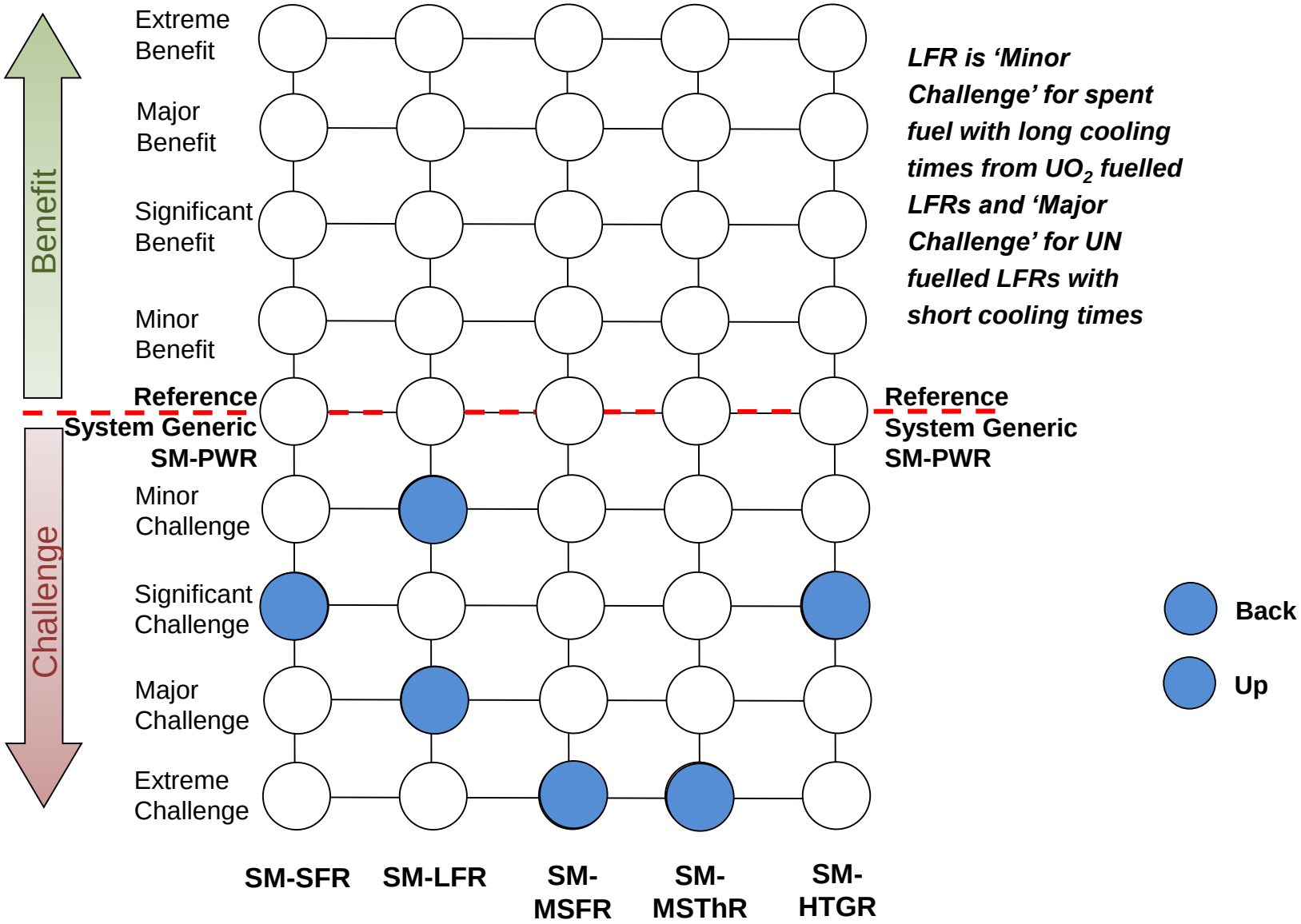
Overnight Construction Cost




Fuel Security
Benefit
Challenge
Extreme Benefit
Major Benefit
Significant Benefit
Minor Benefit
Reference System Generic SM-PWR
Minor Challenge
Significant Challenge
Major Challenge
Extreme Challenge
PB
Pri
Reference System Generic SM-PWR
Back
SM-SFR
SM-LFR
SM-MSFR
SM-MSThR
SM-HTGR

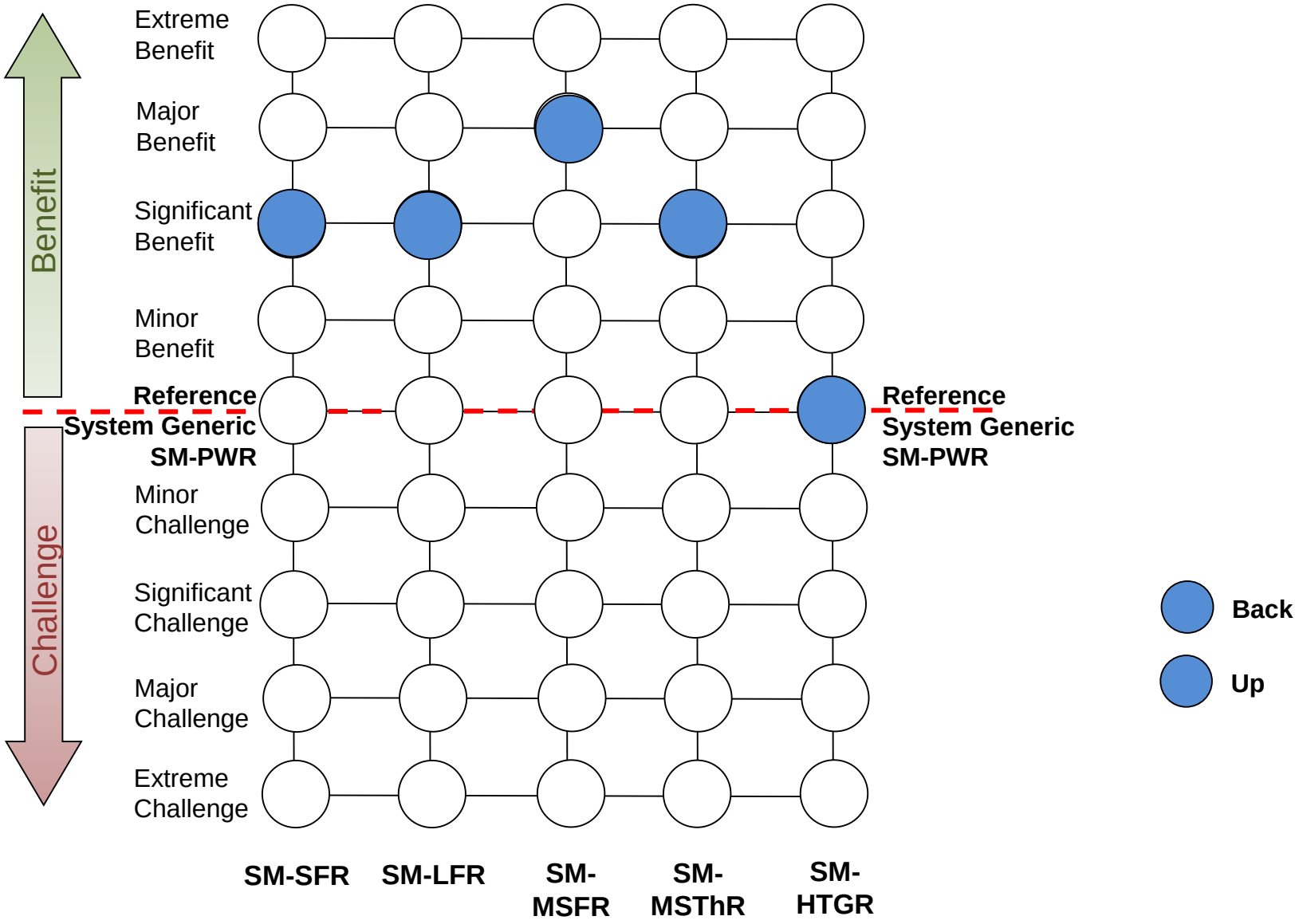

Disposability
Benefit
Challenge
Extreme Benefit
Major Benefit
Significant Benefit
Minor Benefit
Reference System Generic SM-PWR
Minor Challenge
Significant Challenge
Major Challenge
Extreme Challenge
L
L
S
S
SM-SFR
SM-LFR
SM-MSFR
SM-MSThR
SM-HTGR
L – long cooling times allowed
S – short cooling times required
Reference System Generic SM-PWR
Back
Down 1
Down 2

3b.1 Waste forms – number and type of waste forms compatible with current waste processing technology?

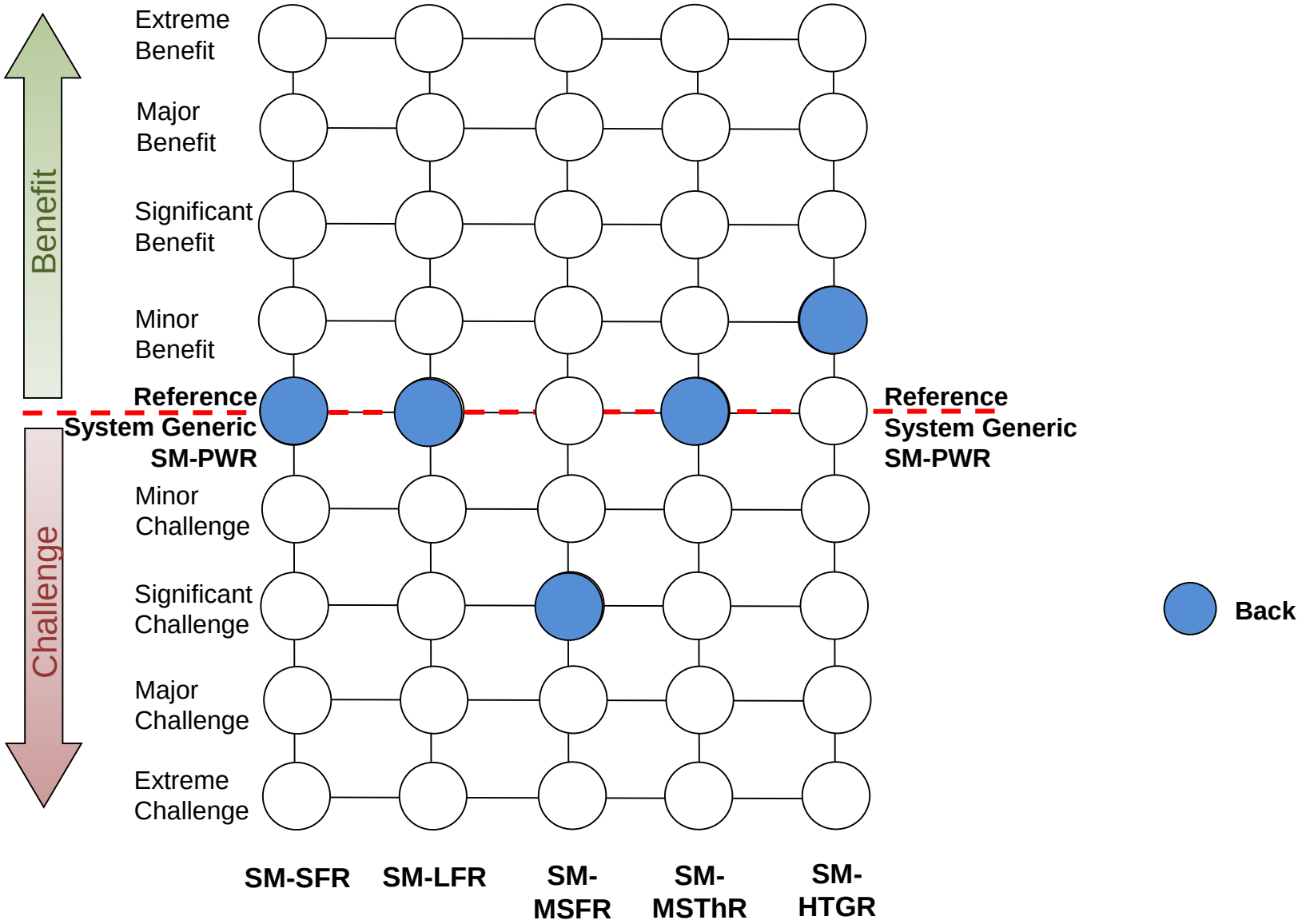


LFR is 'Minor Challenge' for spent fuel with long cooling times from UO_2 fuelled LFRs and 'Major Challenge' for UN fuelled LFRs with short cooling times

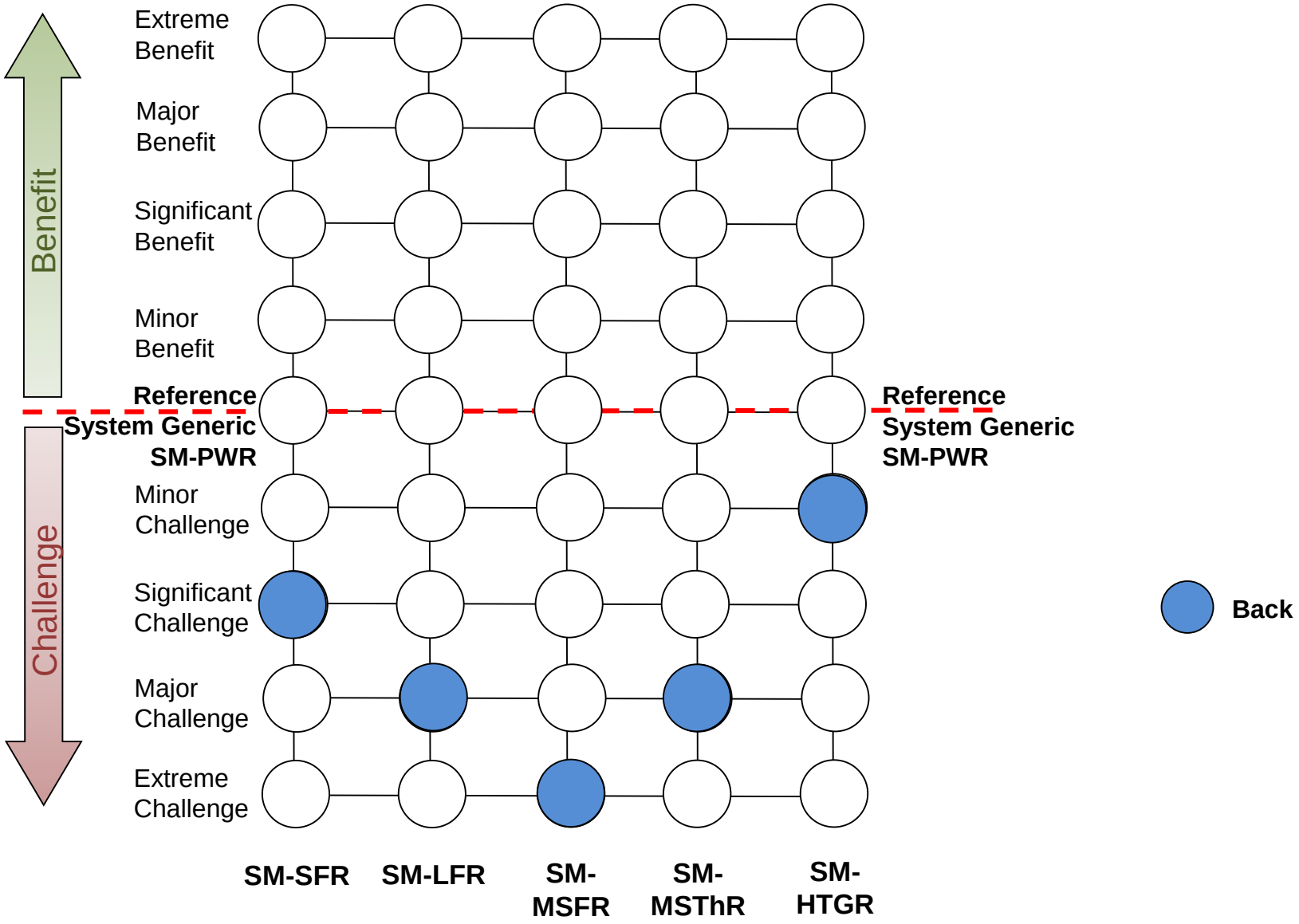
3b.3 GDF disposal impact – long term decay heat

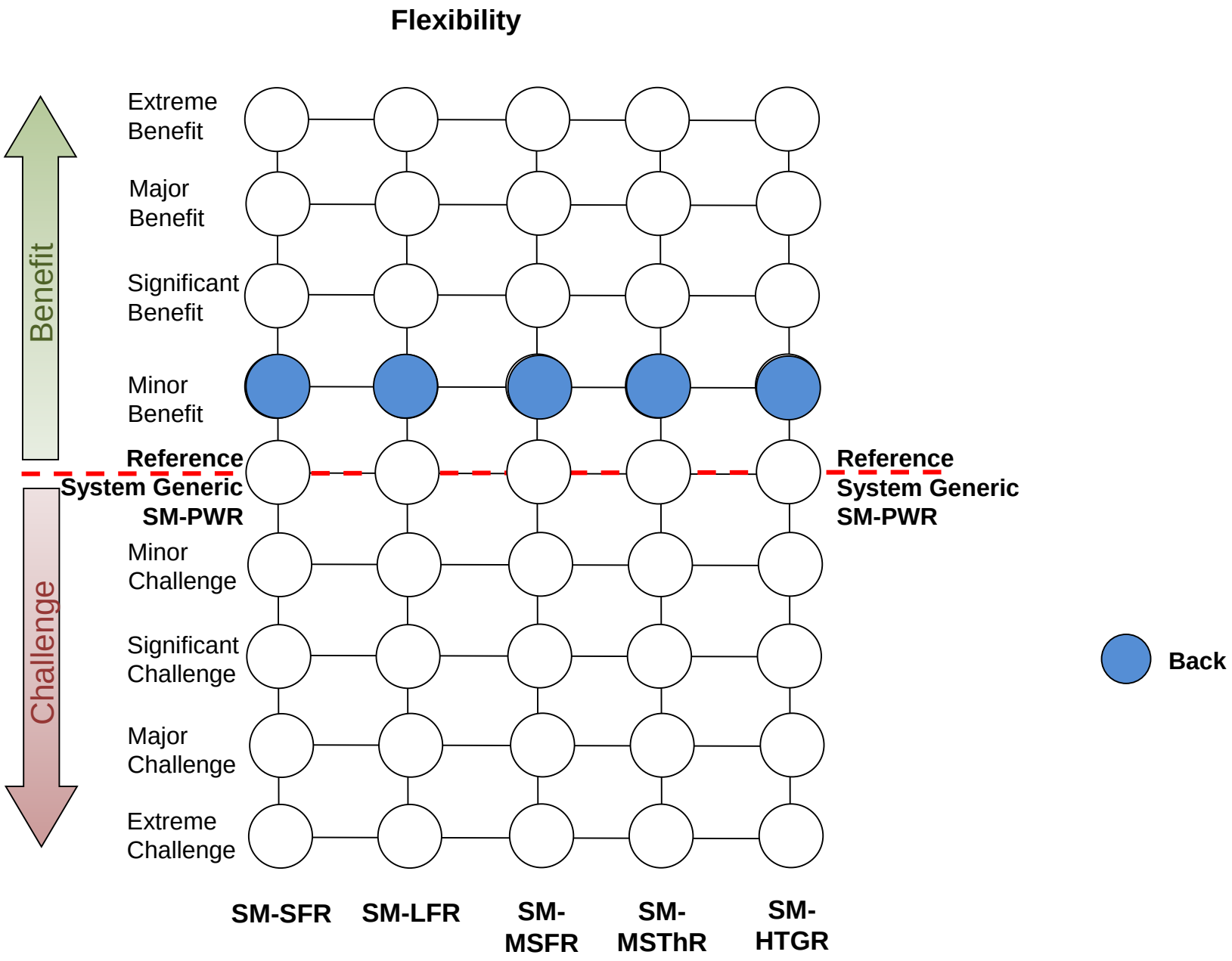


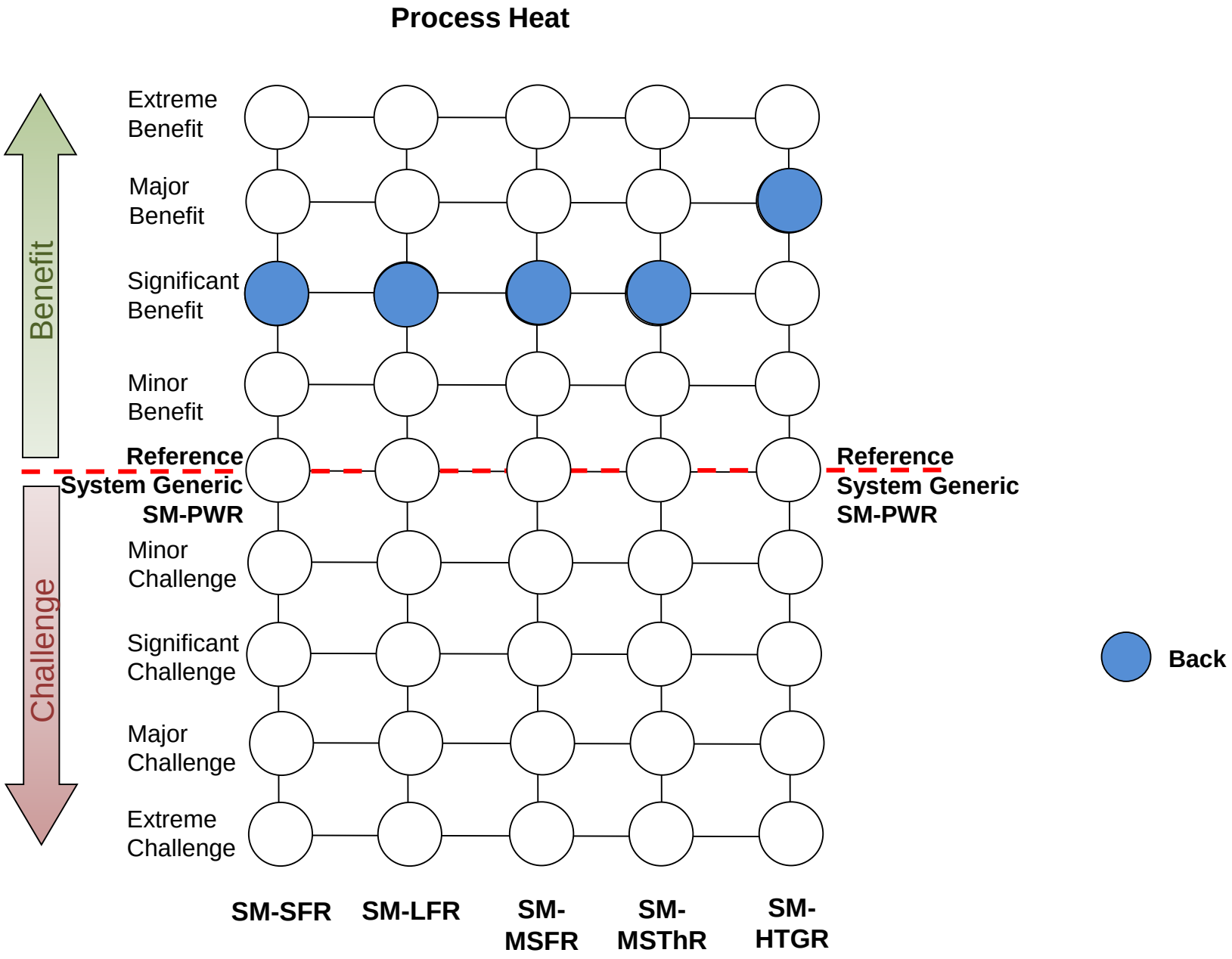
Siting – Reactor and Fuel Cycle



Time and Cost to Deployment




Flexibility
Benefit
Challenge
Extreme Benefit
Major Benefit
Significant Benefit
Minor Benefit
Reference System Generic SM-PWR
Minor Challenge
Significant Challenge
Major Challenge
Extreme Challenge
Reference System Generic SM-PWR
Back
SM-SFR
SM-LFR
SM-MSFR
SM-MSThR
SM-HTGR


Process Heat
Benefit
Challenge
Extreme Benefit
Major Benefit
Significant Benefit
Minor Benefit
Reference System Generic SM-PWR
Minor Challenge
Significant Challenge
Major Challenge
Extreme Challenge
Reference System Generic SM-PWR
Back
SM-SFR
SM-LFR
SM-MSFR
SM-MSThR
SM-HTGR